LONG TERM PLAN

PLANS AND PERSPECTIVES FOR ITALIAN ASTROPHYSICS

INAF

ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

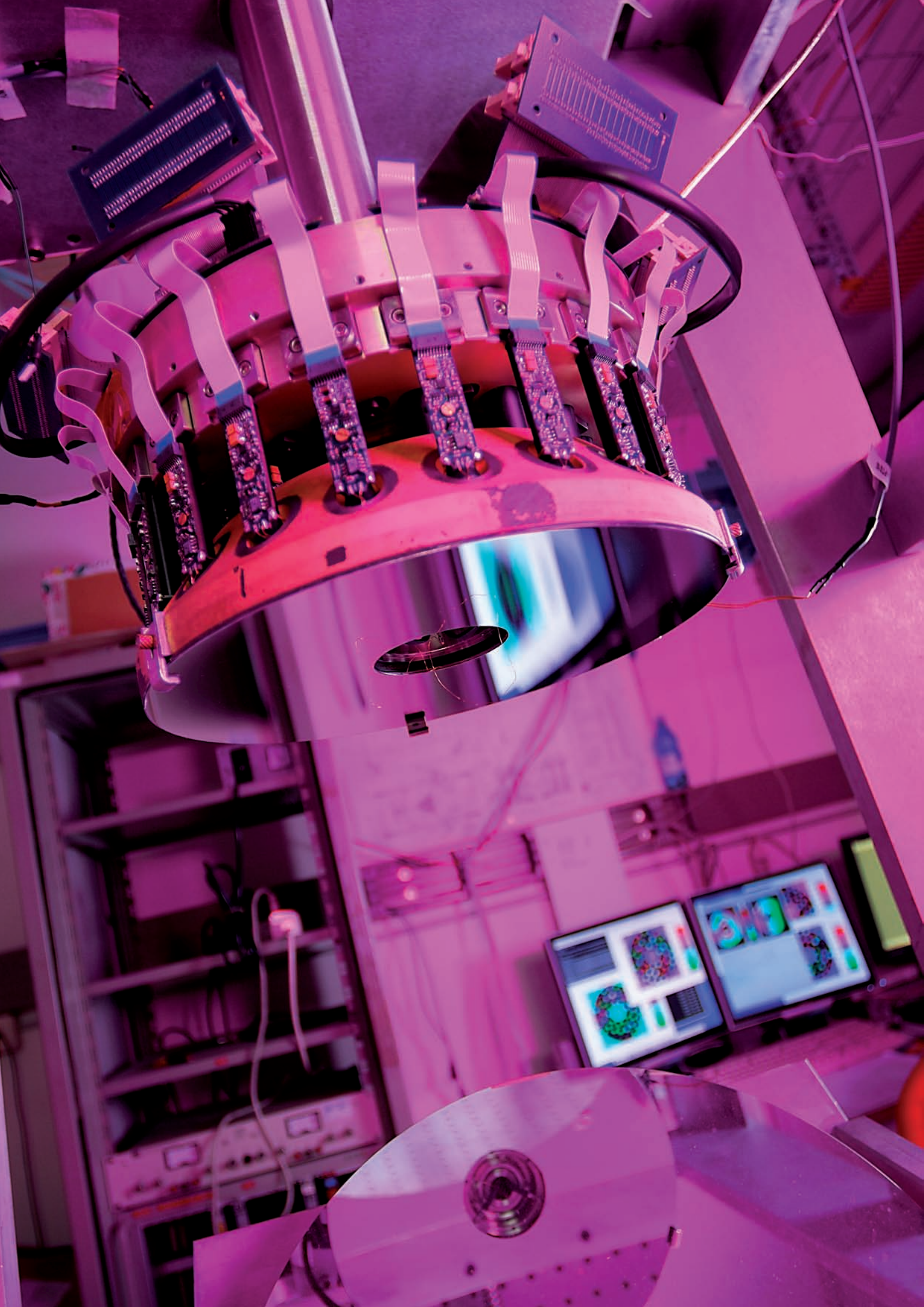
Cover image: artist's impression of a quasar located in a primeval galaxy a few hundred million years after the Big Bang - © ESA and Wolfram Freudling (ST-European Coordinating Facility/ESO).

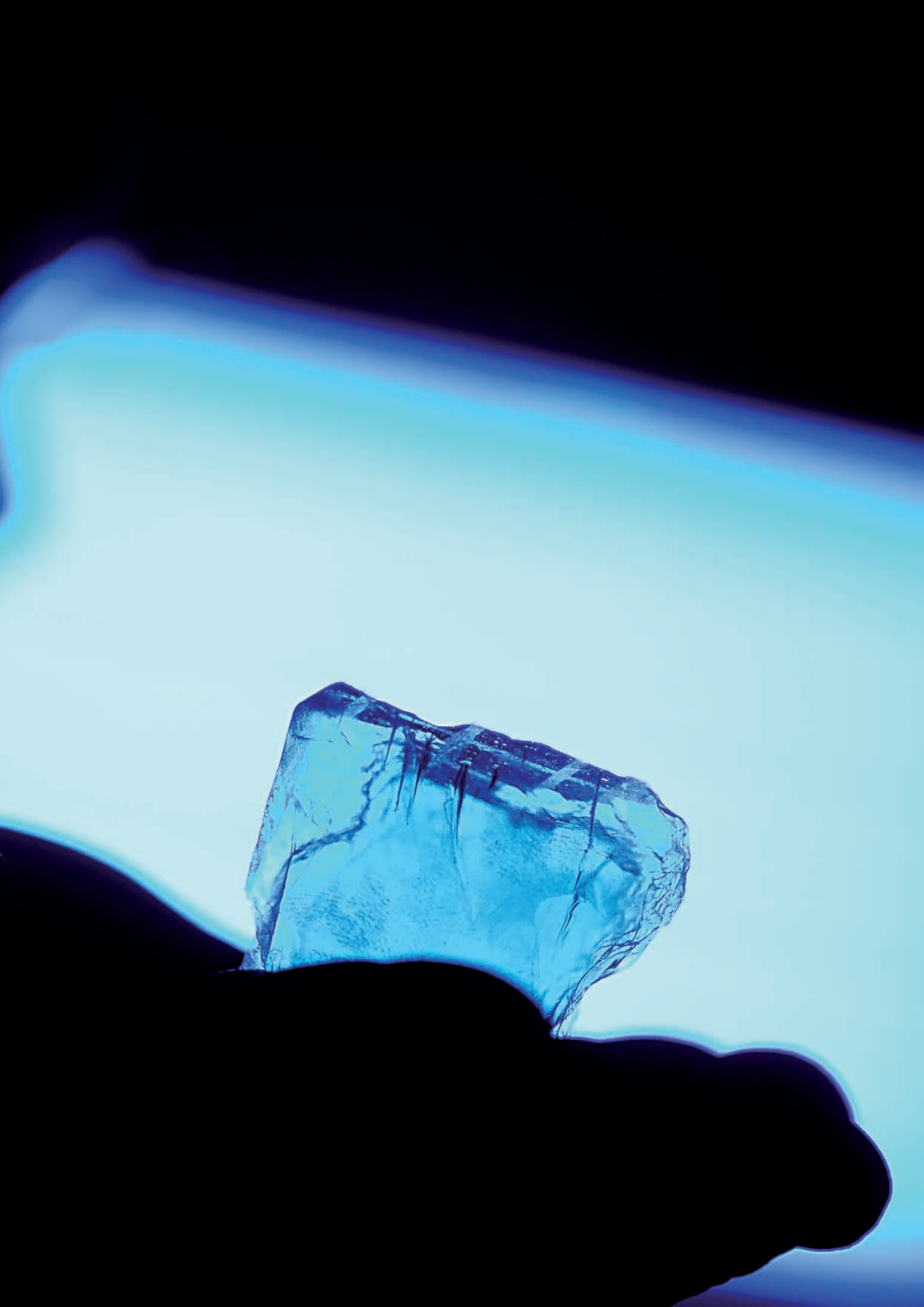
LONG TERM PLAN

PLANS AND PERSPECTIVES FOR ITALIAN ASTROPHYSICS

DECEMBER 2006

TABLES OF CONTENTS





PREFAZIONE

L'astrofisica moderna è un settore di ricerca in straordinaria evoluzione. Questa evoluzione è governata sia dalla disponibilità di tecnologie sofisticate che dallo sviluppo di nuovi strumenti concettuali, entrambe settori a cui i ricercatori italiani hanno dato e danno un contributo significativo. Nei prossimi anni ci attendono altre e più entusiasmanti scoperte, grazie all' entrata in funzione di nuovi strumenti da terra e dallo spazio, strumenti che ci forniranno una visione molto più profonda e dettagliata dell'Universo in cui viviamo.

Come sempre accaduto nella storia millenaria dell'astronomia, le nuove scoperte influenzeranno sia le scienze collegate, quali la fisica fondamentale, la bio-astronomia, la climatologia, che la nostra visione del mondo, arrivando a un livello di penetrazione nel pensiero comune caratteristico di poche altre discipline.

Per le sue caratteristiche di universalità e di scienza di base l'astrofisica gode di uno straordinario livello di internazionalizzazione. Gli strumenti più sofisticati richiedono l'impegno congiunto di molte nazioni, i gruppi ricerca sono sempre più internazionali ed il risultati delle ricerche sono prontamente accessibili attraverso il WEB a tutta la comunità.

In questo contesto, per poter ottimizzare le limitate risorse da destinare alla ricerca astrofisica e massimizzarne l'impatto, è fondamentale che la comunità astronomica italiana sviluppi una visione unificata dell'astrofisica, ne individui la possibile evoluzione nei prossimi anni, ed elabori le proprie priorità.

Partendo da questa esigenza l'Istituto Nazionale di AstroFisica (INAF), che ha come compito istituzionale quello di promuovere, realizzare e coordinare l'attività di ricerca nel campo dell'astrofisica in collaborazione con le Università che con altri soggetti pubblici e privati, nazionali e internazionali, ha elaborato il suo primo Piano di Lungo Termine (PLT).

L'elaborazione di questo piano è stata affidata, secondo il Regolamento di Organizzazione e Funzionamento dell'INAF, al Consiglio Scientifico che ne ha curato la redazione tra il maggio 2005 e l'ottobre 2006 e ne detiene l'esclusiva responsabilità. Il Consiglio Scientifico dell'INAF è composto da 12 scienziati appartenenti all'INAF, all'Università e ad Enti di Ricerca internazionali, attivi in vari campi dell'astrofisica, in parte eletti dalla comunità e in parte nominati dal Consiglio di Amministrazione e dal Presidente del-

l'INAF.
La struttura del PLT è nata da un'analisi attenta degli analoghi piani strategici preparati da istituzioni nazionali e internazionali, tra cui la Decadal Survey dalla N.S.F. degli Stati Uniti ed il piano Origins della NASA, il NRC-NSERC Long Range Plan canadese, il PPARC Strategic Plan inglese, quello olandese di NCA-NOVA-NWO e quelli preparati dalla European Science Foundation, dall'ESO, dalla European Astronomical Society e dall'ESA (Cosmic Vision). Sono stati anche recepiti i contenuti di recenti documenti preparati dalla comunità astronomica italiana in risposta a richieste di studi di da parte dell'Agenzia Spaziale Italiana (2003-2004).
Nel febbraio '06 il CS ha presentato al CdA dell'INAF la struttura del PLT e una prima ricognizione delle problematiche scientifiche e delle priorità identificate. In seguito, ha approfondito una serie di temi mediante incontri con gli scienziati italiani che, per la loro responsabilità in progetti scientifici o per la loro attività scientifica generale, sono stati considerati rappresentativi per questi temi o delle comunità estese.
Dopo aver terminato una prima stesura del PLT, il CS ha presentato e distribuito una prima versione alla comunità italiana nel maggio 2006, tramite incontri con i Direttori delle Strutture di ricerca ed i rappresentanti delle Macro-Aree tematiche, che rappresentano gli astronomi italiani secondo aree scientificamente omogenee.
L'insieme dei commenti ricevuti ha portato ad un ulteriore raffinamento del testo, che è stato definitivamente approvato dal Consiglio Scientifico il 5 ottobre 2006 ed adottato dal Consiglio di Amministrazione il 10 ottobre 2006.

Il PLT è organizzato in 6 Parti. La Parte 1 ("Executive summary") riassume le principali raccomandazioni e priorità indicate dal Piano. La Parte 2 presenta una rassegna delle principali sfide scientifiche che ci attendono e che saranno presumibilmente l'oggetto principale della ricerca astrofisica del prossimo decennio. Questa parte discute anche se questi temi di primo piano possano essere affrontati con la strumentazione attuale o necessitino piuttosto dello sviluppo di nuova e più sofisticata strumentazione. La Parte 3 illustra in dettaglio i progetti strumentali esistenti, o in preparazione, che sono considerati ad alta priorità per la comunità italiana, perché in grado di incidere significativamente sulle nostre conoscenze. La Parte 4 descrive l'organizzazione, le strutture di ricerca e l'attività dell'INAF attuale, mentre la Parte 5 analizza le innovazioni tecnologiche che potrebbero permettere l'avvio di progetti e strumentazione innovativi. Il risultato globale di tutta questa analisi è condensato nella Parte 6 sotto forma di road-maps e raccomandazioni organizzate secondo livelli di priorità che ispireranno le scelte e le azioni future dell'INAF. Le road-maps sono proposte e discusse per ogni area strategica su base temporale (progetti in corso, preparazione e nuovi) e di priorità. Queste ultime sono assegnate sulla base dell'importanza scientifica del progetto, del livello di coinvolgimento italiano, del livello di risorse INAF dedicate al progetto, del contesto internazionale (e perciò dell'unicità e della competitività del progetto), e della qualità dei partner internazionali.

RINGRAZIAMENTI

Questo lavoro non sarebbe stato possibile senza l'aiuto, i suggerimenti, il contributo e gli incoraggiamenti di un gran numero di membri della comunità scientifica italiana. In primis desideriamo ringraziare per il loro contributo fondamentale alla prima stesura del PLT Nicola Vittorio (Univ. Tor Vergata) e Fabio Favata (ESA), che sono stati membri del Consiglio Scientifico fino al maggio 2006.

Inoltre ringraziamo i seguenti colleghi per i loro consigli e commenti:
Luca Amendola, Ester Antonucci, Bruno Bavassano, Francesco Berilli, Daniela Bettoni, Giuseppe Bono, Jan Brand, Gianfranco Brunetti, Roberto Bruno, Maurizio Candidi, Fabrizio Capaccioni, Enrico Cappellaro, Vincenzo Carbone, Maria Bice Cattaneo, Gianna Cauzzi, Fabio Cavallini, Alberto Cellino, Claudio Chiuderi, Andrea Cimatti, Andrea Comastri, Giovanni Comoretto, Angioletta Coradini, Stefano Cristiani, Nichi D'amico, Domitilla De Martino, Silvano Desidera, Ilaria Ermolli, Jacopo Farinato, Luigina Feretti, Patrizia Francia, Emanuele Giallongo, Paola Grandi, Raffaele Gratton, Laura Greggio, Loretta Gregorini, Francesco Haardt, Hugh Hudson, Francesco Leone, Marco Limongi, Dario Lorenzetti, Dario Maccagni, Piero Madau, Francesco Malara, Franco Mantovani, Laura Maraschi, Silvia Masi, Giorgio Matt, Francesca Matteucci, Nicola Menci, Carlo Morello, Stefano Orsini, Isabella Pagano, Giovanni Pareschi, Fabio Pasian, Giampaolo Piotto, Luigi Piro, Isabella Prandoni, Roberto Ragazzoni, Maria Sofia Randich, Fabio Reale, Kevin Reardon, Alvio Renzini, Paolo Salucci, Marco Salvati, Roberto Scaramella, Salvo Sciortino, Giuseppe Severino, Daniele Spadaro, Sperello di Serego Alighieri, Luigi Spinoglio, Luigi Stella, Marisa Storini, Thomas Strauss, Gianni Strazzulla, Gianni Tofani, Amedeo Tornambè, Monica Tosi, Edoardo Trussoni, Pietro Ubertini, Rita Ventura, Andrea Zacchei, Gianni Zamorani, Gaetano Zimbardo.

Ringraziamo infine l'Ufficio Comunicazione e Immagine INAF, in particolare Caterina Boccato, per il paziente lavoro nella correzione delle bozze e nella realizzazione grafica di questo documento.

IL CONSIGLIO SCIENTIFICO INAF.

Magda Arnaboldi, Angela Bazzano, Piero Benvenuti, Marco Bersanelli, Armando Blanco, Pasquale Blasi, Enrico Costa, Fabrizio Fiore, Adriano Fontana, Giovanni Peres, Leonardo Testi, Massimo Turatto, Giovanni Valsecchi.

PREFACE

Modern astrophysics is rapidly evolving. This evolution is driven by the availability of sophisticated technologies and by the development of news conceptual instruments. Italian researchers are giving a significant contribution to both areas. In the next years new exciting discoveries will be produced by the instrumentation today in preparation. These new ground-based and space-borne instrumentation will provide a much deeper and detailed view of the Universe.

The new discoveries will most likely have a big influence on other research branches, like fundamental physics, bio-astronomy, climatology, and, more in general, on our view of the world.

Because of its characteristics of universality and of fundamental science, astrophysics is a highly international enterprise. The most sophisticated instruments require the common effort of many countries, and, accordingly, the research groups often include scientists working worldwide.
The results of the researches are promptly distributed through the World Wide Web to the scientific community.

To optimize the exploitation of the limited resources dedicated to astrophysics it is imperative that the Italian community develops a unified vision of astrophysics, identifies its likely evolution and sets priorities.

To this purpose, the Istituto Nazionale di AstroFisica (INAF), which has the duty of promoting and coordinating the astrophysical research activities, in collaboration with the Universities and other national and international Institutes, has elaborated its first Long Term Plan (LTP).

The preparation of this plan has been assigned to the INAF Scientific Council (CS), according to the INAF regulations. The CS is composed by twelve astrophysicists from INAF, Italian Universities and international research institutes. The CS drafted the LTP between May 2005 and October 2006 and holds full responsibility for all statements, recommendations and conclusions included in this document.

The LTP structure follows that of similar plans prepared by other international institutions like the United States N.S.F. Decadal Survey, the NASA Origins plan, the Canada NRC-NSERC Long Range Plan, the UK PPARC Strategic Plan, the Dutch NCA-NOVA-NWO plan e the long term plans prepared by the European Science Foundation, by ESO, by the European Astronomical Society and by ESA (Cosmic Vision). The strategic indications included in three studies committed by ASI and performed by the Italian astrophysical community during the years 2003-2004 have also been considered.

The CS presented a first draft of the LTP to the INAF “Consiglio di Amministrazione” during February 2006. In the following months the CS finalized the documents also through a series of meetings with leading Italian scientists who have prime responsibilities in specific scientific projects.

The first complete version of the LTP has been presented to the Italian community during May 2006, through a series of meetings with the Directors of the Italian Observatories and Institutes and the representatives of the thematic “Macro-Aree”.

Comments from these large boards have been included in the final version of the LTP presented to the CdA on 2006 October 5th. The CdA approved the document on 2006 October 10th.

This LTP is organized in 6 Parts. Part 1 is the Executive Summary and reports the main recommendations and priorities included in the Plan. Part 2 presents an overview the major open astrophysics topics, which are most likely to focus researches’ efforts in the next decade, and whether they can be investigated either with current or future instrumentation. Part 3 includes a detailed presentation of those projects considered as high priority for prospective important breakthrough. Part 4 presents the organization, the structures and the main scientific activities of INAF. Part 5 analyzes the technical innovations that may enable the undertaking of new projects and instrumentation.

The final result of this detailed analysis is given is Part 6 in the form of road-maps and sets of priorities which INAF should take into account in its future actions. The road-maps have been proposed and discussed for each strategic research area, based on the timeframe (on going projects; projects in preparation; new projects) and priorities. Priorities were assigned according to the scientific relevance of the project, the level of national and INAF involvement, the level of INAF internal resources committed to the project, the international context (and therefore the level of uniqueness and competition of the project), and the quality of the international partners.

ACKNOWLEDGEMENTS

This work would not have been possible without the help, the contributions and the advice of a large number of Italian scientists. First, we would like to acknowledge the fundamental contributions provided by Fabio Favata (ESA) and Nicola Vittorio (University of Roma II), former members of the CS, to the preparation of the first complete version of the LTP.

The following colleagues also contributed with specific comments, suggestions and discussions:

Luca Amendola, Ester Antonucci, Bruno Bavassano, Francesco Berilli, Daniela Bettoni, Giuseppe Bono, Jan Brand, Gianfranco Brunetti, Roberto Bruno, Maurizio Candidi, Fabrizio Capaccioni, Enrico Cappellaro, Vincenzo Carbone, Maria Bice Cattaneo, Gianna Cauzzi, Fabio Cavallini, Alberto Cellino, Claudio Chiuderi, Andrea Cimatti, Andrea Comastri, Giovanni Comoretto, Angioletta Coradini, Stefano Cristiani, Nichi D'amico, Domitilla De Martino, Silvano Desidera, Ilaria Ermolli, Jacopo Farinato, Luigina Feretti, Patrizia Francia, Emanuele Giallongo, Paola Grandi, Raffaele Gratton, Laura Greggio, Loretta Gregorini, Francesco Haardt, Hugh Hudson, Francesco Leone, Marco Limongi, Dario Lorenzetti, Dario Maccagni, Piero Madau, Francesco Malara, Franco Mantovani, Laura Maraschi, Silvia Masi, Giorgio Matt, Francesca Matteucci, Nicola Menci, Carlo Morello, Stefano Orsini, Isabella Pagano, Giovanni Pareschi, Fabio Pasian, Giampaolo Piotto, Luigi Piro, Isabella Prandoni, Roberto Ragazzoni, Maria Sofia Randich, Fabio Reale, Kevin Reardon, Alvio Renzini, Paolo Salucci, Marco Salvati, Roberto Scaramella, Salvo Sciortino, Giuseppe Severino, Daniele Spadaro, Sperello di Serego Alighieri, Luigi Spinoglio, Luigi Stella, Marisa Storini, Thomas Strauss, Gianni Strazzulla, Gianni Tofani, Amedeo Tornambè, Monica Tosi, Edoardo Trussoni, Pietro Ubertini, Rita Ventura, Andrea Zacchei, Gianni Zamorani, Gaetano Zimbardo.

We finally thank the INAF Public Relations and Communication Office, especialliy Caterina Boccato, for proof reading and editorial support.

THE INAF SCIENTIFIC COUNCIL

Magda Arnaboldi, Angela Bazzano, Piero Benvenuti, Marco Bersanelli, Armando Blanco, Pasquale Blasi, Enrico Costa, Fabrizio Fiore, Adriano Fontana, Giovanni Peres, Leonardo Testi, Massimo Turatto, Giovanni Valsecchi.

PARTE 1: SOMMARIO ESECUTIVO

L'astrofisica è una delle principali branche della fisica fondamentale, in quanto il suo scopo è quello di descrivere l'Universo, la sua origine ed i suoi componenti in termini di leggi della fisica, e di verificare le teorie fisiche in quei laboratori privilegiati che sono gli oggetti astronomici, nei quali le condizioni sono estremamente distanti e molto più probanti di quelle che si possono avere sulla Terra.

Nell'ultimo decennio le conoscenze astrofisiche sono cresciute esponenzialmente e, come accade sovente nella scienza, nuove scoperte hanno portato a domande nuove e legate a problemi più profondi. Dagli esperimenti sul Cosmic Microwave Background (CMB, fondo cosmico a microonde) e dalle campagne osservative dello telescopio spaziale Hubble abbiamo appreso che l'Universo sta accelerando la sua espansione, e che oltre il 90% di esso è costituito da due elementi misteriosi, la cosiddetta "Dark Energy" (energia oscura), che ne determina l'accelerazione, e la "Dark Matter" (materia oscura), che è responsabile dell'attrazione gravitazionale che governa il moto delle sue componenti luminose, quali stelle e gas.

Galassie e buchi neri supermassicci sono stati osservati a distanze superiori a 12.5 miliardi di anni luce, corrispondenti all'incirca ad appena 800 milioni di anni dopo il Big Bang: come queste strutture si siano aggregate è ancora poco chiaro. Si sono studiate le esplosioni più energetiche della storia dell'Universo, i cosiddetti Gamma Ray Bursts, o lampi gamma: nonostante questi fenomeni siano tuttora mal compresi, forniscono tuttavia un promettente strumento di esplorazione delle leggi fondamentali della fisica. Si sono osservati raggi cosmici di energie straordinariamente superiori a quelle ottenibili nei più potenti acceleratori terrestri, la cui natura è tuttora sconosciuta. Sono stati scoperte centinaia di pianeti intorno a stelle vicine al Sole, senza però trovarne ancora alcuno simile alla Terra, e, soprattutto, senza trovare alcuna prova di vita extraterrestre.

La nostra comprensione della formazione delle stelle e dei pianeti e dello sviluppo delle condizioni necessarie alla vita sulla Terra (e sui pianeti extrasolari simili al nostro) è tuttora estremamente limitata. L'esplorazione del nostro stesso sistema solare ha solo cominciato a svelare quanto complesso ed eterogeneo sia il processo di formazione planetaria. Lo studio della nostra stella, il Sole, si è rivelato fondamentale per capire sia le proprietà fisiche delle stelle in generale che la sua influenza sul clima e l'ambiente della Terra.

Questi non sono altro che alcuni esempi dei problemi aperti che verranno affrontati nel prossimo decennio, e che rappresentano il nucleo della ricerca astrofisica descritta in questo Piano di Lungo Termine.

Negli ultimi decenni l'astrofisica italiana ha raggiunto posizioni di vertice, divenendo una delle comunità di riferimento a livello internazionale in vari campi osservativi e teorici quali, ad esempio, la cosmologia CMB, l'astronomia X, Gamma e di raggi cosmici, la cosmologia osservativa, la formazione ed evoluzione stellare e planetaria, l'esplorazione del Sole e del sistema solare. Inoltre, l'Italia è stata molto attiva nella progettazione e costruzione di grandi infrastrutture sia terrestri sia spaziali. Per questo motivo, gli astronomi italiani si trovano in una situazione che può permettere loro di avere un ruolo di punta nelle ricerche più importanti del prossimo decennio.

Lo scopo di questo documento è l'identificazione delle aree scientifiche e tecnologiche nelle quali l'Istituto Nazionale di AstroFisica (INAF) dovrebbe concentrare sforzi e risorse, in modo da permettere ai ricercatori italiani di mantenere posizioni di vertice nel prossimo decennio. A questo scopo, il documento presenta un'unica visione globale degli argomenti principali dell'astronomia e dell'astrofisica del prossimo decennio. Si intende che questo Piano di Lungo Termine dovrebbe essere periodicamente rivisto ed aggiornato al fine di includere progetti ed idee innovative.

Questo documento non contiene piani operativi, né discute come si debbano dedicare risorse a specifiche attività: piuttosto, esso identifica le condizioni necessarie a mantenere un ruolo di primo piano. A questo scopo occorre garantire: i) accesso a strutture osservative d'avanguardia; ii) un livello almeno costante nel numero e nella qualità degli astrofisici che lavorano in Italia; iii) finanziamenti adeguati per la ricerca libera e per lo sviluppo di strumentazione innovativa. E' estremamente difficile che le risorse attualmente disponibili per l'astronomia e l'astrofisica in Italia permettano di soddisfare questi requisiti; in particolare, esse non permetteranno alla comunità scientifica italiana di partecipare ad importanti grandi iniziative in corso di sviluppo sia a livello europeo che mondiale. In questa situazione, è indispensabile fissare delle priorità.

Sulla base di questa impostazione, e dopo una approfondita analisi delle problematiche scientifiche più importanti, e degli sviluppi strumentali e teorici attesi, si formulano pertanto le seguenti raccomandazioni:

- La ricerca libera, sia osservativa che teorica, è una risorsa strategica e deve essere incoraggiata come attività prioritaria.
- Il livello scientifico è il criterio più importante per lo sviluppo di nuovi progetti.
- Va incoraggiata l’organizzazione di grandi collaborazioni e grandi programmi, incluse grandi “surveys” (campagne osservative) e ricerche teoriche dedicate.
- Non si devono iniziare o portare avanti nuove grandi infrastrutture tecnologiche se questo avviene a spese dell’adeguato supporto alle attuali attività scientifiche di punta dell’INAF.
- Il ruolo dell’INAF all’interno di organizzazioni internazionali quali l’ESO e l’ESA deve essere più attivo ed incisivo.
- Le proposte di nuovi progetti, strumentazioni ed infrastrutture osservative devono essere in ogni caso selezionate attraverso un processo bottom-up, partendo dalla loro rilevanza scientifica.
- Occorre coordinare le strategie con le università italiane, attraverso la stipula di accordi formali, allo scopo di creare una comunità astrofisica nazionale coesa, che integri in profondità l’attività’ di ricerca con quella didattica di alto livello, e permetta un’idonea mobilità del personale fra l’INAF e le università.
- La collaborazione ed il coordinamento su progetti comuni con altri istituti di ricerca italiani dovrebbero anch’essi essere rafforzati.

L’acquisizione di un ruolo di preminenza nelle più importanti infrastrutture internazionali, capaci di portare a risultati rivoluzionari, è da considerarsi come una priorità assoluta. L’INAF dovrebbe, perciò, sostenere il coinvolgimento tecnologico in un certo numero di progetti chiave previsti per il prossimo decennio e per quelli successivi. Qui di seguito sono riassunti sinteticamente questi progetti chiave, con le relative raccomandazioni per il coinvolgimento italiano.

- L’accesso della comunità italiana alle principali infrastrutture internazionali presenti e future, aventi un significativo contributo italiano, deve essere garantito e, se possibile, aumentato attraverso iniziative dedicate. La lista di queste infrastrutture comprende **VLT**, **XMM**, **SOHO**, **Herschel**, **GLAST**, **Auger**. E’ inoltre auspicabile l’aumento dell’accesso italiano ad altre importanti infrastrutture internazionali nelle quali siamo poco coinvolti, quali **HST, Chandra e Spitzer ed in futuro JWST.**

- Occorre sviluppare strumentazione innovativa, a guida italiana, per grandi telescopi da terra, ed in particolare occorre agire per mantenere la strumentazione di VLT al massimo livello e sostenere attivamente lo sviluppo delle prossime generazioni di strumenti.
- Va preparata la comunità nazionale allo sfruttamento scientifico delle prossime grandi imprese ESO ed ESA quali **ALMA** e **GAIA**.
- Si deve partecipare allo sviluppo delle prossime grandi infrastrutture come **ESO-ELT, SKA**, osservatori ad alta sensibilità sia negli **X molli che negli X duri**, a condizione che sia garantita una partecipazione rilevante della comunità alla strumentazione e/o allo sfruttamento scientifico dei dati.
- Va adeguatamente sostenuta la comunità coinvolta in **Mars-Express, Venus-Express e ROSETTA** e la preparazione di **BepiColombo** ed **ExoMars**.
- Per gli studi sulle fasi iniziali dell'universo, l'INAF deve garantire il pieno sfruttamento scientifico dei dati di **Planck** ed il mantenimento del ruolo di punta negli **esperimenti suborbitali di CMB**, anche in preparazione alla partecipazione ad una missione dedicata alla rivelazione della **polarizzazione B del CMB**.

L'INAF ha ereditato quattro grandi progetti tecnologici (TNG, LBT, VST e SRT), tutti nati in contesti (scientifici e politici) drasticamente diversi dalla situazione attuale. LBT, SRT e VST si basavano su finanziamenti dedicati di fatti insufficienti per il loro completamento, e in mancanza di piani di finanziamento adeguati per le loro operazioni e per lo sfruttamento scientifico. Ci si aspetta che LBT, SRT e VST diano luogo ad alti ritorni scientifici per la comunità nazionale, benché da un lato essi richiedano investimenti consistenti per essere completati, e dall'altro il loro pieno sfruttamento sia ancora soggetto ad una quota significativa di rischio.

Per questi progetti si suggeriscono le azioni seguenti:

- Sebbene il completamento di queste infrastrutture non sia qui messo in discussione, esso non deve aver luogo a scapito delle attività scientifiche attuali dell'INAF;
- Il supporto al futuro sfruttamento di questi osservatori, e lo sviluppo di nuova strumentazione, devono essere messi in competizione con tutti gli altri progetti dell'INAF.

Le priorità principali per questi progetti sono:

- Sostenere le operazioni di **LBT** per facilitare l'accesso della comunità italiana e per lo sfruttamento ottimale delle sue capacità scientifiche. **LBC** deve essere sfruttata a pieno attraverso grandi campagne osservative dedicate;
- Ad un livello di priorità più basso, **TNG** dovrebbe essere reso più competitivo attraverso un uso finalizzato a progetti specifici;
- Prendere provvedimenti efficaci ad assicurare il rapido completamento di **VST**. Sostenerne l'uso attraverso grandi campagne osservative, a seguito di un riesame critico e di un aggiornamento dei programmi scientifici, con il coinvolgimento di tutta la comunità italiana;
- In campo radioastronomico, **SRT** è la prima priorità a corto e medio termine, fatta eccezione per ALMA, purché sia prima dimostrata la sua capacità di raggiungere con buoni livelli di efficienza frequenze di 40-100 GHz.

Altri progetti importanti richiedono livelli di investimento INAF medio o basso (centinaia di kEuro/anno o meno), ma hanno potenzialmente un grande impatto sulla comunità. Questi progetti includono:

- Strumentazione per immagini e spettroscopia a grande campo da terra e dallo spazio; interferometria nel vicino infrarosso al VLT ed all'LBT (VLTI, Link-Nirvana) e, in futuro, dallo spazio; SPICA;
- Swift, INTEGRAL ed il suo eventuale successore, missioni X dedicate (polarimetria e spettroscopia ad alta risoluzione); AGILE; telescopi Cherenkov come HESS, MAGIC e CTA; la prossima generazione di esperimenti di raggi cosmici;
- Cassini, una nuova missione al sistema gioviano e l'esplorazione in situ di un NEO;
- Solar Orbiter ed un grande telescopio solare basato a terra.

PART 1: EXECUTIVE SUMMARY

Astrophysics is a major branch of fundamental physics. Its ultimate goals are to understand the origin and the constituents of the Universe in terms of the laws of Physics, and to test both new and conventional physics in privileged laboratories that provide conditions far more extreme than those available on Earth.

During the last 10 years, the fund of astrophysical knowledge has experienced an exponential growth and, as usually happens in science, the new discoveries have spawned new, more intriguing and still more crucial questions. We know now, from the Cosmic Microwave Background (CMB) experiments and from the Hubble Space Telescope (HST) deep surveys, that the Universe is accelerating its expansion due to the existence of the so-called 'Dark Energy', and that 'Dark Matter' is responsible for the majority of the gravitational pull that drives the motions of its luminous components: the gas and the stars.

Galaxies and accreting super-massive Black Holes have been detected at distances of more than 12.5 billion light-years, corresponding to epochs a mere 800 million years after the Big Bang. How these massive structures were assembled is still unclear. The most energetic explosions in the history of the Universe, the so-called 'Gamma Ray Bursts', have been extensively studied. While they remain puzzling phenomena, they represent a most promising tool to explore the fundamental laws of physics. Cosmic rays with energies exceeding the ones achievable in terrestrial accelerators have been detected, although their origins and acceleration mechanisms remain unknown. Hundreds of planets have been discovered around nearby stars, but we have not yet detected any Earth-like planets, nor have we gathered evidence for extraterrestrial life.

Our understanding of the formation of stars and planetary systems as well as of the development of the conditions required for the appearance of Life on Earth (and possibly Earth-like exoplanets) is still very limited. The exploration of our own solar system has only begun to reveal how complex and heterogeneous the process of planet formation is. The study of our star, the Sun, is of fundamental importance for the understanding of the physical properties of Stars in general and for its influence on the Earth's climate and environment.

These are a few examples of the open questions that will be central for astrophysical investigation in the next decade and they represent the core of the astrophysical research described in this long-term plan.

Over the last few decades, Italy has gained a top-level position in astrophysical research, holding the leadership in a number of observational and theoretical topics, for example CMB cosmological studies, X-ray, gamma-ray and cosmic-ray astronomy, observational cosmology, formation and evolution of stars and planetary systems, and the exploration of the Sun and of the solar system. Furthermore, Italy has been very active in planning and building major observing infrastructures, both on the ground and in space. Italian astronomers are therefore in a position that will allow them to play a leading role in the areas of research that are anticipated to be in the forefront of physics during the next decade.

This document is aimed at identifying the scientific and technological areas where INAF should focus its efforts and resources so that Italian researchers can retain their leading position during the next decade. To this purpose, this document presents a unified vision of the main topics in astronomy and astrophysics in the foreseeable future. The intention is to periodically revise and updated it to include innovative new projects and ideas.

The document does not contain an operational plan nor does it discuss how resources should be allocated to specific activities. However, the minimum necessary conditions for keeping such leadership are identified in: i) ensuring the access to the state-of-the-art observing infrastructures; ii) keeping at least at constant level the number and quality of the astrophysicists working in Italy; iii) providing adequate funding for free research and development into new cutting-edge instrumentation. The present level of resources available for astronomy and astrophysics in Italy will barely allow the fulfillment all these requirements. In particular, it will not allow the Italian scientific community to play a leading role in all the important large enterprises under development both in Europe and worldwide. In such a situation, it is mandatory to set priorities and formulate recommendations. These are listed below:

- Fundamental research, both observational and theoretical, is a strategic resource that must be encouraged as a high priority activity.
- Scientific priority is the most important criterion for selecting

new projects.
- The organization of large collaborations and programs should be encouraged, including large surveys and the associated theoretical research.
- New large technological infrastructures should not be started or continued at the expenses of an adequate support to the current INAF scientific activities.
- The role of INAF within international organizations like ESO and ESA should be more active and effective, in particular regarding the development of the next large international infrastructures.
- Proposals for new projects, instrumentation and observing infrastructures must always be selected through a bottom-up process, based on their scientific relevance.
- Strategic coordination with Italian Universities should be pursued through formal agreements in order to create a compact national astrophysical community that allows a close integration of research, higher education and staff mobility between INAF and Universities.
- Collaboration and coordination with other Italian scientific institutions on common projects should also be strengthened.

Achieving a leading role in those major international projects that can produce outstanding scientific breakthroughs is a top priority. INAF should therefore support technological involvement in a number of key projects planned for the coming decade and beyond. These important international projects and the recommended Italian involvement are briefly described below.

- The access of the Italian community to major present and near future international facilities with significant Italian contributions must be guaranteed and possibly increased through dedicated support. Such facilities are: **VLT, XMM, SOHO, Herschel, GLAST and Auger**. Improving the access to other major currently operating international facilities with little Italian involvement, like **HST, Chandra, Spitzer** and in the future **JWST**, would also be desirable.
- Develop Italian-led **innovative instrumentation for large ground-based telescopes** and, in particular, actively support the development of the next generation **VLT** instruments. Contribute to keeping the VLT instrumentation at the top level.
- Prepare the community for the exploitation of the next large ESO and ESA facilities like **ALMA** and **GAIA**.
- Participate in the development of the future major facilities like

ESO-ELT, SKA, high-sensitivity observatories in both soft and hard X-rays, provided that a relevant participation of the community in the instrumentation and/or to the science is guaranteed.

- Support the community involved in **Mars-Express**, **Venus-Express** and **ROSETTA** and the preparation of **BepiColombo** and **ExoMars**.
- INAF should act to guarantee the full exploitation of **Planck** data and to maintain its leadership in **CMB sub-orbital experiments**, also in the preparation of the participation in a mission dedicated to the detection of the **B mode polarization of the CMB**.

INAF has inherited four large technological projects (TNG, LBT, VST and SRT) started in frameworks dramatically different from the current situation. LBT, SRT and VST benefited from dedicated funding that turned out to be inadequate for their completion, operation and exploitation. LBT, VST and SRT are expected to produce a high scientific return for the Italian community, but they require a high level of investment for their completion (including development of adequate instrumentation), operation and data analysis. Furthermore, their full exploitation is still subject to significant risks.

For these projects the following is recommended:

- The completion of these infrastructures, although not questioned here, should not jeopardize the principal scientific activities of INAF.
- The level of support for the future exploitation of these observatories and the development of new instrumentation must be subject to scientific competition with all other INAF projects.

The main priorities for these projects are:

- Supporting and enabling the access of the Italian community to **LBT** for the best exploitation of its scientific capabilities is a first priority. **LBC** should be best exploited through dedicated large/legacy surveys.
- **TNG** should be made more competitive by focusing its use on a few, large specific programs.
- Take radical actions to ensure the rapid completion of **VST**. Support large/legacy surveys, following a critical review and update of the scientific plans, with the involvement of the Ita-

lian community at large.
- In the field of radio-astronomy, **SRT** is — apart from ALMA— the first priority on short/medium timescales, provided that its capability to operate efficiently high frequencies (40-100 GHz) is first demonstrated.

Other important projects require a medium or a low level of funding (hundreds of kEuro/yr or less) but have a potentially large impact on the community.
These include:
- **Wide field optical/NIR imaging and spectroscopy** from ground and space telescopes; **NIR interferometry** at VLT and LBT (VLTI, Linc-Nirvana) and, in the future, from space; **SPICA**.
- **Swift, INTEGRAL** and its possible successor, **dedicated X-ray missions** (polarimetry and high resolution spectroscopy); **AGILE; Cherenkov telescopes** like HESS, MAGIC, and CTA; the next generation of **Cosmic Ray experiments**.
- **Cassini**, a new mission to the **Jovian system** and to the **in situ exploration of a NEO**.
- **Solar Orbiter** and a **large ground-based solar telescope**.

PART 2: MAJOR CHALLENGES IN ASTRONOMY OVER THE NEXT DECADE

Introduction: summary of science cases

This Part describes some of the major themes on which astrophysicists will be involved in the next decade and present a list of related hot topics that may be tackled with the instrumentation presently available or in preparation, or through new and more ambitious enterprises. In the following we present a short summary of the nine themes, which are discussed in more detail in the next sections.

I. Geometry and fundamental nature of the Universe

• The study of the early Universe will remain a central topic of modern Physics in the next decade. What were the physical properties of the primordial Universe? What produced the initial spectrum of fluctuations? Was there a Universe before the Big Bang? Did the Universe go through an inflationary acceleration, and what drove it? Theoretical studies, also concerning the development of grand-unification schemes, as well as observations, in particular the search for signatures of the inflations in the B-mode polarization of the CMB, are both needed to explore these issues.

• The discovery that ordinary matter barely constitutes ~4% of the total energy budget of the Universe, the remaining 96% being a mixture of some form of dark matter and dark energy, is one the major achievements of science – not simply of astronomy. Rather than solving the puzzle, such a discovery has opened up new basic questions: what is the nature of dark matter and dark energy? How are they related to the fundamental properties of space-time? Astronomical surveys will remain a leading tool to explore these topics: future observations of weak lensing, high redshift standard candles and large scale baryonic oscillations will help in finding the equation of state of the Universe and its evolution with the cosmic time.

II. The formation and the evolution of the structure in the Universe

• When and how did the first objects started to shine? What was the typical mass of the first stars and accreting Black Holes? How did the Universe get ionized? Addressing these and other questions is the motivation for the exploration of the last, farthest frontier in the observable Universe: the end of the "dark ages". This is an incredibly difficult task and requires the development of next generation ground and space based telescopes.

- According to the "standard cosmological model" the birth, assembly and evolution of galaxies occurred in a bottom-up, "hierarchical" fashion. Are the observations at low and high redshifts consistent with the basic predictions of this scenario? Can we model the physical processes that led to galaxy formation and evolution? Can we unify into a single, coherent picture the evolution of galaxies and of the AGNs that they harbour? Pinning down such broad scenario will be one of the major goals of science in the next decade. As in all complex processes, it is not possible to identify a priori the leading physical mechanism driving these phenomena. A global picture will likely emerge from both studies of galactic—scale phenomena, such as interaction between galaxies or influence of the surrounding environment, and cross-disciplinary achievements in fields, such as star—formation, of stellar populations, feedback from supernovae and AGNs.

- Not only baryons form a small fraction of the Universe, but also only a minority of this fraction is locked in luminous objects like stars. Most baryons in the Universe at $z<1$ are hidden in structures that are so far poorly observed. Determining what fraction is in the form of compact obscure objects, or in the form of a tenuous, warm Inter Galactic Medium, or in more exotic structures, is a challenging, cross-disciplinary task for the next decade.

III. The history of the Galaxy and of nearby galaxies

- In the last years we have been able to study galactic stellar clusters and external nearby galaxies on a star-by-star basis providing robust constraints on the Star Formation history and on the IMF of simple and complex stellar systems. However, the current scenario still presents several unsettled problems. Indeed the available deep observations are limited to a few bands, although also UV and NIR data are required in order to remove uncertainties on element abundance and age. We still miss dynamical models that will allow us to understand the interplay between stellar evolution and dynamical evolution in crowded environments. In principle with such studies it will be possible to derive the IMF from the study of the luminosity functions.

- The role of stellar clusters as ideal test-benches for evolutionary models has recently been challenged by observations showing that some globular clusters exhibit at least two generations of stars. In addition, the large number of exotic objects in clusters, many of which still unclear, shows that the stellar evolution in star clusters is not passive but is affected by the dynamical evolution of the cluster mentioned above. But models need observational inputs, among which the most important ones are accurate distance, reddening, metallicity, which can be determined with systematic photometric and spectroscopic projects at various wavelengths on large ground based and space telescopes.

- During their evolution, stars produce heavy elements, which are returned to the intergalactic medium and can be used in subsequent stellar generations. Thus, the study of chemical abundances at the various cosmological epochs provide us important constraints on the cosmic history of star formation and, through complex modelling, on the formation and evolution of individual galaxies. Further investigation is certainly needed to get more refined input parameters, e.g. accurate abundance determinations, SN rates, IMF, nucleosynthesis yields, and to obtain better descriptions of the relevant processes, such as inflows, outflows and stellar dynamics. This analysis will be applied to both the Galaxy and to individual nearby galaxies such as dSph, DIGs and BCDs, and it is a prerequisite for modelling the evolution of more distant galaxies on the sole basis of their integrated light.

IV. The birth of stars in the nearby and in the far Universe

- The study of the composition and evolution of the interstellar medium throughout the Universe is a key to understand the local and cosmological star formation. In the forthcoming decade we expect enormous progress in the characterization of the interstellar medium in forming galaxies at high redshift, which will constrain the models for the early enrichment of the universe and the formation of the first stars. In the local universe, enormous progress is foreseen in understanding the chemical evolution of the ISM and the possible connection with the formation of planetary systems and astrobiology.

- In spite of the enormous progress in the theoretical and observational understanding of local star formation, we still lack a comprehensive understanding of this phenomenon. One of the key areas that require a dedicated effort is a deeper understanding of the star formation process as a whole, this is a challenging problem that requires substantial advances in our understanding of the microphysics at work in very different environments, from diffuse clouds to circumstellar environments and proto-stellar interior, both on the theoretical and observational side. The formation of the most and least massive stellar (and sub-stellar) objects still challenge our current understanding of star formation and need to be thoroughly addressed. We also expect substantial progress in the understanding of the formation of the first stars and star formation in extremely metal poor environments.

- The stellar Initial Mass Function is one of the basic outcomes of the star formation process we are still unable to predict or understand. Is the IMF universal? There are observational and theoretical hints that the IMF should depend on the environment. The knowledge of the IMF and of its variations is essential to understand the evolution of galaxies.

- How do planets form? Is the formation of planetary systems a common outcome of the star formation process? Is our own Solar System a common product of the planetary formation process? Much work will be dedicated in the coming years to address these questions as new instrumental developments in the infrared through radio bands will allow a detailed study of the properties and evolution of proto-planetary and debris disks and possibly the direct detection of forming planets.

V. The life cycle of stars

- What is the structure of stars and how do stars evolve? This classic question has an impact on most of modern astronomy, as stars constitute the building block of much of the visible Universe. They are also the basis of the “cosmic age ladder”. Yet many aspects of stellar structure and evolution are still not understood properly: the role of magnetic fields, of rotation, and of other mixing processes is still unclear. The ability to understand stellar structure and to quantitatively and reliably determine the evolutionary structure of individual stars and stellar aggregates remains a key astrophysical goal for the future.

- Accurate and precise stellar abundances are an essential tool for understanding e.g. the chemical evolution of the Universe, spanning from the high redshift Universe (all the way to the Big Bang Nucleosynthesis) to the Solar neighbourhood. Yet even the abundance of the Sun (which allows exquisitely accurate spectra to be collected and spatially resolved information) are still the subject of significant discussion. To be able to e.g. unambiguously constrain the abundance of elements of cosmological importance it will be essential to be able to model the complex atmospheric structure of stars, and to couple this with high quality spectral data.

VI. Solar, interplanetary and magnetospheric physics

- The Sun has a key role in Astronomy. Beyond the obvious influence it has on the Earth, it is a sort of Rosetta stone to study in detail the phenomena occurring on stars and in the interplanetary space. Several key problems remain open: How is the magnetic field generated and dissipated from the solar surface? What originates the heating of the upper solar atmosphere? What is the source of acceleration of the solar wind? What is the physical origin of the solar variability? To address these issues, solar and interplanetary physics are focused on studying the magnetic activity: important breakthroughs will be achieved with the combination of space-based instruments and high resolution, innovative instrumentation from ground.

VII. The solar system

- The current solar system is the result of the complex interaction of physical, chemical, geological, and dynamical processes. Notwithstanding the vast amount of data gathered and studied in recent years, we still lack satisfactory answers to questions like: how did our own solar system form, and how long did it take to each individual planet to form? How did the impactor flux decay during the solar system's youth, and did this decline influence the timing of life's emergence on Earth? What is the history of water in the solar system? Why do the past evolutions of the terrestrial planets differ so dramatically?

- It is important to determine the size of the cores of Jupiter and Saturn. When, where, and how Jupiter formed, as well as the evolution of its orbit after the formation, is likely to have played a key role in the formation of the other planets, including the Earth. The exploration of the inner solar system is vital to understand how Earth-like planets form and evolve and how habitable planets may arise. The atmosphere and biosphere of the Earth are fragile entities easily perturbed by planetary-scale processes. Much remains to be learned from the other terrestrial planets, where similar processes have produced vastly different results.

- Comets and asteroids are the residues of the accretion of the planets, and in fact represent samples of the proto-planetary material at various distances from the Sun; in fact, many of them can be considered truly primitive (in the sense that they have not been substantially heated or otherwise changed since the time of their formation). The in-situ exploration of comets and asteroids will help to reconstruct the physical and dynamical history of the populations to which they belong. Near-Earth asteroids and comets are the immediate parent bodies of most meteorites; understanding their origin and dynamics allows assessing their role in the evolution of the surfaces of the terrestrial planets.

VIII. The search for extraterrestrial planets and life

- The discovery of the first extra-solar planet has led to a dramatic increase of the investigations on the frequency of occurrence and the formation of planetary systems around other stars, with the goal of understanding the mechanisms of formation and evolution of planets and, in perspective, of discovering other planets able to host life.

- Current and future methods of detection of extrasolar planets exploit a) dynamical perturbations of the star by the planet, b) transits of the star disk by the planet, c) microlensing of the planet on background objects, d) direct observation of the planets, e) miscellanea of other effects. Although in special conditions it is possible to measure the chemical composition of exoplanets atmospheres with HST, in general the characterization of the atmospheres of exoplanets requires challenging, direct observations of very faint objects in the glow of bright stars. We reasonably expect to characterize gaseous giants with the instrumentations already envisaged, but the direct observations of terrestrial planets (the only ones able to host life, as we know on Earth) require a leap toward a new generation of ground and space-based instrumentation.

IX. The violent universe

- Black Holes are among the most fascinating objects in Astrophysics. The first priority is to obtain a direct, incontrovertible evidence of the existence of an event horizon. BH and other compact objects may also provide invaluable tools to study strong field GR effects can and will be studied through spectroscopy and polarimetry of emission lines distorted by relativistic effects, by highly

accurate timing of binary radio pulsars and by tracking the phase and amplitude of gravitational waves emitted by binary BHs or binary compact objects. A common feature of BH is the ejection of both winds and jets at relativistic speed: their study might be a key to understand how the central engine works.
BH and other compact objects are also ideal laboratories to study matter in extreme conditions. As different energy bands in these variable systems test different emission components and jet scales, simultaneous observations across the whole electromagnetic spectrum (from radio to gamma-rays) are paramount.

- Gamma Ray Bursts are the most energetic and spectacular explosions after the Big Bang. GRBs combine many themes of 21st century astrophysics: physics of matter in extreme conditions, special and general relativity, particle acceleration processes, jet formation, galaxies at the age of the star-formation. GRB associated to massive stars can be used to investigate the star formation rate and the ISM of the host galaxies as a function of redshift, and might even be a feasible way to probe the Dark Ages.

- After nearly 100 years from their discovery the origin and acceleration of Cosmic Rays remain puzzling. On the one side, there are evidences that the bulk of CR are probably accelerated during and after supernovae explosions, but definitive proofs of such an origin are still lacking: improved Cherenkov telescopes, coupled with hard X-ray imaging might provide the long-sought “smoking gun” of this mechanism. Even more intriguingly, the origin of the so-called ultra high energy cosmic rays (UHECRs) is completely unknown: are they accelerated within powerful astrophysical objects such as super-massive BH, or are they produced by exotic remnants of the Big Bang itself? An accurate measurement of both the spectrum of UHECRs and their chemical composition is the most promising way to solve this mystery.

2.1 Geometry and fundamental nature of the Universe

The discovery by Edwin Hubble in 1929 of the expansion of the Universe opened up the way to the dramatic progress of Cosmology in the XX° Century. Today, 75 years later, we have gained a great amount of new insights on the physical nature, structure and evolution of the Universe. At the same time, new deep questions stand out waiting for new investigation and discoveries. A number of independent cosmological experiments (most notably precise measurements of the cosmic microwave background and observations of high-redshift Supernovae) point towards the so-called "concordance model": the universe is consistent with being spatially flat, with baryonic matter contributing about 4% of the total energy content, non-baryonic Dark Matter (DM) to about 30%. An unknown form of Dark Energy (DE), possibly associated with vacuum energy, provides the remaining two thirds. These observations show that, contrary to what most cosmologists believed until very recently, cosmic expansion is speeding up rather than slowing down.

The Universe that we see today originates from small perturbations in the primordial distribution of matter and energy, which, in turn, are believed to have been created from tiny quantum fluctuations in the very early universe. In the present universe, these perturbations are described by the shape and the amplitude of their power spectrum, which provides the amplitude of density unhomogeneity at different scales. The shape can be predicted theoretically by specifying the Hubble constant, H_0, the matter and baryon density, Ω_M and Ω_B, the nature of the non-baryonic DM content and the properties of dark energy. The amplitude of the power spectrum is commonly expressed through the parameter σ_8, defined as the r.m.s. density perturbation within a sphere with a commoving radius of 8 Mpc. The three years data release of operation of the WMAP satellite leads to σ_8=0.7-0.8.

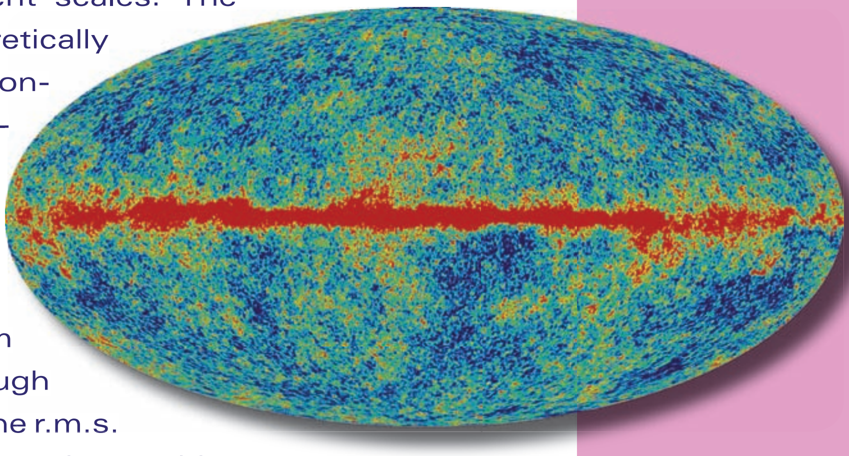


Fig. 2.1.1 Full sky map from the WMAP first year survey data in galactic coordinates. The dominant horizontal feature is the contribution from the Galactic plane. High latitude fluctuations are CMB anisotropies, with amplitude DT/T~10-5. The angular power spectrum of the fluctuations provides a powerful tool to measure fundamental cosmological parameters.

Density perturbations in the early universe are traced by angular fluctuations ("anisotropies") in the cosmic microwave background (CMB) radiation. Recent sub-orbital and space borne measurements of CMB anisotropies have provided major contributions to the "concordance model" and yielded accurate estimates of several cosmological parameters, including H_0, Ω_M, $\Omega_{B,}$ and the total energy density $\Omega_0 = \Omega_M + \Omega_B + \Omega_\Lambda$. In the next decade, the new generation of experiments now being developed or planned will surely maintain the CMB in its central role in Cosmology, and will likely lead to unprecedented precision in the determination of cosmological parameters.

2.1.1 Testing inflation

Inflation is commonly regarded as a brilliant avenue to solve some of the problems of the basic Big Bang scenario: it postulates an early exponential expansion of the universe on time scales of the order of $t \sim 10^{-35}$ s, so to bring distant regions of the universe (much larger than the current size of the horizon) in causal contact at such early times. This simple idea leads to two crucial predictions: 1) the universe is expected to be surprisingly close to flat; 2) the universe should appear extremely isotropic, even in regions that in the present universe should never have been in causal contact. The most crucial consequence the inflationary paradigm is in the implication that the primordial perturbations, as observed in the CMB and later amplified to turn non linear and seed the formation of structures, originate from quantum fluctuations in the very early universe.

The flatness and the isotropy appear to be both confirmed by measurements of the CMB on all scales and to a different extent they are both confirmed by observations of the large scale structure of the universe. Although this does not confirm directly the inflationary scenario, it certainly provides extremely strong arguments in its favour. In these firsts moments in time Physics has to be pushed to the extreme and possibly beyond our current understanding of it, which makes cosmological studies of the highest importance.

Observations foreseen in the next decade have the potential to verify specific predictions of Inflation and discriminate between different versions of the theory. It should be possible to test the energy scale of inflation, the amount of primordial gravitational waves generated during inflation, and their B mode polarization, and, at the same time, the spectrum of initial perturbations, both of scalar and tensor type.

Observations of the CMB have a unique potential in investigating inflation: the position of the first peak in the power spectrum as measured by several experiments clearly indicates that the universe is flat. The second and third peaks provide information on the abundance of baryons and dark matter. The information that can be inferred from the power spectrum alone is however far less than what can be understood from the combined analysis of the power spectrum of CMB and its polarization.

Recently the first detections of E-mode CMB polarization have been carried out, showing that the amplitude of the E-mode polarization is only at a few μK level, confirming theoretical expectations. In the next few years, precise measurements of the spectrum of the “E-mode” will likely allow us to improve on the estimate of the cosmological parameters, thus moving another step ahead towards precision cosmology.

The major long-term goal is the direct detection of the B-mode spectrum that is associated with primordial tensor perturbations in the early universe and will provide decisive confirmation of inflation. Such deep polarization maps may give indications on the inflationary energy scale and probe ultra-high energy physics to levels beyond what can be obtained with any conceivable terrestrial particle accelerator. The ultimate aim of this investigation is testing inflationary models by checking a sort of consistency between scalar and tensor perturbations, by measuring deviations from gaussian and by achieving an even better determination of the spectrum of the primordial fluctuations.

The amplitude of the B-modes induced by gravitational waves is very difficult to predict in the context of any theory, but it is typically expected to be < 1 percent of temperature anisotropy. This imposes new challenging requirements on instruments and observational techniques. A high signal-to-noise, full-sky imaging required to reach this goal is beyond the foreseeable future, but it is important to move some intermediate steps that can lead to the necessary technology. Advances in both bolometer and coherent receiver technology appear promising, particularly for large focal plane arrays.

2.1.2 The nature of dark matter

The evidence for the existence of a large, obscure component of the Universe (Dark Matter) is nowadays supported by a set of astronomical observations, like the rotation curves for a large number of spiral galaxies, the mass of galaxy clusters as determined from X-ray observations and gravitational lensing, the peculiar velocity field of galaxies, CMB anisotropies, the observed growth of large scale structures.

This finding has arisen many fundamental questions. What is the nature of DM? Is it of particle nature or not? Despite the fact that most solutions to the DM conundrum involve new particles, the possibility that the DM puzzle is solved by other type of new physics, e.g. modification of gravity at large distances, is still alive. However recent measurements carried out on merging clusters of galaxies have posed strong constraints on these scenarios: there are instances now of situations in which a clear spatial separation between the light-emitting baryons and the centers of concentration of matter are identified through combined use of X-ray astronomy and gravitational lensing. If matter is not where baryons are, modifications of gravity have a somewhat harder time to explain observations.

If DM is made of particles, which new particle is it? Which is its strength of interactions (strong, weak, gravitational interactions or a new and yet unknown type of interaction)? What is its mass? Is it at the weak scale, much below the weak scale, much higher than the weak scale? All these questions are strictly related to fundamental and particle physics.

Most of the dark matter might be of “Cold” DM type, implying that the matter was not relativistic at the time when it decoupled from the thermal plasma in the early universe. The best motivated among the various suggested candidates is a particle that is already invoked for other particle-physics reasons, the lightest supersymmetric particle (LSP), named neutralino, which is a member of the generic family of weakly interacting massive particles (WIMPs). Such particles are naturally predicted at the observed density by supersymmetry theories, in a mass range from 100 GeV to 1 TeV. Other non-thermal candidates are particles which have never been in thermal equilibrium with the surrounding thermal plasma during the evolution of the Universe. These include Axions, invoked to resolve the strong CP violation problem, superheavy particles (“WIMPZILLAs”), topological solitons, and DM from extra-dimensions. It is important to notice that the spatial distributions of DM within halos may depend on the nature of the particle, leading to possible ways of investigating their nature through astronomical observations.

Two basic methods can be used to search for DM: direct or indirect search. Direct searches depend on dark matter particles actually passing through detectors and physically interacting with them. Indirect searches look for secondary products obtained when DM particles annihilate each other. Indirect searches are aimed to study possible signatures of thermal and non-thermal WIMPs and are divided into searches for high-energy neutrinos from the center of the Sun or of the Earth and searches for the yields from WIMP annihilations in the halo of the Milky Way or external galaxies. The latter may result in a variety of phenomena at radio, X and up to gamma ray frequencies.

A major breakthrough is expected from the forthcoming laboratory experiments in particle physics and from astronomical observations carried out in the gamma ray range, combined with other multifrequency observations. Additional contributions from astronomical observations during the next decade will likely consist of a refinement of the Standard Cosmological Model using new observational data on CMB anisotropies, new observational data on large-scale structures from galaxy redshift surveys, a refinement of N-body models for the formation and evolution of galaxies and large scale as well as from microlensing or infra-red, sub-millimeter observations of small clouds.

As for the indirect detection of super-heavy dark matter, their annihilation products can give rise to ultra-energetic cosmic rays whose detection can be accomplished by studying the Ultra High Energy Cosmic Rays (see section 2.9.4).

2.1.3 The enigma of dark energy

In 1998, observations of Type Ia supernovae provided evidence for an acceleration of cosmic expansion, believed to be caused by a new “dark energy” component, contributing to the total energy density by as much as $\Omega_\Lambda \approx 0.7$, fully consistent with CMB results. Dynamical models of dark energy have been introduced for the purpose of generalizing the concept of cosmological constant, so as to provide a “natural” explanation for the observed value of the DE density. If p and ρ are defined as the pressure and energy density terms of DE, respectively, then the corresponding equation of state is described by $w = p/\rho$. Accelerated expansion requires $w<-1/\,[3(1-\Omega_m)]^{-1}$, with $w=-1$ corresponding to the case of a non-evolving cosmological constant. So far, observations indicate $w<-0.8$.

In general, different models of DE predict different evolutions of the equation of state, which is often parameterized to first order as $w(z)=w_0+w_1z$. To date, observations do not provide strong constraints on a possible DE evolution, although recent HST observations suggest $w_1 \approx 0$.

It should also be noted that alternative interpretations of the observed acceleration have been proposed: for example, acceleration might be the result of the back-reaction of cosmological perturbations, rather than the effect of a negative-pressure dark-energy. Many theoretical proposals concerning the nature of DE link this component to new physics. The cosmic acceleration could be then an effect of large or warped extra dimensions, a signature of string effects, an effective modification of gravity at large scales, or a new long-range force. The intriguing indications that the equation of state might require w less than -1 are also prompting new investigations at the frontier of physics. Accurate measurements of standard sources at a variety of cosmological distances, together with high precision measurements of CMB fluctuations, X-ray observations, weak lensing and other methods may provide new constraints to dark energy models in the next decade.

Geometrical test

The most direct study of DE involves the detection of its effect on the apparent size and on the luminosity distance. This requires the calibration of high-luminosity standard rows and/or standard candles, such as Type-Ia Supernovae. A number of dedicated projects have been proposed to perform systematic searches for SNIa, both from ground and from space and others will be proposed which will surely boost the amount of data on distant supernovae in the next several years, shedding new light on the nature of cosmic acceleration. The search and calibration of new standard candles (e.g. core-collapse SNe and gamma-ray bursts) is also an area of research that is attracting more and more attention.

An additional method is based on comparing the physical scales involved in the baryonic fluctuations of the CMB power spectrum and in the power spectrum of the galaxy distribution. The observed features in the radiation and matter power spectra should involve the same physical scale. Therefore, by comparing them at $z \sim 1000$ (measured by CMB) and at $z \sim 1$ and $z \sim 3$ (measured by galaxy distributions) one performs a standard geometrical cosmological test. The cosmic volume to be explored in order to measure clustering in the linear regime is huge, of the order of 1 cubic Gpc. At redshift of about 0.5 this translates to an angular size of about 10,000 square degrees. Galaxy surveys over such huge area are in preparation and will provide an accurate measure of w0. To measure w1 a wide field galaxy survey at higher redshift should be performed.

Large weak lensing surveys will provide further constraints on DE. The distortion introduced on background galaxies by the foreground mass concentration depends both on the distance of the sources and lenses and on the gravitational growth of the fluctuations, all of them being functions of the cosmological parameters. Large surveys are currently in preparation and several proposals aim at producing large lensing shear maps.

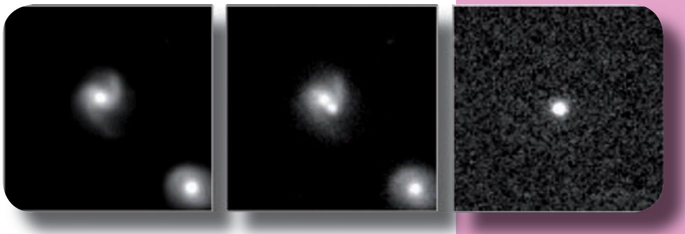


Fig. 2.1.2 Example of Supernovae Ia image event from the SNLS Program. Left: reference image. Center: SN event. Right: subtraction image. The system allows to accurately determining the SN coordinates via PSF fitting on the subtraction image.

An additional geometrical test to constrain cosmological parameters is based on the study of the evolution of the gas fraction within galaxy clusters. Requiring that the baryon fraction does not evolve with redshift leads to constrain the z-dependence of the apparent-size distance. The potential systematic errors to keep under control in this geometrical test are related to the intrinsic scatter in the value of the baryon fraction, which is due to the complex dynamical history of clusters. In order to minimize this scatter, only fairly relaxed clusters should be considered.

Dynamical tests

The evolution of perturbations from their initial stage to their non linear regime and finally to the gravitational collapse that leads to the formation of gravitationally bound objects depends quite sensibly on the cosmological scenario. It follows that comparing observations on the abundance of large scale structures at different redshifts with theoretical predictions, for given cosmological parameters (Ω_m, Ω_Λ and DE equation of state), provides precious information on the latter. This line of thought is now routinely applied to clusters of galaxies, in particular through observations of their X-ray emission. In fact the X-ray luminosity correlates with the dark matter mass of the cluster, and this allows to infer the luminosity function of clusters and to investigate its temporal dependence.

Besides X-ray observations, a powerful observational probe is the Sunyaev-Zeldovich (S-Z) effect, i.e. the local spectral distortion of the CMB spectrum due to photon interaction with the hot gas ($T \sim 10^8$ K) from clusters of galaxies. Accurate S-Z measurements can be made to high redshifts, all the way back to the cluster formation. The detection of the Sunyaev-Zeldovich effect opens the possibility of carrying out large-area surveys of clusters. Thanks to the redshift-independence of the S-Z distortion of the CMB spectrum, S-Z observations allow us in principle to detect clusters out to arbitrarily large distances, the only limits being represented by source confusion and contaminations from radio sources. In this respect, X-ray and SZ surveys are quite complementary to each other: the first ones provide a detailed mapping of the ICM structure and of small clusters at redshift $z < 0.5$, while the second ones allow us to identify very massive clusters out to higher redshifts.

In addition, once S-Z is identified and mapped, sky regions free from S-Z and other local foregrounds could be searched for fainter secondary signatures, such as those from gravitational collapse of large scale structures, bulk motion of plasma (Ostriker- Vishniac effect), signatures of the evolution of gravitational potentials on CMB photons (integrated Sacks-Wolf and Rees-Sciama effects), lensing-induced effects from clusters, signatures of local ionization events, and details of the ionization history of the Universe.

2.1.4 Fundamental physics

The universe is an extremely promising laboratory to investigate fundamental physics, and more specifically extensions of physics to very high energies or very small spatial scales. This potential follows from the large distances involved, which allow us to investigate tiny effects that may become detectable when integrated over such long times.

It has been recently proposed that the radiation from GRBs may be used to probe some fundamental laws of physics and that GRBs will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. According to these theories, space-time is granular at the Planck scales $\sim 10^{19}$ GeV. Photons of different energies excite vacuum fluctuations differently as they propagate through this medium, giving rise to a non-trivial dispersion relation resulting from tiny violations of Lorentz symmetry. A photon of energy E traveling a distance L acquires a time delay with respect to the case of propagation with constant speed c, independent of the energy. This delay is of the order of E/E_{QG} L/c where E_{QG} is an effective quantum gravity energy scale. Alternative theories of Lorentz non-covariant Quantum Gravity predict a birefringency of space resulting in a rotation of the linear polarization plane with energy and with distance on very long scales. Polarimetry of GRBs can provide a very sensitive measurement of these effects.

Many GRBs show a temporal structure in their emission with variability on time scales down to fractions of ms. In principle, this variations can be used as a tool to investigate effects that may happen on comparable scales, for photons of different energies. For ΔE=100 MeV, Δt=1msec and $L=10^{10}$ pc, GRB observations would be sensitive to $E_{QG}\sim 1/L_P \sim 10^{19}$ GeV. Of course, the time structure of GRB is far to be understood, and therefore the above effect must be disentangled from other effects due to more conventional physics. However, the medium effects will be linear in source distance and energy, which would not be the case for time shifts at the source. Observations of msec time shifts in a sample of GRBs may therefore provide robust constraints on the quantum-gravity energy scale. These observations will be possible in the next years with the next generation of space-borne gamma ray observatories.

A modification of the dispersion relation of light is not the only consequence of tiny violations of Lorentz invariance, and in fact it is not even the most prominent. Extremely small violations change in a rather dramatic way the kinematics thresholds for several physical processes, such as pair production or photopion production, thereby making these processes either active at lower energies than they should or, in some cases, kinematically not allowed at all, depending upon the form of the violation. Additional processes, which are not allowed in normal conditions, such as photon decay in two photons may also become allowed. The most striking consequence of these violations is perhaps the inhibition of pair production due to scattering of photons in the TeV range with the infrared universal background. Although hints of the appearance of this process have been claimed in the literature, there is at present no firm evidence and observations are used to impose constraints on the energy scale of the alleged violations or on the type of violations that may be allowed in principle.

2.2 The formation and the evolution of the structure in the Universe

Outside our Galaxy, the Universe is made an impressive variety of structures at different scales. Galaxies have a variety of morphological shapes, ranging from smooth, homogeneous "Ellipticals" to grand-design Spirals, to a zoo of irregular galaxies, and are made of a mixture of stars and gas with different ages and chemical compositions. The Universe is also far from being spatially homogeneous, since the density of galaxies is very high in a few, dense region, where a hot diffused gas is also present, but enormous regions devoid of massive galaxies fill most of the volume of the Universe. Galaxies may harbor Active Galactic Nuclei (AGN), in a variety of forms (Quasars, Radio Galaxies, BL-Lac), that are often more luminous than the overall stars in the host galaxy.
One of the most challenging goals of modern cosmology is to understand what are the physical processes that drove the formation and evolution of such structures.

Over the last decade a tremendous progress has been made in three different directions. First, the emergency of a "concordance" cosmological scenario has finally ended the quest for the fundamental parameters of the Universe: this has provided a clear timescale for the evolution of the Universe and the definition of the dynamical properties of its basic constituents (Dark Matter, Dark Energy and baryons). Second, Galaxies and AGNs have been detected all the way to look back times corresponding up to 90% of the age of the universe, enabling the study of their evolution over the whole history of the Universe. Finally, theoretical modelling of galaxy formation in a cosmological context has been developed with both numerical and analytic techniques. These advances have brought to the formulation of a physical and cosmological scenario where galaxies and larger structures form as a result of the growth of tiny perturbations of the Dark Matter density field, which are created by some primordial mechanism, such as inflation. On large scales, above, say, 10 Mpc, the evolution is essentially driven by gravitational instability, leading to the collapse of the over-dense regions to form self-gravitating haloes, and again gravity drives the assembly of larger and larger haloes at later times (hierarchical clustering). On smaller scales the complex physics of cosmic baryons starts playing a leading role in determining the properties of cosmic structures as we observe today. Because they can efficiently heat up, cool, dissipate energy and angular momentum, cosmic baryons, unlike DM, are found in a highly different systems. A large fraction is in a warm phase shock heated during the collapse of density perturbation, the remaining end up in the hot intracluster medium (ICM) of clusters of galaxies on one side, and in Galaxies (i.e. instars and colder gas clouds) on the other side. Finally, stars and gas can coalesce to form supermassive BH (SMBH) in galaxy nuclei.

Understanding the fate of cosmic baryons and the history of their transformation is the ultimate challenge and goal of observational cosmology.

2.2.1 The first luminous objects in the Universe

What were the first luminous sources in the Universe? When did the first stars started to shine? How was the Universe reionized? These fundamental questions are entirely unanswered, since no observational detection of “first light” objects has been obtained so far. The universe was opaque to its own radiation until recombination took place. The first luminous objects could form only much later when perturbations could grow non linear and eventually collapse gravitationally. The end of what is usually called “the dark age” of the universe is of extreme importance for the many implications it has: the universe could get reionized by the light coming from these very first objects, thereby affecting the formation of future structures as well as the propagation of the photons of the CMB.

The observations of well-developed galaxies and AGNs up to redshifts $z \leq 7$ already provide a lower limit on such epoch. Direct information on the early thermal history of the universe (up to redshifts as high as $z \sim 5 \times 106$) can be achieved with high precision measurements of the CMB frequency spectrum. The recently observed correlation between the CMB temperature fluctuations and E-mode polarization (“T-E” correlation) on large angular scales suggests that reionization occurred at redshifts $10 < z < 15$, a result that would be important to confirm with independent observations. The “dark ages” can also be probed by using measurements of the CMB anisotropies at angular scales smaller than about 1 arcmin. At these scales, the CMB is highly influenced by the interaction with intervening ionized material, so that in the next decade the study of the CMB “back-light” at arcmin scale may become one of the most powerful techniques to observe the very early processes of structure formation.

Based on theoretical expectations, first stars have formed out of metal-free gas in dark matter mini-halos condensing at z=10-15.

Such first stars were likely highly massive (tens to hundreds of solar masses) and assembled in clusters of 105-106 solar masses. These very massive stars exploded as bright SuperNovae in a few 107 yrs. The emitted UV flux of very massive stars and the feedback of SN explosion contributed to re-ionize the Universe. In addition, several of these stars might have quickly collapsed to form black holes. Since they have been formed in rare, high density peaks, such relic BH are expected to cluster in the center of the newly forming bulges, giving rise to the seeds of SMBH. The physical conditions in the center of these young, gas-rich proto-galaxies may favor gas accretion onto the BH, giving rise to the light-up of “mini-quasars”. Again, the ionizing flux from these mini-quasars might have largely contributed to the reionization.

The direct detection and study of this re-ionization process is one of the major challenges of present-day astrophysics. The direct detection of first generation stars is beyond the possibilities of current facilities, since they are expected to be very rare and their emitted light is so much redshifted to be observable only in the IR regime, at flux levels below the current sensitivity. Similarly, the X-ray emission from primordial BH can be detected only with future, more sensitive X-ray missions. The redshifted 21 cm emission could also be detected from structures in the early Universe. Gravitational waves produced by coalescing BH binaries at high-z might be detected only from future space-based experiments.

2.2.2 Birth and evolution of galaxies and SMBHs

According to the standard cosmological scenario the first “proto-galaxy size” DM halos (M 108-109 solar masses) started to collapse at z~10. Radiative cooling of the gas contained in these DM haloes give rise to star-formation and accretion onto SMBHs. Galaxy interactions were frequent at high redshifts, stimulating both the conversion of gas into stars and nuclear accretion. Thus, the first galaxies were probably very different from the rather passive objects we see in the local Universe, they were sites of huge activity, with star-formation rates up to hundreds to thousands of times higher than in the Milky Way, implying a correspondingly higher rate of Supernovae explosions. Furthermore, most of these galaxies probably hosted an active nucleus (AGN). A fraction of the energy released by Supernovae and AGN is absorbed by the interstellar matter (ISM), which is heated up to a level that can block further star-formation. Part of the hot gas could be ejected from the galaxies in the intergalactic medium (IGM). More in general, both star-formation and nuclear accretion are most likely self-regulated by "feedback" mechanisms. It is clear that these feedbacks (and metal enrichment) from SNe and AGNs can create a complex interplay between the diffuse IGM and ICM baryons and the condensed baryons in galaxies (Figure 2.2.1 shows an example).

Although many evidences show that structures do evolve following the hierarchical paradigm, we still observe fundamental deviations with respect to the basic theoretical expectations and we do not have a good understanding of the physical processes that drove the evolution of the baryonic component. We briefly list below the main open issues.

In most of this section we will mention the "co-evolution" of galaxies and AGNs. Indeed, the discovery of "relic" SMBH in the center of most nearby, bulge dominated galaxies, and that their masses are tightly proportional to bulge properties like mass, luminosity, velocity dispersion and concentration, suggests that a fundamental mechanism for assembling BH and forming spheroids in galaxy halos must be in place, and motivates the study of the feedbacks between active nuclei and their host galaxies as a key process in shaping galaxy evolution.

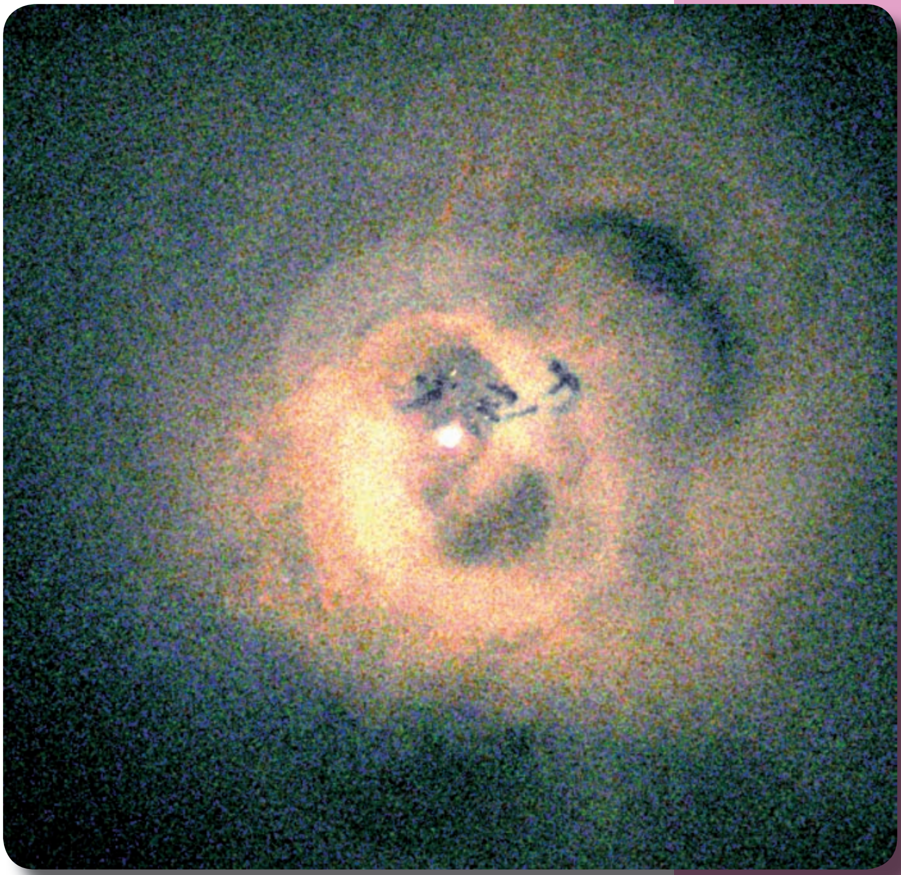


Fig 2.2.1 The Chandra X-ray image of the cluster Perseus-A (Fabian et al. 2003). The central galaxy NGC1275 is a radio source injecting radio bubbles in the ICM.

A crucial aspect in understanding the co-evolution of galaxies and AGNs is constituted by the so-called "downsizing". Several evidences, both locally and at high redshift, show that the more massive galaxies are characterized by a star formation history peaked at high redshifts, while lower mass galaxies are typically younger systems. Similarly, the density of the high luminosity QSOs is peaked at high redshift and declines strongly afterwards, while lower luminosity AGNs follows a much smoother behavior, peaking at lower redshifts z=1-1.5. In principle, such a trend is not in contrast with the basic features of hierarchical picture, where massive galaxies form earlier in the rare, high density peaks that collapse at higher redshift, compared to low-mass systems. However, the detailed match of the model predictions with the observed characteristics of massive galaxies is far from being satisfactory, suggesting the some fundamental physical process is not understood. Understanding the origin of such a downsizing within a cosmological framework constitutes a major goal for the next years.

A related question concerns the dependence of the above processes on the environment. In the local Universe we observe a clear relation between the density of galaxies and their physical properties: galaxies in dense environment are typically more massive and older than those in less dense regions. Such a trend is also starting to be detected at intermediate and high redshift. On the other hands, several theoretical models for AGN evolution envisage galaxy interactions as a major trigger for black hole accretion. Understanding the dependence on the environments of both the star formation and the black hole accretion is crucial in discriminating among the different models of AGN feeding and in understanding in detail the role of galaxy interactions in both the AGN feeding and the starbursts.

Finally, ΔCDM models for galaxy formation and evolution make very naturally strong predictions on the clustering of galaxies at each redshift. Therefore the study of the cosmic evolution of the clustering, as a function of the galaxy mass, color, presence of an active nucleus etc. can provide tight constraints on these models. The measure of the clustering and its evolution up to z=3-4 seems a realistic goal for the next decade

Other particularly hot topics are the origin and evolution of the galaxy morphologies and dynamics, and their relationship with the merging histories and the star-formation processes. In hierarchical models radiative cooling of the halo gas determines its collapse toward the centre until the setting of rotational equilibrium, thus naturally forming galactic disks. In such picture spheroids form from the merging of disks of comparable mass. However, it is not clear whether this mechanism is able to explain the large range of masses covered by spheroids and, more in general, whether there is a relationship between large Ellipticals, and compact dwarf Ellipticals. In addition to such broad scenario, the detailed physical processes that led to the variety of morphologies observed in present-day galaxies must still be described adequately by detailed physical models.

The interactions between the baryons and the DM halos are also a key issue. The determination of the dynamical mass (DM + baryons) of galaxy halos, of the galaxy mass to light ratio, its evolution with cosmic time and its correlation with galaxy luminosity and morphology remain among the hottest open problems. Extending up to z =3-4 the galaxy dynamic studies performed so far for the galaxies of the local Universe and up to z~1 is one of the primary goal for the next decade. The correlation between baryons and the DM halos can also be studied though the so called "scaling laws", because they imply strong links between galaxy dynamics (driven by the DM) and of the history of the star-formation and evolution of the stellar population. Again feedback processes may be responsible for these links.

Fig. 2.2.2. Different phases of the merger of two galaxies with central SMBH. From top to bottom, the individual images of the sequence show the gas of two colliding spiral galaxies. After the first encounter, they first separate again from each other, but then come together for a second encounter and subsequent coalescence. Gravity is driving gas into the centers of the galaxies and leads to the formation of extended tidal arms. As a result of the nuclear inflow, the BH grows strongly during QSO phase. This phase lasts up to 100 million years and releases enough energy to heat the gas and to expel it into extragalactic space. At the end an elliptical galaxy remains (its stars are not shown in the image sequence) which contains almost no residual gas and hosts at its center the merged pair of SMBH. Adapted from Volker Springel 2005.

How can we verify and improve such a broad scenario? The unique advantage of present-day and future Observational Cosmology is that we can observe Galaxies and AGNs as they form and evolve over most of the Universe life, and use these observations to improve our understanding of the physical mechanisms involved. At this purpose, observations at low and high redshift are both crucial.

Detailed observations of the low redshift ("local") Universe have two purposes: first, they represent a reference sample over which we can quantitatively measure evolution over cosmic time; second, they provide detailed boundary conditions that any model of galaxy formation must satisfy. In this context, the recently terminated Sloan Digital Sky Survey has provided a wonderful data set that will be used for several years to come, to fully describe the physical properties of low redshift galaxies. Similar future surveys, especially those at longer wavelengths, will improve our understanding of the local Universe. Detailed study of high density regions (like groups or clusters) will also improve our understanding of the physics of galaxy formation.

However, the primary emphasis in the next decade will be focused on the exploration of the high redshift Universe, where the physical processes can be directly observed "in action".

Multi-wavelength surveys are main tools for the exploration of the high redshift Universe: the combination of imaging and spectroscopy over large area of the sky allows to identify the galaxy and AGN population at different cosmic times. The final gal of these studies is the assembly of large statistical samples (luminosity and stellar mass functions, color distributions, clustering analysis), that will be used to compare with and eventually constrain the theoretical models with unprecedented accuracy and reduced biases induced by sample variance effects. Multi-wavelength coverage – ideally extending from the far IR to the X ray, with a fine sampling of the IR-optical region – allows to derive the physical properties of individual galaxies (stellar mass, dust content, star-formation rate), and to estimate their redshift with the so-called "photometric redshifts". Spectroscopy of large samples of galaxies allows a much more accurate study of their physical properties and of their cosmological distance, and is also necessary to study in detail large scale cosmic structures. Several large multi-wavelength surveys are planned or designed for the next decade. The most significant advances are expected from near and far—IR instrumentation, that is critical to detect and study both passively evolving objects and dust—enshrouded, star—forming galaxies at high redshift: the study of these objects will likely shed light on the formation of massive galaxies at high redshift.

On a different line, detailed study of individual galaxies at high redshift is definitely necessary to better understand the physical processes in act. The goal here is to observe high redshift galaxies with a level of detail comparable to the observations of local galaxies, in order to study their stellar population, gas content and dynamical state. The first instruments capable of this are coming on line at the largest telescopes, in particular adaptively—controlled IR spectrographs. However, the leading science in these field will be provided by future space—based large telescopes, operating in the near of far—IR, as well as from the next generation of extremely large ground—based telescopes.

Finally, the Cosmic X-ray Background (CXB) represents the integrated history of accretion onto SMBH and therefore X-ray surveys have been so far extensively used to probe the assembly and growth of SMBH. However, the SMBH mass function obtained integrating X-ray luminosity functions produces a poor fit of the above mentioned “relic” BH mass function. The reason is probably that today X-survey, being limited to the band below 10 keV, miss most of the very highly obscured AGNs. The strategies to find these elusive objects is to look either in the mid-to-far infrared, searching for dust reprocessed AGN emission, and at hard X-ray energies, above the photoelectric cutoff, fully probing the peak of the CXB at 30-40 keV. Discovering the physical link between the assembling of SMBH and the formation of spheroid, and understanding the physics of feedbacks and its role in the evolution of galaxies of different kind and masses are among the main goals in the next 10 years.

2.2.3 The fate of baryons

As discussed in Section 1 baryons form a small minority (~4%) of the energy content of the Universe. Surprisingly, only a small fraction of this 4% is found in stars, dense gas and dust. We now know that most of the baryons actually resides in tenuous and low luminosity systems. At high redshift most of the baryons are in the so called Lyman-α clouds, large gas clouds of density similar to the average density of the Universe and temperature <104 K. HST observations during the 90’ showed that the number of these clouds strongly decreases with the redshift, opening one of the major problem of the last decade: which is the fate of the majority of the baryons in the local Universe? Numerical works first suggested the answer. Hydrodynamic simulations showed

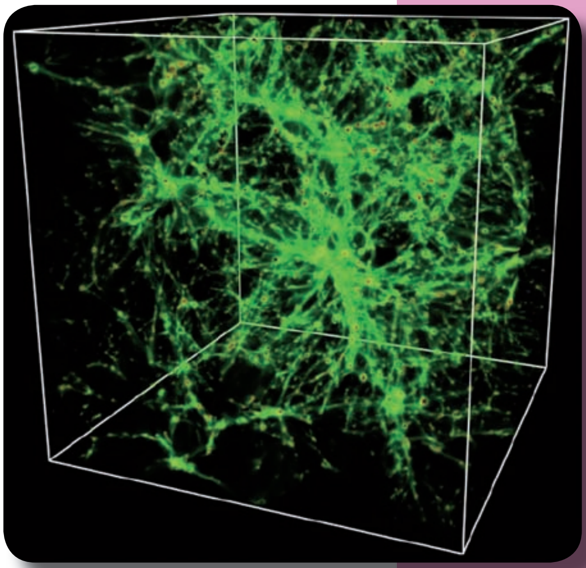


Fig 2.2.3 A representation of the Cosmic net from a simulation of the Princeton group. The green/yellow regions have a densities ~10/100 times the average density of the Universe. Small red regions represent clusters of galaxies.

that at z<1 a large fraction 30-40% of the baryons in the Universe should be in a tenuous (density ~10 times the average density of the Universe) warm phase, shock-heated to temperatures of 105-107 K during the collapse of density perturbations in the filaments connecting galaxy clusters and in clusters outskirts (an example of these simulations is showed in figure 2.2.3). According to the same simulations 10-20% of the remaining baryons end up in clusters of galaxies (with T>107 K, hot phase), and 30-40% are in stars and colder gas clouds (T<105 K, cold phase). We discuss in the following sections these three phases.

At high redshift, most baryons (mainly H and He) reside in tenuous filamentary structures that are revealed through UV rest frame absorption lines (“Lyman α clouds”). At z>1 these lines are redshifted in the optical and so easily detected in the spectra of bright background sources like QSOs. Such clouds have a typical temperature of 2x104 K and are in ionization equilibrium with a pervading UV background produced by AGNs and galaxies. They show a range of chemical enrichment due to a combination of per-enrichment due to PopIII starts and to the outflows from high redshift star—forming galaxies. The investigation of such enrichment, through the analysis of the correlation between absorbing systems and high redshift galaxies and detailed theoretical modeling, will probably provide the most important results in the next years.

A related issue is the reconstruction of the history of chemical evolution of the whole Universe. The final goal is to obtain a self—consistent picture of the evolution of the different galaxy types and intergalactic medium to provide a comprehensive account of the metal production in the universe. The first models of this kind, which are important for the understanding of the high redshift Universe, have already been developed. Since this field of research has an enormous scientific potential, they certainly will see a major effort in the coming years.

At lower redshifts, a much hotter gas is detected in the intra—cluster medium (ICM). Such gas shines in the 0.1-10 keV band due to bremsstrahlung emission and line emission. Clusters of galaxies form through gravitational merger processes of sub-clusters and groups of galaxies. Major cluster mergers are the most energetic events in the Universe since the Big-Bang: in these mergers, the sub-clusters collide at velocities of ~ 2000 km/s, releasing gravitational binding energies of as much as 1064 ergs.

Surface brightness profiles obtained with the past and present generation of X-ray observatories probe ICM temperature and metallicity up to about 1/2 of the virial radius. This is most unfortunate as the regions around the virial radius, the cluster outskirts are expected to contain much information on the formation process of galaxy clusters. In the cluster outskirt, indeed, shocks are expected to occur where the free-falling gas collides with the ICM, converting the bulk of the kinetic energy of the free-falling gas into thermal energy. Relatively massive in-falling substructures, such as groups, are likely to retain at least part of their structure all the way down to the cluster central regions. Shocks generated by these structures will likely leave in their wakes turbulence, which will eventually be dissipated at smaller scales. A solid observational characterization of these regions would allow us to improve considerably our understanding of the physics of galaxy clusters as a whole.

Non thermal phenomena are also detected in clusters, and suggest that complex physical processes are in action. Indirect evidence of the existence of cluster magnetic fields derives from studies of the Rotation Measure of radio galaxies embedded within the cluster thermal atmospheres or located behind them. The origin of his ICM magnetic fields (primordial, injected from galactic winds or from active galaxies) is unclear. The compression associated to shocks will amplify the strength of the magnetic fields, which are frozen in the high conductivity plasma; particles will likely be accelerated at the site of the shock. These two latter components generate diffuse radio emission, seen in several clusters. Evidence for non-thermal hard X-ray emission has been recently reported for a few nearby clusters, although these results are still controversial. The most likely interpretation of this non-thermal radiation is inverse Compton of the cosmic microwave background (CMB) photons by the same electrons responsible for the synchrotron emission observed at radio wavelengths. A definite confirmation of the detection of hard tails and substantial improvements in their characterization require instruments with at least an order of magnitude improved sensitivity with respect to the instruments of the present generation. This information is crucial to assess the origin of the energetic particles and their acceleration processes.

About 70-80% of clusters show evidence of surface brightness excess in the innermost 100-200 kpc with respect to a simple hydrostatic model. X-ray observations of these systems have shown that a minimum temperature of 1-3 keV characterizes the cool gas in their core. This finding is in clear violation of the previously adopted cooling flow model, leaving a fundamental question open: what happens to the gas that should be cooling on very short timescales? Two classes of solutions have been proposed: in the first class the cooling gas is there but is somehow hidden from our view; in the second class the gas is prevented from cooling below a minimum temperature by some form of heating (from the ICM outside the cool core, or from a population of AGNs).

Further exploitation and digestion of current X-ray data will certainly further consolidate our observational characterization of cool cores but there is no guarantee that it will eventually lead to the solution of the physical problem they pose. There is growing evidence that gas motions with velocities not much smaller than the sound speed may be rather common in cool cores. Gas motions are very important as they inform us of the degree of virialization of the ICM. Unfortunately current instrumentation does not have the spectral resolution to directly detect the Doppler shift or line broadening of the cluster emission lines. Instruments combining high spatial and spectral resolution would provide a valuable tool to probe cool cores.

The intracluster medium is rich in heavy elements. In particular the Fe abundance is roughly 0.3 times solar, and indeed there is about 2 times more iron mass in the intracluster medium than locked into cluster stars. There has thus been a large pollution for the cluster galaxies to the ICM. Models including galactic winds, have shown that small galaxies suffer stronger winds than bigger ones, and that winds are likely to be the major responsible for the chemical enrichment of the intracluster medium, although ram-pressure stripping can also play an important role. The current understanding of the chemical evolution of clusters is still flagged by uncertainties on the initial mass function, on the progenitors of type Ia Supernovae, which are likely to contribute a substantial amount of Iron, on the processes which result into gas loss from the galaxies. Important improvements in this field are expected with more accurate data on the chemical abundances and thermal status of the intracluster gas, of the chemical abundances of the cluster stars, and of the size and properties of the intracluster stellar population. In addition, the variation with redshift of these properties will give very important constraints to the evolution of the clusters and on cosmological models.

Observations of the warm IGM located away from the high density regions have yielded so far only limited information. Gas with T~105 K has been revealed through OVI absorption z=0.1--0.3, as well as warmer gas (a few 106K) through OVII resonant scattering lines at soft X-ray frequencies. Since such lines are faint, relatively high resolution in the 0.3-0.7 keV band is needed for their detection. Furthermore, the thermal broadening of O VII lines is ~50 km s-1 at the relevant temperatures, implying that a resolution of R~5000 or higher is needed to fully resolve them. Hydrodynamic simulations show that reasonable warm intergalactic gas turbulence may be of 100-200 km s-1, implying a resolution of 1500-3000 to resolve these lines and measure the Doppler width b. A simultaneous measure of the temperature of the gas (through OVI, OVII and OVIII line ratios) and of its Doppler width b, can provide information on the heating history of the gas and provide tests and constraints to hydrodynamic models for the collapse of density perturbation and their evolution. The study of the warm filaments and cluster outskirts, in UV and soft X-rays will provide new crucial information on the phase at which galaxies, groups and clusters formed, the metal enrichment and heating histories of the IGM, and the feedback between hot and warm halos and star- formation in galaxies.

2.3 The history of the Galaxy and of nearby galaxies

2.3.1 Stellar Populations

During the last few years stellar populations in nearby stellar systems have been the crossroad of a paramount theoretical and observational effort.
Large, ground-based telescopes provided the opportunity to investigate on a star-by-star basis stellar populations in Galactic clusters and in a large fraction of nearby galaxies. At the same time, data collected with HST and Spitzer provided the unique opportunity to investigate the stellar content in systems located well beyond the Local Group (Virgo, Fornax) and characterized by different environments and galaxy types. On the other hand, stellar evolution models shook-off their speculative nature and are able to provide robust predictions to be directly compared with actual stellar properties over a broad range of evolutionary phases.

This new wealth of information has been adopted to constrain fundamental astrophysical parameters such as stellar ages, chemical compositions, and distances. These basic information provided, in turn, robust constraints on the star formation history and/or the initial mass function in both simple (clusters) and complex (galaxies) stellar systems that have been investigated. These findings play a major role not only in the improvement of our knowledge in galaxy formation and evolution, but also independent constraints on relevant cosmological parameters such as the age of the Universe, the Hubble constant, the primordial light elements abundances, and the cosmic distance scale. Moreover and even more importantly, nearby stellar populations are fundamental analogs to constrain, here and now, the Spectral Energy Distribution (SED) of complex stellar systems located at cosmological distances.

If the perspectives for the field of stellar populations are very promising, current scenario still presents several unsettled problems. The comparison between theory and observations is mainly based on Color-Magnitude diagrams (CMDs). This approach presents several advantages, but it is often hampered by uncertainties affecting both reddening and absolute distances. The Luminosity Functions (LFs), present several positive features (Poisson limited) when compared with CMDs, but deep and complete LFs are only available for a restricted number of Galactic Globular Clusters (GGCs). Moreover, current photometric data are typically restricted to optical bands (B,V,I) which are affected by uncertainties in stellar ages and heavy element abundances. Current UV and NIR data are barely capable to probe the stellar populations at and below the Turn-Off in GCCs and, as a consequence, current stellar population templates (GGCs, dwarf galaxies in the Local Group) are largely inadequate. Space observations of star cluster sequences at these wavelengths are strongly needed.

Moreover, deep NIR observations of the Galactic bulge are mandatory to determine the SED of metal-rich stellar populations which is the only nearby analog of stellar populations in elliptical galaxies. Similarly, nearby dwarf elliptical and irregular galaxies will provide the templates for stellar populations in metal-poor and young galaxies. On the other hand, deep UV data are crucial to figure out the UV emission of both intermediate-age (main sequence) and old (hot horizontal branch) stellar populations in different galaxy types. This information will provide useful hints on the subtle intrinsic and systematic errors that might affect the use of UV flux to trace back in time the SF history in the Universe.

As a necessary complement to photometric observations, spectroscopy, especially high multiplex multi-object spectroscopy, has become an essential tool to investigate the properties of stellar populations. High resolution spectroscopy in particular allows to derive the kinematical and chemical properties of the populations.

It is worth mentioning that dynamical models of star clusters are becoming more and more realistic, and the advent of powerful computer facilities will allow to develop reliable N-body models (with up to 106 particles, appropriate for GGCs). These will allow to understand the interplay between stellar evolution and dynamical evolution in crowded environments, a basic ingredient to fully understand the stellar population also in far, unresolved objects.

Even more importantly, realistic dynamical models of star clusters will allow to follow the dynamical history of the clusters, i.e. the influence of the Galactic potential on its evolution. In this way it will be possible to reconstruct the cluster Initial Mass Function (IMF) from the observed one. Observations in clusters with different properties (age, metallicity, density) will allow to answer to the still open question on whether there is an universal IMF. Similar arguments are valid on the observations and modeling of binary/multiple stellar systems.

Most of what we know of the star formation history, metallicity and dynamical evolution of the Local Universe is a result of the detailed comparison between observations of stellar populations and numerical models based on stellar evolution theory. Clearly the improvements expected in the stellar evolutionary models, such as convective transport and efficiency of mass loss (cfr. Sect. 5) will have deep impact on the study of stellar populations and our understanding of the properties and history of the Local Universe, including the fundamental steps of the distance scale ladder. It should be emphasized that the comparison between theory and observations relies on the accuracy of absolute distance determinations. Unfortunately, accurate trigonometric parallax measurements are only available for a limited number of stars, hence current primary standard candles do not rely on robust geometrical calibrations. Space-based observations in the UV, optical and IR domains as well as the use of large ground-based telescopes, will allow us to settle some of these long-standing problems in the next years but only the advent of GAIA will fix the cosmic distance scale and, as a consequence, the kinematics, ages, and abundances of the Milky Way stellar populations.

2.3.2 Stellar Clusters

In the context of stellar populations the stellar clusters are fundamental. Indeed their stars can be considered to be at the same distance, to have the same initial chemical abundance, to be formed at the same epoch and to suffer comparable extinction. For these reasons they are ideal for evolutionary studies.

Globular Clusters (GC) have been considered single population objects and have been used as prime laboratories for testing theoretical models of stellar evolution. However, there is a growing body of evidence that chemical inhomogeneities in GC stars exist and stars sharing similar physical parameters can show very different surface abundances of light elements (C, N, O, Na, Al). In particular, the very recent discovery of a double main sequence in Omega Centauri and NGC2808, explained with a presence of (a second generation of) stars with markedly high He abundances, points in the direction of multiple stellar populations. This calls for the possible presence of more than one generation of stars within at least some galactic GCs.

This may also explain the presence of extremely hot horizontal branch stars considered to be the main candidates to explain the anomalous UV flux of ellipticals and spiral bulges. Because of the implications on our understanding of the (unresolved) stellar population in external galaxies, a complete census of abundance anomalies, and photometric anomalies like multiple main sequences and extended horizontal branches is needed.

Galactic GCs host a large number of exotica (millisecond pulsars, low-mass X-ray binaries, cataclysmic binaries blue stragglers, hot horizontal branch stars, etc.) which shows that the stellar evolution in star clusters is not passive but is affected by the dynamical history of the cluster. The models that will become available in the next years (cfr. Sect. 3.1) need a number of observational inputs, which include accurate proper motion and radial velocity distribution, binary properties (fraction, period and mass distribution, radial distribution) as well as a complete census of the exotica (with observations from the X-band to IR) and their photometric and chemical properties.

In the next few years we will be able to determine absolute ages for GGCs with errors smaller than 1 Gyr. To accomplish this result, absolute distances will be obtained with proper motions from multi-epoch space measurements, reddening, and metallicity will be determined with multi-fiber high resolution spectroscopy on 8-10m class telescopes. Ongoing space surveys in optical and NIR bands will also allow to have high quality photometric homogenous color-magnitude diagrams for accurate relative ages while next generation space missions will allow to extend the temporal baseline and the wavelength range. It will be therefore possible to determine the formation timescale of the Milky Way GC system.

Both Globular and Open clusters are ideal testbeds for stellar evolutionary models and provide a unique tool to test improvements in the theory. As an example, young open clusters (10-30 Myr) provide a unique bench to test the prediction of pre-main sequence tracks and to test our models of the stellar interiors. Testing on Open Clusters populations the detailed predictions of light elements burning timescales and stellar instabilities in these age range are a powerful tool to improve the evolutionary models.

Open clusters also have an important role for our understanding of the detailed structure and evolution of the disk of the Galaxy and of stars from the most massive to the intermediate/small mass ones, from their formation to the final stages (SNe/WDs/PNe). As an example, old open clusters provide the best tool to test the formation and evolution of the disk of our Galaxy, e.g. by allowing an accurate determination of the abundance gradients throughout the disk.

2.3.3 Star formation history and chemical evolution of local galaxies

As a result of their evolution, stars produce heavy elements, which enrich the interstellar and intergalactic medium and get partly incorporated in subsequent stellar generations. Thus, the analysis of chemical abundances at the various cosmological epochs allows us to infer important constraints on the cosmic history of star formation, on the process of galactic inflows and outflows, and on the formation and evolution of individual galaxies. In the past years it has been shown that certain abundance ratios can be used as cosmic clocks. In particular, ratios of abundances such as Nitrogen/Oxygen and alpha-elements/Iron can be used to infer the formation timescales of stellar systems. This is because, while Oxygen (and in general the elements produced by alpha capture) is produced in massive stars, with short evolutionary lifetimes, Nitrogen and Iron are produced by longer lived progenitors. Thus, a stellar system with a large Oxygen/Iron abundance ratio must have formed within a short timescale, so that star formation stopped before the bulk of the Iron was released to the interstellar medium. In addition, the particular star formation history influences the growth of the absolute abundances, such as the abundance of Fe (more intense star formation induces a faster growth of abundances). Therefore the well-known diagram alpha/Fe vs. Fe/H is affected also by the particular star formation history, which characterizes different types of galaxies.

The interpretation of the observational data requires a thorough modeling of the chemical evolution of galaxies, taking into account detailed nucleosynthesis from stars, a star formation history, an initial mass function and possible inflows and outflows. With these models one is able to understand the abundance patterns observed in the Milky Way, in nearby galaxies and, ultimately, to derive clues on the nature and the age of high redshift objects such as Damped Lyman-alpha systems.

Chemical evolution of the Milky Way

Nowadays very accurate abundance determinations are available for the stars in our galaxy, although variations on the absolute calibration due to solar values are possible (cfr. Sect. 5.1). Their analysis via detailed chemical evolution models lead to the conclusion that the galactic halo formed on a timescale of 1-2 Gyr, whereas the disk formed on a timescale of several Gyr, increasing with increasing galactocentric distances. This suggests that the disk of the Galaxy, and possibly of spirals in general, form inside out. In addition, there are observational indications of the possible occurrence of a hiatus in the Star Formation activity between the formation of the halo (and thick disk) and that of the thin disk. Stellar abundances in the galactic bulge have shown that this component also formed within a short timescale, but, different from the halo, the chemical enrichment proceeded up to a very high metallicity. In spite of the richness of the data, the early phases of the evolution of the Milky Way are still unknown. In the last few years, with the advent of very large telescopes and very precise spectrographs, it has been possible to derive with high accuracy the abundances of several chemical species down to very low metallicity ([Fe/H]= log(Fe/H)star-log(Fe/H)sun=-4.0, i.e. four orders of magnitude lower that the Fe abundance in the Sun!). This study put constraints on stellar nucleosynthesis and the early star formation history of our Galaxy, i.e,, whether the enrichment events are due to single SNe or single burst events, reflecting the ejecta of a generation of SNe averaged over a IMF, challenging the modelers. Further investigation is certainly needed to improve our understanding of the formation of the different components of our galaxy, with on the one hand more accurate abundance determinations, especially in the galactic bulge; on the other hand, with models based on updated input parameters (e.g. stellar nucleosynthesis and lifetimes, initial mass function, rate of supernovae events), and with a better description of the relevant processes (e.g. inflows and outflows, and stellar dynamics). In particular, accurate data for stars of very low metallicity will help understanding if the stellar initial mass function varied in time, if a generation of very massive stars (Population III stars) ever existed, and if the theoretical stellar nucleosynthesis computed for massive and very massive stars is correct. At the same time, accurate measurements of abundances in HII regions, in Cepheids, in Planetary Nebulae and Supergiants along the Galactic disk will allow us to understand how abundance gradients form and evolve in disk galaxies.

Chemical evolution of external galaxies

Sophisticated instrumentation on board of HST and careful data analysis have allowed us to unravel the star formation history, initial mass function, and chemical composition of gas and stars for many dwarf spheroidal (dSph), irregular (DIG) and blue compact dwarf (BCD) galaxies inside the Local Group as well as outside it. For the nearest objects, high-quality data are becoming available, which will enable us to study the target galaxies with the same degree of precision now obtainable only for the solar neighborhood. The chemical pattern in the interstellar medium of dwarf galaxies suggests that winds are likely to occur in these objects, possibly selectively ejecting the products of SNII explosions. In this framework, it is useful to construct detailed chemical evolution models in order to follow the evolution of specific dSph, DIGs and BCDs, for which the star formation history is known from the Color-Magnitude Diagram of their stars. Among the dwarf galaxies, particular attention will have to be devoted to the Magellanic Clouds for which a large amount of data will be available in the near future, and to the dwarf spheroidals of the Local Group. Some work has already suggested that the abundance ratios in dwarf spheroidals are quite different from those of stars in the Milky Way. Much experimental evidence needs to be collected through spectroscopy of stars and the interstellar medium, and chemo-dynamical models must be developed to fully interpret the observations. Understanding the chemical evolution and star formation histories of nearby galaxies, for which a large amount of information is available from the resolved stellar populations, or, in other words, a detailed understanding of the “Local field cosmology”, is a prerequisite for modeling the evolution of more distant galaxies on the sole basis of their integrated light.

2.4 The birth of stars in the nearby and in the far Universe

Most of the visible matter in the Universe is in the form of stars. While observations at other wavelengths have revealed important quantities of matter in other forms (i.e. HI at 21 cm, hot intra-cluster gas in X-rays), stars are still the most important tracer of matter in the Universe: they trace the structure and gravitational potential in our Galaxy, they emit the visible light in which we 'see' distant galaxies, allowing us to study both their large scale distribution (and thus the Universe's geometry and texture) and their morphology. Additionally, stars are the only chemical factory in the Universe, with all heavy elements fabricated in nuclear reactions in stellar interiors. Additionally, stars are the Universe's clock: through our understanding of stellar structure and evolution we can determine the age of a coeval stellar population or (less reliably) of individual stars. This we use to determine the age of any stellar aggregate, be it stellar clusters or whole galaxies and their components, as e.g. discussed in Sect. 3.1 and 3.2. Thus, a full understanding of the life cycle of stars, from the processes leading to formation of stars starting from the diffuse interstellar medium, to their evolution along the main sequence (where they spend most of their life) through the final, often violent stages of their evolution, is still a topic of key importance for our global understanding of the Universe. Last but not least, planetary systems form, evolve and may lead to the development of habitable planets around stars. A comprehensive understanding of the formation of stellar and planetary systems is a key to estimate the frequency and characteristics of planetary systems in our Galaxy.

Stars (and their attending court of planets) are born from the gravitational collapse of clouds of dust and gas in the ISM. Going from this simple statement to a full understanding of the involved processes, and building a theory with predictive powers, is proving to be a very difficult and complex enterprise. At the same time, the early stages of a star's life present a rich and fascinating phenomenology, with a wide range of physical processes involved. In addition to the obvious interest of understanding star formation as the beginning of most of the visible matter in the Universe (as well as of the support to all possible life forms), this phenomenology makes its study a very interesting topic per se.

2.4.1 Interstellar Medium

The interstellar medium is the fundamental ingredient out of which stars will form. As discussed in previous sections, only the simplest elements are synthesized in the early universe. The first generation of stars formed in this dust-free and extremely low metallicity environment. Subsequent generations of stars formed out of the interstellar medium polluted with heavy elements and dust particles produced by previous stellar generations. The Earth and our own bodies are mainly made of elements produced inside stars and injected in the interstellar medium.

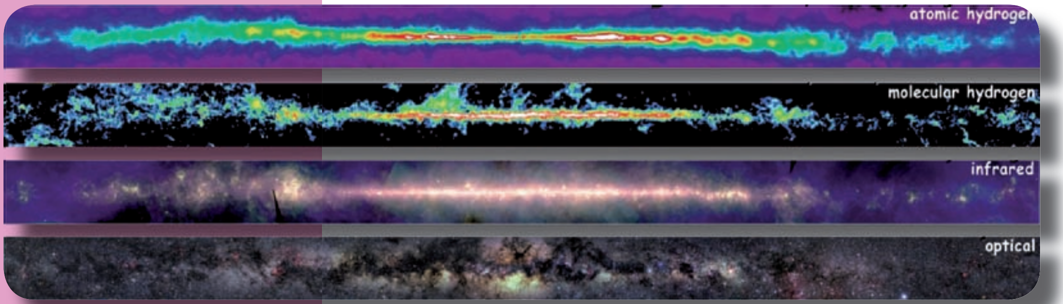


Fig 2.4.1 The Milky Way as seen in atomic hydrogen, molecular gas, far infrared and optical (from top to bottom). The images are centered on the Galactic Center and span the complete longitude range from -180 to 180 degrees and from -10 to +10 in latitude. Compared to the atomic gas, the molecular gas is concentrated on the mid-plane and the inner regions of the Galaxy as traced also by the dark clouds in the optical view.

The understanding of the composition and evolution of the interstellar medium is thus a key for the understanding of the star and planetary formation process. Since hydrogen is the most abundant element in the ISM, the most important classification of the ISM in galaxies is based on its status, either atomic or molecular. Most of the ISM mass of our Galaxy is in atomic form (HI clouds), but in selected regions of high density, the gas can shield itself from the diffuse UV radiation and the molecular form of hydrogen (H2) becomes dominant (molecular clouds). Within such molecular clouds even complex molecules can form. The inventory of molecules and their abundance in clouds is determined by their physical and chemical evolution, a theme which is still poorly understood, and new molecules (either simple or very complex) are discovered continuously in the dense ISM.

Another issue that is being explored and will be tackled with the advanced observational and modeling techniques, that will become available in the future, is the origin of complex molecules and solids in our own solar system. Many of the molecules, dust particles and ices present in planets and comets can be synthesized within molecular clouds. Nevertheless, there are some that require processing in a more complex and energetic environment, as in circumstellar disks around newly formed stars.

Enormous progress is needed in the coming decade both in our theoretical understanding of chemical models of dense clouds and circumstellar disks and in our ability to observe, on all relevant scales, the molecular diversity of the Galactic ISM. An essential asset will also be the ability to extend the detailed studies of the ISM to external galaxies.

2.4.2 Stellar birth

While stars are known to form in clouds, the early phases of the process, i.e. the collapse of an otherwise stable lump of gas and dust into a self-gravitating proto-star, are still far from being understood, and, one could say, still enshrouded in mist. To collapse, a cloud must be able to efficiently cool away the heat produced, and it must somehow shed away the primordial angular momentum which would otherwise lead the proto-star to rotate at breakup speed. Also, the gas, which has a significant ionized component, must be able to collapse against the ambient magnetic field. Finally, it has recently become apparent that cloud turbulence can be a major supporting force against collapse. The role of the different mechanisms supporting molecular clouds and their lifetimes is still debated, and competitive views on the roles of magnetic fields and turbulence make different predictions that will be tested observationally in the coming years. Accurate measurements of magnetic field strengths, velocity fields and chemical and physical parameters of molecular clouds will allow to settle this debate.

Yet, notwithstanding this array of difficulties, stars manage to form throughout the history of the Universe. Understanding in detail how this happens is a key challenge for astronomy. The observational difficulties are formidable, because the early collapse phases are likely to be very rapid (and it is thus difficult to 'catch them in the act'), and per definition happening in very obscured environments, hidden away by very large optical depths of dust. Only low-energy radiation from cool dust and rare molecular species are likely to escape, whose detection with sufficient sensitivity and angular resolution is still very challenging today. Finally, the state of the ISM prior to the collapse must be understood in detail, as discussed in Sect. 4.1.

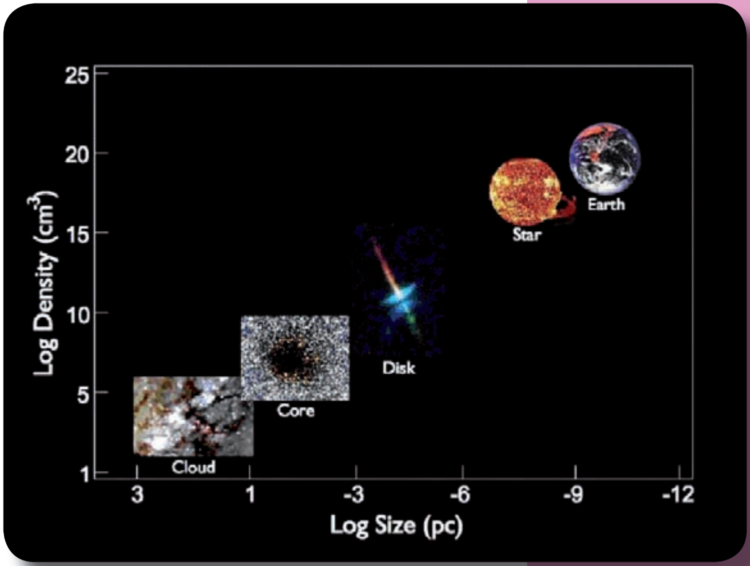


Fig 2.4.2 The range of scales and densities involved in the star and planet formation processes. The process span over ten orders of magnitudes in both parameters, illustrating the difficulties in obtaining the required dynamical range both in the observations and the numerical simulations.

Theoretically, the processes leading to and governing the collapse of ISM clouds must be understood in detail. Given their complexity, it is likely that predictive calculations will only be feasible through advanced numerical simulations, requiring adequate skills and infrastructures in computational physics.

The hot topic for the next decade will be to understand whether star formation is globally a dynamic process, involving short-lived molecular clouds either forming stars or disappearing on turbulence decay timescales, or is indeed a slow process with molecular clouds evolving into dense cores and eventually protostars through magnetically-controlled quasi-static evolution. This achievement will require both a thorough theoretical analysis and simulation of the physical processes and a large leap in the observational characterizations of star forming regions.

2.4.3 Accretion disks

Once a low-mass star is born and it starts to shine (initially with no nuclear contribution, but only from gravitation energy conversion), observations show it to be still surrounded by a spherical envelope as well as by a disk, from which accretion is observed to take place. It is still unclear whether accretion taking place in this phase is a significant contributor to the final stellar mass. While the steady accretion rates observed are often too small to be significant in terms of final mass, strong episodic accretion outbursts are observed (e.g. FU Ori-type objects), which, if frequent enough in the lifetime of a young star, could add up to a significant mass. Whether such high accretion phases are common to all low-mass stars and thus whether they are globally important is an open issue.

Accretion disks are a common structure across a range of astrophysical systems, from accretion onto compact, evolved stellar objects to accretion disks around black holes powering AGNs (see Sect. 9.3). Young low-mass stars offer a unique opportunity to study accretion physics and the physics of the disks: accreting PMS stars are numerous in the nearby star-forming regions, and are sufficiently nearby (starting at some 150 pc) that they can be studied in detail at a range of wavelengths (including optical light). Accretion appears to be channeled through the star's magnetosphere, adding complexity (and interest) to the process.

2.4.4 The first steps toward planetary formation

The early phases of a star's youth are also of key importance as it is in this stage that planets form. In the last decade a bewildering zoo of extra-solar planets has been discovered, in configurations much unlike our solar system, as discussed also in Sect. 8. While the current population of exo-planets is strongly biased by the observational techniques, it is already very clear that planetary systems do exist in a vast array of configurations. One key, unanswered question is how do they form? What factors lead to the formation of different configurations, and what is the difference in birth process of our solar system (with its gas giants in far away orbits) and of the systems with hot gas giants?

Planets are expected to form within and from the material of circumstellar disks. The structure and evolution of circumstellar disks, once the main accretion phase to the parental core is finished, is mainly dominated by the interaction with the central star. Dust is the main actor in the first phases of planetary formation, as this is the source of the solid mass that forms rocky planets and the cores of giant planets. As the ISM dust is composed of particles smaller than a fraction of a micron, during the initial phases of planetary formation, dust has first to grow to considerably larger sizes (up to meter-size boulders) then further processes as gravitational attraction and gas accretion can take place to form planetary systems (see Sect. 8).

During these initial phases grains are expected to settle differentially to the mid-plane of the disk and coagulate to form larger and larger particles in this process. Within disks dust particles are also subject to chemical and structural modifications with the formation of crystalline grains of various nature. On an observational side, we have now hints that in many disks the dust properties are very different than those of the interstellar dust, but a detailed comprehension of the physical processes, timeline and likelihood of dust growth and evolution in disks is still far from being achieved, further progress

Fig 2.4.3 Dust evolution and planets formation in circumstellar disks. Left: artistic view of the formation of "pebbles" in circumstellar disks as suggested from millimeter wave observations of the TW Hydrae system. Right: simulation of gap formation in the disk around a young star due to the gravitational effect of a newly formed giant planet.

is required both on the observational and theoretical sides.

2.4.5 High mass stars

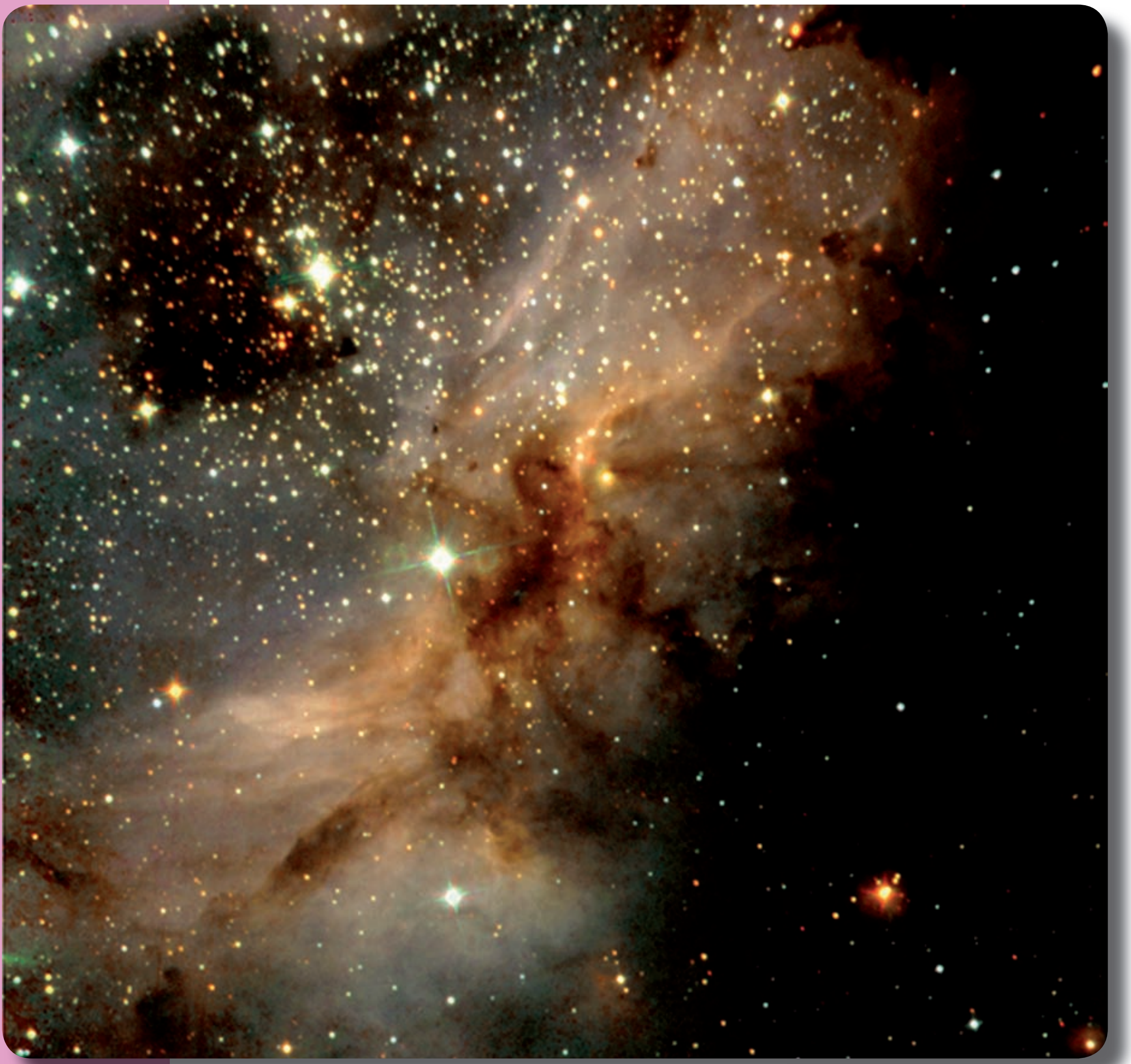


Fig 2.4.4 Near infrared "truecolor" image of the young stellar cluster in the M17 star forming region. The formation of massive stars is usually associated with dense clusters, the existence of a genetic link between the two is at the moment a tantalizing possibility (Photo courtesy ESO)

Most of our understanding of the star formation process is limited to the formation of stars similar to our own Sun. However, the most massive stars dominate the energetics of galaxies the chemical evolution of the Universe. Due to their shorter evolutionary timescales and strong interaction with the surrounding medium, the formation of massive stars in a canonical accretion scenario as described for low-mass stars is problematic. Several different theories including coalescence in dense stellar clusters have been proposed to explain the formation of massive stars. We still lack the ability to test the predictions of these theories with appropriate observational data. The frequency and characteristics of (accretion) disks around young massive stars, the structure and properties of outflows from massive protostars, and the link between massive stars, young clusters and their dynamical properties are all far from being established.

Large scale surveys of our galaxy in the infrared and millimeter range, combined with detailed and high resolution studies in the far infrared and millimeter range of selected samples of objects are expected to provide a breakthrough in our understanding of the high mass star formation process.

2.4.6 Feedback processes and jets

Once a star is born, its presence will change the conditions in the parent ISM cloud, and thus affect the formation of other stars from the same cocoon. The relevant processes are numerous, and act on different scales. As soon as a star is born, it becomes a powerful source of energetic radiation (UV, X-rays) and particles, which will shine onto the circumstellar matter and onto the disk, ionizing it and acting as a catalyst for chemical (and possibly nuclear) reactions. The stellar magnetic field will regulate the accretion flow and interact with the disk, generating a feedback mechanism.

Jets and outflows on a variety of scales (from tens of AU to few parsecs) are observed to be common in a wide variety of young stellar objects, and thus likely to be a ‘universal feature’ of star formation. Jets are likely to play an important role in carrying away angular momentum from the contracting star, and will inject momentum back in the cloud. Through the formation of shocks they can also be the seat of energetic processes.

Finally, early supernova explosions of the most massive stars in a given star-forming cloud will result in a drastic change of conditions, i.e. blowing away the surrounding gas and dust, and thus stopping star formation in their immediate surrounding. At the same time, the traveling shock may trigger star formation farther away, initiating the collapse of other parts of the cloud.

2.4.7 The Initial Mass Function

The global outcome of star-formation from a given parent cloud can be described through the Initial Mass Function (IFM), i.e. the number distribution of newborn stars as a function of their mass.

Whether the IMF is a universal feature of star formation (thus encoding some deep physical meaning) or whether it depends e.g. on the initial conditions of the cloud (metallicity, mass, etc.) thus being a diagnostic of the mode of star formation (i.e. low efficiency star formation vs. starbursts) is still a debated question. A proper understanding of the IMF and of its (possible) universal character is an essential tool to e.g. understand far away (and thus unresolved) galaxies, through the study of the integrated light from their stellar population, as described in Sect. 3.2.

In addition to the theoretical understanding of the star-forming process necessary, major advances in this field will rely on the complete, unbiased census of stars in a number of young, pristine stellar population spanning as broad a range of conditions as possible.

2.4.8 First stars and low metallicity environments

One theme of particular interest is the birth of the first stars (so-called Pop III stars). The conditions in the early Universe were clearly very different from the ones of present-day star formation: no metals (and thus no dust) were present, and obviously no (proto-)galaxies to nurture the ISM. Yet stars did form, and they were clearly the progenitors of all subsequent generation: they had a key role in providing the UV radiation which re-ionized the early Universe (see Sect. 2.1), and they produced the first heavy elements, starting the chemical evolution of the Universe. Understanding how did the first stars form, when they formed and what stars where produced in the process is clearly a key issue in our understanding of the early Universe. The lack of metals is a key issue, as in the early collapse phases IR radiation from molecules and dust grains is one of the key cooling processes for the cloud. Thus, the collapse and consequent star-forming process was different than what’s observed today in different degrees of detail in our Galactic neighborhood. So far we have been unable to detect Pop-III stars even in our and in nearby galaxies, although the results are not conclusive yet. This lack is an indication that only (very) massive stars formed in the first generation(s), as low-mass stars would have survived until today and thus be visible, while none has been found thus far.

Theoretically, the work is much linked to the understanding of local, present day star formation. Observationally, the key is to relate general theories to the specific properties of star formation in very low metallicity environments, similar to those expected in the primordial universe. The study of the interstellar medium and (young) stellar populations in nearby metal poor dwarf and irregular galaxies is thus an essential tool to constrain theories of primordial star formation.

Fig 2.4.5 Primordial star formation in the extremely low metallicity blue compact dwarf galaxy IZw18 (NASA/ESA)

2.5 The life cycle of stars

Once a star is fully formed, gravity ceases to be an important source of energy and primordial circum-stellar matter has been largely dissipated, a star begins its permanence on a well define region of the color-magnitude diagram, called main sequence, where it will spend most of its life. The actual lifetime on the main sequence is a strong function of stellar mass, ranging from about a million years for the most massive stars to tens of billion years for the smallest stars, i.e. longer than the Universe's age. Life on the main sequence is relatively quiet, with the stars burning their nuclear fuel in the core and radiating the resulting energy away in space. Little (and slow) visible changes in the outer appearance take place while in the core elements are steadily fused together with new elements being fabricated. With time the chemical composition is modified and new reactions are required to sustain the star. New equilibrium configurations are reached which can imply deep changes in the appearance of the star. Depending on the mass of the star and on the possible presence of companion stars, the end point of such evolution can be either a dramatic explosion which disrupt the star, or the quenching of the nuclear reactions leading to the slow, progressive cooling of the star.

2.5.1 Life on the main sequence

Stellar evolution on the main sequence is governed by fairly simple principles, and indeed its large scale features have been modeled analytically already in the 1950's, assuming a spherically symmetric star, made of gas in hydrostatic equilibrium, in which gravitational pressure is balanced by the energy produced by nuclear reactions. Once the equation of state and reaction rates, as well as opacities, are known the basic features of main sequence life can be described.

Reality is however much more complex, with the assumption of spherical symmetry steadily violated, e.g. by rotation, which is present in all known stars (and which creates internal flows resulting in steady mixing) and by magnetic fields, which have been found to be present in most stellar types. While radiative heat transfer is fairly well understood, convection (which is present in all stars, either in the core or in the outer envelope) is still an ill-understood process, with issues such as overshooting very poorly modeled. Convection and rotation are two examples of additional mixing processes, which strongly influence the evolution of stars: they influence the lifetime of a star on the main sequence (by supplying additional fresh fuel to the nuclear burning core), and they influence the yields with which new elements are assembled in the core. The mechanisms generating stellar magnetic fields (the stellar dynamo) need to be understood in detail, to be able to trace back the observable surface magnetic fields into the stellar interior. While the Sun is and will be a fundamental reference point for solar-type stars, other types of dynamo (e.g. turbulent dynamos) are likely at work in other types of stars, requiring separate theoretical and observational advances.

The limits of our understanding of stellar structure even on the main sequence are shown by the fact that in well studied nearby star clusters (i.e. the Pleiades) different ages are derived by different methods, with for example the turn-off age (determined on massive stars) differing by 30 % or more from the age determined by Li burning in brown dwarfs. Similarly to what happens with the distance ladder, such uncertainties in the age ladder reflect in our understanding of the age of the Universe.

Fig 2.5.1 The Pleiades Star Cluster (NASA, ESA and AURA/Caltech)

Note that the lack of understanding is even more acute in the pre-main sequence (PMS) phase, where different workers produce widely different estimate of e.g. stellar masses and other fundamental parameters.

Another example of the still very incomplete understanding of stellar evolution and of its importance is the issue of Li in Pop II stars: the discovery in the early 1980’s of a reasonably constant abundance of Li in Pop II stars led to the inference that the measured value must be representative of the primordial, Big Bang nucleosynthesis (BBN) abundance. As the value was indeed in agreement with the computed BBN values, this was considered as a very nice confirmation of the 'standard' cosmology. Things have however recently become more complex, with the BBN value computed on the basis of the WMAP-derived cosmological parameters discrepant with respect to the currently accepted Pop II stellar values, which in recent work also appear not so constant as once thought. More in general, the behavior of Li in stars is far from being understood, specially in Pop I stars, with apparently similar (and coeval) stars showing very different abundances and thus evidence for very different mixing processes, bringing surface Li in the stellar interiors where it is readily destroyed.

Recently, apparently well established 'fundamental' values, such as the solar photospheric metal abundances, have been significantly changed by more precise determinations. The implications of this are broad ranging: most abundance analyses are made relative to the Sun, and thus are in need of revision. The updated abundances have also destroyed the almost perfect agreement between helioseismic observations and the 'standard solar model', used as a calibrator for much stellar structure work. While this is a topic of current debate, it shows how far are stellar structure and evolution from a full understanding.

The reason for the change is the use of detailed model atmospheres, replacing the simple, plane-parallel atmosphere used in most work up to now. While significantly more difficult to use and to compute, 2- or 3-d atmospheres are clearly more physically representative. How important is their use across the broad range of stellar types, and what are the implications on the inferred fundamental stellar parameters, remains to be assessed.

The frontiers in stellar structure studies are both theoretical and observational: theoretically, new models must be built which account for the critical stages of stellar evolution with all physical ingredients which affect the life of real stars. This will require improved understanding of the physics (especially convection) as well as improved computational capabilities. Observationally, these models must be empirically validated, especially with the new observables which will become available in the near future, such as seismic oscillation frequencies.

Up to now classical observables include stellar masses which can only be determined dynamically from the study of resolved binary systems. While this is a very classic discipline, the number of accurate stellar masses is still disappointingly low, especially for crucial stages of stellar evolution. Significant in this respect is the recent dynamical calibration of the mass–luminosity relation at very low stellar masses and young ages, which has demonstrated that the previous determinations of the masses at the faint end of the IMF, based on theoretical models, were off by a factor two, and that the frequency of brown dwarfs and planetary mass objects in young stellar clusters were overestimated.

2.5.2 The outer stellar atmosphere

One discovery dating back from the early '80s is that most stars are X-ray sources. This implies that they are surrounded by a hot, magnetically confined outer atmosphere (the corona). Observations have shown that the most active stars can have coronal plasma at temperatures of hundreds million degrees during large flares, with peak X-ray luminosity up to 10% of the star's photospheric luminosity. Even the mechanism heating the relatively quiet solar corona is still not understood (Sect. 6.4), and the problem is of course much more severe in active stars, in which the corona can be as much as 10,000 times more luminous in X-rays than in the Sun.

The corona, both directly and through the confining magnetic field, has a significant effect on the evolution of stars: magnetic fields will change the interior stellar structure (e.g. influence convection, affect mixing, etc.), and the high energy processes in the corona can be nucleosynthesis sites, e.g. generating key elements such as lithium (with the attending cosmological implications). In the younger stars, the magnetic field is though to channel accretion, and thus its understanding is the key to understanding the stellar formation.

The study of large flares (similar but much larger than the solar events described in Sect. 6.4) is one of the few tools allowing to derive both the physical scale and the magnitude of stellar magnetic fields, and has allowed to show that the energetics of the corona can be an important element in a star's total energy balance.

Finally, as X-ray luminosity strongly evolve with stellar age, X-ray surveys are a very effective tool for tracing young stars throughout the Galaxy, and thus to trace the structure of the youngest populations as well as to constrain the star formation rate.

2.5.3 The structure of the Sun and the Sun as a star

The Sun, being the nearest star and the only one on which significant spatial resolution is possible, can be studied to a much higher degree of detail than possible in other stars, as discussed in detail in Sect. 6.2. The advent of helioseismology has made possible to constrain its interior structure all the way to the core, and thus to empirically validate solar models, which constitute a fundamental benchmark for stellar structure models. Thanks to the availability of both space observations and ground based networks seismic observations of the Sun have flourished in the last decade, with the solar oscillation frequency being the most precise astrophysical observable known. Among the most notable achievements, one can mention the 3-d mapping of the interior rotation of the Sun. One of the frontiers is detecting the gravity-driven modes (g-modes), important because they reach and sample the Sun’s core. The investigation of the interactions between the solar granulation, resulting from the turbulent dynamics, and solar global oscillations, has given encouraging results as far as the detection of g-modes is concerned. Helioseismology, directly connected to studies of solar inner structure and of the Sun as a whole, has paved the path to studies of stellar seismology, which is expected to flourish in the near future thanks to the availability of new space-based data.

However, the apparent beautiful agreement between seismic data and models has recently been perturbed by the updates on the metal abundances for the Sun (Sect. 5.1) making it necessary to reconsider some facts considered as acquired. At the same time, the long base line of the extant seismic observations is starting to allow to study the internal dynamics of the Sun, and to address questions such as the structural changes linked, e.g. to the solar cycle, to the dynamo processes, etc.

In parallel, understanding the cyclical behavior of the Sun in the context of the cycles observed in other stars has an obvious interest also for the habitability of our planet. Is the Sun’s behavior typical? Is it constant? Assuming that the Sun is a ‘normal’ star, understanding the population characteristics of stars at large in terms of cycle frequency, behavior, amplitude, etc. assumes a relevance that transcends astrophysics. Interestingly, there’s some evidence for the Sun to be ‘different’, evidence that needs to be corroborated on a solid observational basis.

2.5.4 Post main sequence evolution

Once the hydrogen in the core is finished, the star leaves the main sequence and starts its rapid evolution toward the final stages.

Observations of evolved stars below around 2 $M_\odot$ reveal the existence of fundamental problems in canonical stellar modeling, as the isotopic mix of light and intermediate-mass elements (up to oxygen at least) cannot be accounted for by standard convective mixing. In particular, unexpected chemical anomalies are found above the so called *luminosity bump* of the red giant branch. Slow non-convective circulation of material exposed to partial H burning has been usually assumed to explain the above mentioned evidence. However, to overcome some difficulties of pure rotational mixing models, it has recently been proposed that magnetic fields may have the capability of providing a suitable engine for driving the required mass circulation, and would mimic a diffusion process from the envelope (“cool bottom process”). However, the full verification of this idea must be verified by means of a complete MHD treatment of the advanced stages of low mass stars evolution.

Low and intermediate mass stars (between 0.8 and 8 solar masses) evolve along a crucial (and complex) stage called Asymptotic Giant Branch (AGB). During this evolutionary phase these stars contribute significantly to the synthesis of Li, C, N and heavy s-process elements, from Kr to Pb. As a consequence the understanding of the chemical evolution of the galaxies is strictly correlated to the production of reliable models of AGB stars. Models especially need to be improved in the areas of mass loss efficiency and mixing phenomena within the stellar interior. . During the ascent of the AGB, efficient mass loss drives the removal of the envelope after a certain number of thermal pulses. The efficiency envelope removal, and thus the duration of the AGB phase, the remnant mass and the yield for ISM enrichment, is still a matter of debate.

Planetary Nebulae (PNe) are the endpoint of the evolution of AGB stars. As such, they occupy a strategic ground between stellar and interstellar physics; they are the key ``recycling path’’ through which light elements (He, C and N) are fed back in the ISM and then in the future generations of stars, and represent important sources of UV radiation and kinetic energy for the ISM. Their complex structures are still largely unknown although their knowledge is necessary to address many of the main open questions regarding the mass loss history, the wind interaction, the ionization processes, the effect of magnetic fields, of the binary structure of the central star and microstructures, the formation and evolution of dust, the synthesis of complex molecules.

Fig 2.5.2 The Cat's Eye Nebula, formally cataloged NGC 6543 (NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/ AURA))

2.5.5 Pulsating Stars

Pulsating stars are found across the HR diagram, from pre-main sequence to main sequence and post main sequence stars. The study of stellar instabilities (asterosismology) provides a unique tool to investigate stellar interiors and to test both the stellar structure and the physical processes within them. New ground based and space facilities planned for the coming decade will allow to obtain excellent accuracy observations of stellar oscillations for a variety of stars in different evolutionary stages. These data are expected to provide a unique benchmark for testing and improving stellar evolution models.

Among the radially pulsating variable stars, the intermediate mass ($3 \leq M/M_{\odot} \leq 10$) Classical Cepheids and the low mass (~0.8 $M_{\odot}$) RR Lyrae play a very crucial role in many fields of the modern astrophysics. These intrinsic variables, both in the core He-burning phase, are commonly adopted as stellar tracers of young and old stellar populations, respectively. Nevertheless, their most important role is in their use as distance indicators. Thanks to their Period-Luminosity (PL) relation and to their intrinsic high luminosity, Classical Cepheids allow to determine the distance of far away resolved stellar systems with recent star formation episodes. While the distance determination of old stellar systems can be obtained from RR Lyrae stars by using their Cepheid-like PL relation in the infrared (J, K bands) as well as their Luminosity-Metallicity relation. However, at present the theoretical understanding of these stars still suffer large uncertainties mainly related to the treatment of convection and its coupling to the pulsation phenomenon.

2.5.6 Exploding stars and their remnants

Massive stars ($M>10\ M_{\odot}$) play a major role in the evolution of the universe since, among the other things, these are responsible for the chemical enrichment of the ISM, eject a substantial amount of energy either as neutrinos and as kinetic energy of the ejecta, and are the direct progenitors of neutron stars and black holes. “Massive stars” go through all the hydrostatic nuclear burnings, from the H to Si, and finally explode as core collapse supernovae. Their evolution and final explosion are qualitatively understood, there are, however, many uncertainties that prevent a full understanding of these objects. The lack of a proper treatment of convection is, once again, a serious limitation to the construction of reliable progenitor models. In this context, the relevant point is the correct evaluation of the mixing timescale that, for these stars, is comparable to the thermonuclear timescale. The related uncertainty significantly affects the final extension of the iron core, the final mass-radius relation, the physics of the core collapse and, in turn, the properties of the explosion. A full coupling between convection and nuclear burning would provide the best approach to the computation of the internal structures of the progenitor stars. However, this is beyond the capabilities of current computational facilities and will require the next generation of computer machines.

The rate at which mass is lost from luminous blue variable stars, red and blue supergiants and Wolf-Rayet stars is also still highly uncertain. Indeed we miss both reliable empirical mass loss rates and quantitative theories to provide a self- consistent picture. In particular, the mass-loss of Wolf-Rayet stars and its dependence on metallicity are largely unknown and these critically affect the estimates of the yields produced by these stars.

While single, low mass stars will quietly evolve into a white dwarf, not before having gone through the AGB phase mentioned before, the final stages of stellar evolution
of massive stars and low mass stars in close binary systems are the most energetic ones and produce the most energetic events known in the Universe, i.e. supernovae and hypernovae (with the attending GRB, as discussed in Sect. 2.9.4).

Supernova explosions are of key importance in the long term evolution of galaxies (and thus of the Universe) as they disperse the newly formed elements back in the interstellar medium from which future generations of stars will form, thus driving much of the Universe's chemical evolution. At the same time, they are an important source of energy and turbulence for the ISM, and can by themselves trigger the formation of new generation of stars. Overall, supernovae are fundamental tracers of the global properties of stellar population: through stellar evolution theories, they represent the link between the star formation history and IMF with the chemical evolution of the galaxies.

Understanding the final, fast stages of massive stars evolution, which lead to the collapse of the core, is not easy, as the star evolves on very fast time scales, out of equilibrium, with rapid nucleosynthesis taking place. The mechanism itself for the core collapse supernova explosion remains unknown. Current 3-d models including sophisticated physics such as the neutrino transport, the fluid instabilities, rotation, magnetic fields, general relativistic effects, equation of state of sub- and super-nuclear density material still do not yield explosions. Initial inhomogeneities present in the star will likely be amplified, leading to significant asymmetries in the explosion as well as in the ejecta. After the explosion, a compact stellar remnant will be left behind. Whether a neutron star or a black hole will form, depends on several, not fully understood parameters such as the mass of the progenitor, the mass loss history and fallback. The study of compact objects and their high energy physics is covered elsewhere (Sect. 9).
Current observations seem to indicate that stars of the same mass

explode with different energies and ejected masses of heavy elements. Understanding whether this is a real effect and what are the driving parameters is of the utmost importance.

An important contribution to the understanding of the processes taking place during the SN explosion may come from present and future experiments searching for neutrino bursts from stellar gravitational collapses.

SNIa are believed to originate from the thermonuclear disruption of a white dwarf composed of carbon and oxygen, accreting material up to the Chandrasekhar limit either from a companion star or merging with another white dwarf.

The importance of SNIa as standard cosmological indicators cannot be overstressed. In the last decade, the presence of a new form of 'dark energy' in the Universe has been discovered by studying a significant sample of high redshift SNIa (see section 1.3). While the observed deviation from the expansion predicted in the absence of dark energy is by now well established, it rests on the key assumption that SNIa are standard candles. The increasing diversity among the well-studied SNIa has not yet found a theoretical explanation in terms of na-

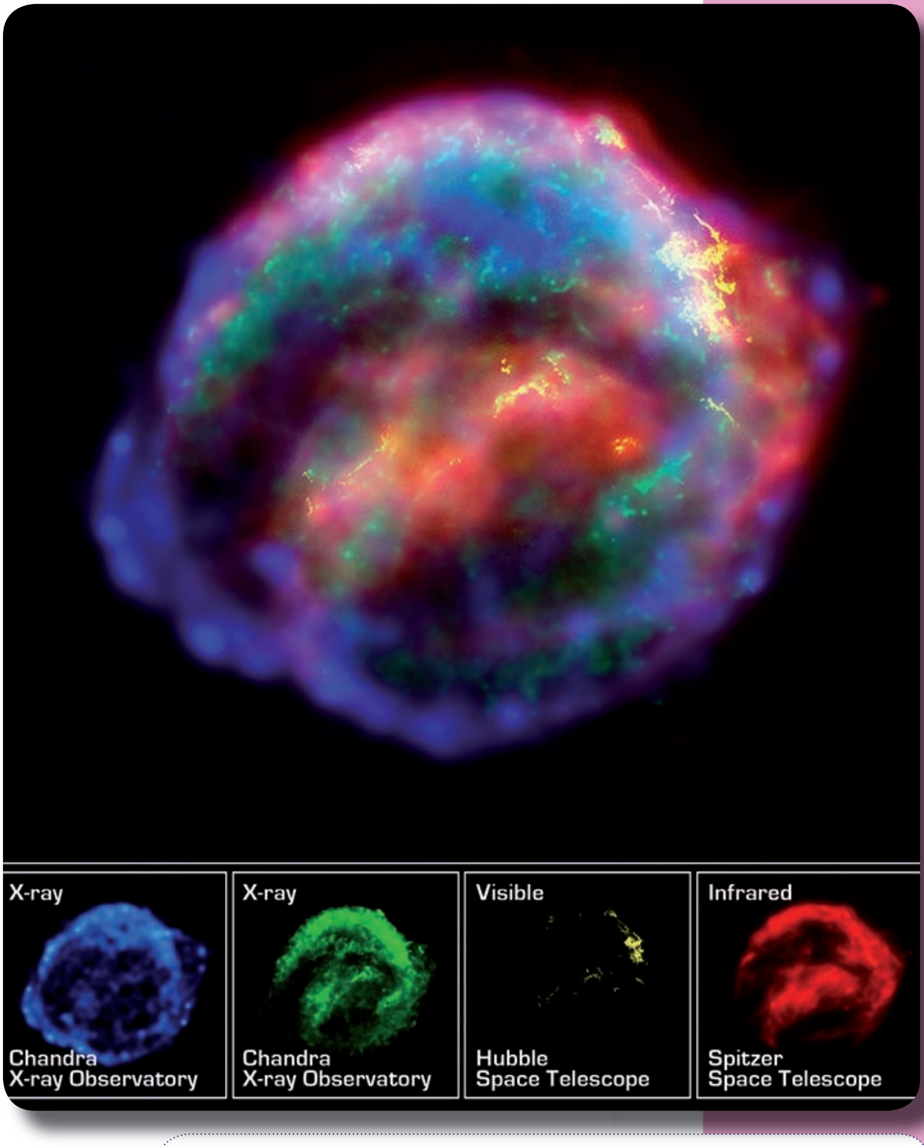


Fig 2.5.3 Multiple Images of Kepler's Supernova Remnant (SN 1604) The combined images in X-rays, optical light and IR light unveil a bubble-shaped shroud of gas and dust that is 14 light years across and is expanding at 2000 kilometers per second. Observations from each telescope highlight distinct features of the supernova remnant, a fast-moving shell of iron-rich material from the exploded star (optical light), surrounded by an expanding shock wave that is sweeping up interstellar gas (X-rays) and dust (IR).

ture of the progenitor systems and of physics and/or explosion mechanisms. Indeed, although the empirical calibrations relating the light curve shape and the luminosity are very effective, their physical understanding is crucial especially if one wants to check the validity of the results in the early Universe, when the environmental conditions were very different. Recently, high resolution X-ray observations of young supernova remnants have opened up the possibility to measure reliably the spatial distribution of metal abundances of the stellar ejecta dispersed by the explosion. In the following years, the comparison between the prediction of refined explosion models and the information given by these observations is expected to contribute enormously to the study of explosion mechanisms in the SNe Type Ia and other kind of SNe.

2.6 Solar, interplanetary and magnetospheric physics

2.6.1 The Sun as a Rosetta stone

Solar Physics, the study of our star, has a key role in Astrophysics: the Sun allows us to observe in detail the phenomena occurring on a star and in the interplanetary space; it also is a laboratory where we can study physical effects not obtained in laboratories on Earth and not adequately observed on more distant astrophysical objects. Solar studies provide unique insight on basic physics of, for instance, magnetized plasma, turbulence, collisionless shock-waves-particle acceleration, spectroscopy. Being very bright over the whole electromagnetic spectrum the Sun is often the target on which new instrumental concepts are first tested. In many respects solar physics is the Rosetta stone of astrophysics, and of many areas of fundamental physics.

The present focus of the Solar, interplanetary and magnetospheric physics is on the variety of phenomena collected under the umbrella definition of **Solar activity.**
The content of this field, very rich of physical effects, arguably could be condensed as: complex interaction of the magnetic field and plasma over a wide dynamic range of conditions.
The magnetic field is generated inside the Sun, threads through the solar atmosphere, the heliosphere and the planets magnetospheres; on the other hand, the entire Sun, the solar wind, the heliosphere, and the outer atmospheres of several planets are in plasma state.

Key aspects and problems of solar physics pertain to:

- what can we learn about stellar activity observing the sun
- magnetic flux emergence and organization at the solar surface
- the heating of the solar outer atmosphere
- coronal explosive events and other plasma phenomena
- the solar wind and the mechanism(s) of its acceleration
- the Sun-Earth and Sun-planets interactions
- spectroscopy and atomic physics

As already discussed in section 5.3, helioseismology, the study of Sun oscillations, provides a very effective tool to explore the inner parts of the Sun and to place stringent constraints on the theory of stellar structure. Analogously, the Sun is the only star where we can observe directly, resolve and study the many features and structures in various spectral bands (spots, plages, active regions, coronal loops and structures), and use them as templates of the possible phenomena at work in the outer layers of stars related to the Sun. For instance, high-resolution observations of the solar photosphere provide a rare directly observed example of convective turbulence and high resolution X-ray observations of coronal structure yield clues on coronal phenomena at work in other stars and fundamental clues to understand stellar activity.

2.6.2 Magnetic flux emergence and organization at the solar surface

A primary and challenging question concerning the emergence and evolution of solar active regions is how buoyant magnetic fields from the convectively unstable layer emerge dynamically into the solar atmosphere and corona.

The structure of the solar atmosphere might be due to the interaction of magnetic fields and plasma flows at the smallest spatial scales, few tens of km on the solar surface, with far-reaching implications. For example, surface convection might be subtly but steadily altered relative to the pure hydrodynamic case, thus introducing further complication in an already ill-understood process of fundamental astrophysical relevance (Sect. 5.1). The interaction of magnetic fields and mass flows ultimately establishes the existence and the removal of magnetic regions on the solar atmosphere, and may play a role in the excitation of solar global oscillations. High resolution vector polarimetry with low-scattering optics is required to test numerical simulations of magnetic regions; an insight into the interaction of magnetic flux and mass flows is also crucial to understand the behavior of magnetic fields on the larger spatial scales typical of other astrophysical objects.

Global dynamo models that attempt to explain large-scale magnetic fields are based on theories involving mean field properties; although the general behavior of the solar dynamo may be understood, no whole-Sun self-consistent dynamo model exists. In particular, a turbulent dynamo action in the convection zone may be essential in a complete dynamo model, since it may produce small-scale magnetic flux concentrations. Such concentrations are thought to undergo a complete renewal every few days at most, and may supply an amount of magnetic energy substantially larger than that provided by large-scale active regions. At last, the application of new analysis techniques, already used for nonlinear dynamical systems, to large-scale magnetic flux concentrations has showed that the main features of the cycle (11-years period, butterfly diagram, etc.) can be obtained by using a small number of modes. The connection to stellar dynamo, galactic dynamo, etc., problems is evident.

Lastly, the observation of carbon monoxide spectra show cool clouds that appear to occupy much of the low chromosphere; only a small part of the volume apparently is filled with hot gas. New unified models of dynamic and inhomogeneous solar atmosphere can explain the spectra. However, the numerical simulations indicate that the temperature is structured on spatial scales unresolved with current solar telescopes. A test of the recent models requires a large-aperture solar telescope that provides access to the thermal infrared. As shown by recent studies, most notably 3-d MHD simulations of the solar atmosphere, small scale phenomena are not "side effects", but are fundamental for global properties. The challenge for the future will be achieving observations with the resolution necessary to study properly them.

2.6.3 Geating of the solar outer atmosphere, coronal explosive events and other plasma phenomena

While the solar visible surface is at 6000 K, the solar outer atmosphere is maintained at a few million degrees by some heating mechanism. Heating of the solar outer atmosphere is still one of the major enigmas of solar (and stellar) physics and of basic plasma physics: we know much more than years ago, but we still miss a detailed grasp (or even an overall picture) of the mechanism(s) at work. Most of the proposed scenarios are based on dynamic magnetic field rooted in the lower solar atmosphere, continuously shacked, shuffled and concentrated by photospheric plasma motion and organized in bundles of sub-arcsec transverse spatial scales. Observations have established that in the lower atmosphere the magnetic field is organized into countless fibrils or flux tubes, which are likely channels for transporting energy from the solar interior to the upper atmosphere or main actors of the heating through magnetic field dissipation. Steady coronal heating has two main candidate theories: the dissipation in the corona of magnetic energy generated by the continuous winding of field lines deeply rooted in photosphere, and the dissipation of Alfven waves generated by chaotic motion in the lower atmospheric layers and propagating along field lines into outer layers. Thus, in order to unravel the mystery of coronal heating one has to understand (in the optical and infrared bands) the properties of magnetic field in the lower solar atmosphere and its interaction with plasma motion plus, at the same time, to study the processes of energy dissipation in the solar corona through UV and X-ray observations. In order to single out the mechanism(s) in the various atmospheric layers it is necessary to measure various physical quantities (plasma velocities, magnetic fields, phase differences between their fluctuations, etc.) with a sub-arcsec spatial resolution, i.e. comparable with the inter-granular scales, a high dynamic range for intensity (104) and a cadence of 1 minute or less, together with nearly simultaneous high resolution UV and EUV images of the transition region and lower corona. The problem of coronal(-like) heating is also fundamental in many other astrophysical objects and understanding the heating of the apparently stable solar coronal magnetic arches is important for fusion plasma studies, along with the related problem of hot plasma confinement in stable configurations.

Flares and flare-like events (i.e. Ellerman bombs, X-ray bright points, etc.) heat large amounts of the solar atmosphere explosively up to 107 K, CMEs hurl up to 1016 g of solar plasma in interplanetary space. These are the most energetic and explosive solar events, due to the sudden release of energy stored in magnetic fields, delivering up to 1032 erg in a few minutes. Flares and CME are somehow related, and often occur together. They manifest themselves over the entire electromagnetic spectrum; they also eject plasma and high-speed particles (i.e. solar cosmic rays), which blast through the entire solar system. One of the best candidates for the plasma mechanisms at work is the magnetic field lines rearrangement and “reconnection”. These phenomena provide a clue to more energetic phenomena occurring in stellar atmospheres (stellar flares reach 108 K) and other astrophysical magnetized plasmas. Key problems in this field are the understanding of the mechanisms through which energy is gradually stored in the magnetic field, the instabilities which trigger the phenomena onset, and the various plasma phenomena which convert the energy into heat, motion, accelerated particles and much more.

Besides solar Physics is a case where plasma physicists can test, apply and extend their studies and where they can do work that is fundamental for the astrophysics as a whole, as well as for basic plasma physics: on the Sun we can observe phenomena not obtainable in the lab and not observable in other astrophysical objects. Reaching angular resolution down to 700 km in the corona and 70 km in the photosphere promises diagnostic power available only in our star. The Sun is a laboratory for plasma physicists; EUV, X-ray and gamma-ray spectroscopy and spectropolarimetry over the whole electromagnetic spectrum are fundamental for the related diagnostics.

Despite its importance, we still have very few measurements of the intensity of coronal magnetic fields. Typically our knowledge of coronal fields is based on the extrapolation to the corona, by means of Maxwell equations, of photospheric magnetic fields obtained through magnetographs.

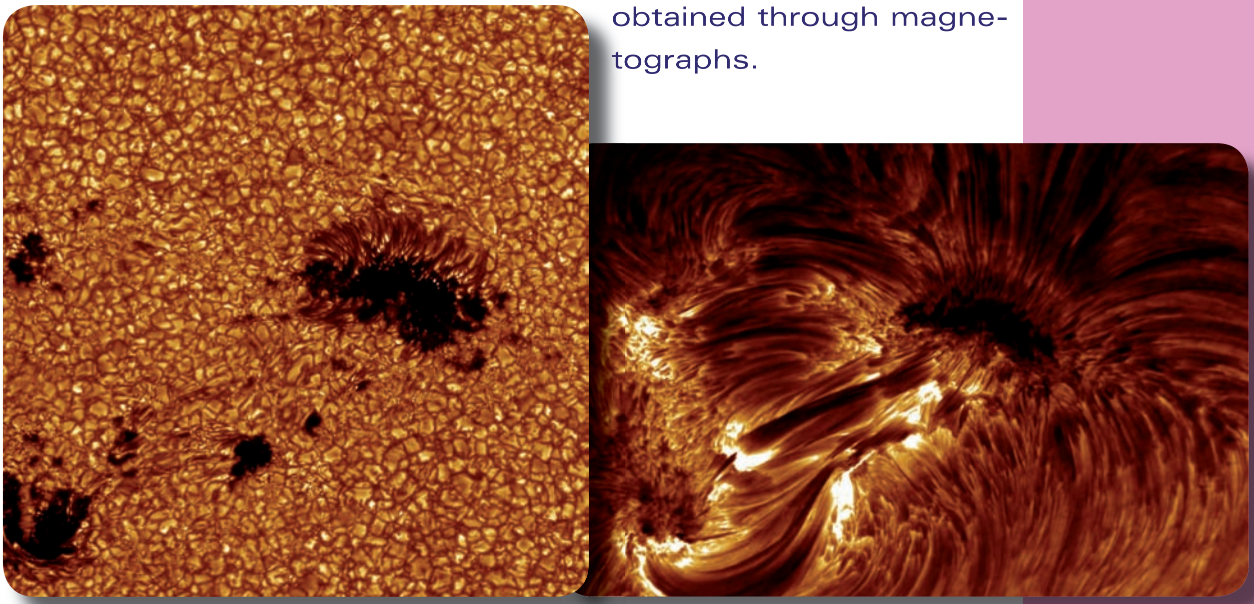


Fig 2.6.1 H-alpha and continuum at 436.4 nm images from the SST show the solar photosphere (left) and corresponding H-alpha features (right). Magnetic active regions mark the places where the feature ends emerge and reenter into the solar photosphere. The SST is operated on the island of La Palma by the Institute for Solar Physics of the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

Direct measurements of the coronal magnetic fields are, however, in principle possible by means of spectro-polarimetric techniques in the ultraviolet (thus from space), because resonance polarization of spectral lines is modified by the magnetic field (the Hanle effect). This effect has been recently applied in astrophysics to the determination of the vector magnetic field in solar prominences and in other astrophysical objects.

2.6.4 The solar wind and the related mechanisms of acceleration

The fast (800 km/s) and the slow (a few 100 km/s) solar winds originate from different parts (respectively open magnetic field regions and coronal streamers) of the solar corona and most likely undergo different acceleration mechanisms. The fast wind is quite accelerated by outgoing waves which preferentially "push heavy ions" as SOHO/UVCS observations suggest (Kohl, Noci et al., 1998); the slow wind is less understood. Understanding the solar winds, their acceleration and their relationship to the originating solar regions and magnetic structure may help us to understand the generation of other astrophysical plasma flows. For instance, since stars lose their angular momentum through winds, the solar wind would bring insight into the problem of angular momentum loss of stars. Observations from space-borne instruments are of vital importance in this context, and in-situ measurements provide unique diagnostics of the plasma characteristics, composition and distribution function.

Studies of the solar wind, of its chemical composition (known to be different from the photospheric one), of its structures in the ecliptic plane and outside of it, its changes with the phases of the solar cycle, its evolution in the outer heliosphere, the physics of the solar wind acceleration, are important scientific problems.

The solar wind rapidly becomes collisionless away from the Sun and shows peculiar phenomena; for instance it is a unique lab where to study plasma turbulence phenomena (with satellites).

2.6.5 The Sun-Earth and the Sun-planets interactions

The Earth and the whole Solar System are immersed in the solar heliosphere, the extension of the solar atmosphere flowing as a wind into the interplanetary and interstellar space. Each body interacts with the solar wind in ways which depend on the body characteristics.

In the Earth's case, the interaction with the solar wind involves mainly the magnetic field and the upper atmosphere. The interaction between the solar wind plasma and the Earth magnetic field generates the magnetosphere, where the solar wind is dominated by the Earth's magnetic field; changes in the solar wind result in changes of the magnetospheric structure, and modifications of the internal plasma and field configuration. The Earth magnetosphere is a highly dynamic system mostly driven by solar perturbations, such as flares and CMEs; these produce dramatic changes of the particle populations, of magnetospheric-ionospheric current systems and of the Earth's environment. The plasma entering and circulating inside the magnetosphere interacts with the upper atmosphere producing the polar Aurorae and energetic neutral atoms (ENA) generated through charge exchange. Auroral activity, modulation of the convection patterns over the polar regions and ULF magnetic waves (1 mHz -- 1 Hz) are signatures, mostly observed from ground, in the polar regions, of processes affecting the magnetosphere. The remote sensing of the ENA from space, that maintain the energy, direction and composition of the parent plasma population, is a technique able to provide a global imaging of the inner magnetospheric plasma distribution and dynamics. Geomagnetic storms and sub-storms are effects of the solar wind-Earth interaction and are due to the variable coupling at the magnetopause, the boundary between the solar wind and the magnetosphere, and can be studied by magnetospheric satellites. A major, still poorly understood issue is the microphysics of the magnetic reconnection which transforms magnetic energy into particle energy and in the wind, one of the important processes for the transport of solar wind energy in the magnetosphere and for its explosive release during geomagnetic storms. Reconnection is known to occur also on the Sun and on more remote astrophysical objects: particles (ions, electrons, neutrals) and fields measurements in situ are vital to improve our understanding of the microphysics of this universal plasma process. Also galactic cosmic rays measurements in the 1 GeV - 1000 GeV energy range sample for us the interplanetary medium, thus complementing in-situ measurements. Understanding the solar-terrestrial relationships in order to forecast the near-Earth space conditions is the aim of the so-called “Space Weather research”.

A similar context is that of the interaction of solar winds with magnetized planets; Aurorae and magnetic storms in the magnetospheres of the largest planets generate strong radio and high energy emissions, yielding clues on the phenomena. Mercury has a weak intrinsic magnetic field but no atmosphere; hence the interaction involves the magnetic field, the exosphere and the surface. The Sun interacts with Mercury (in particular, but also with the other planets) also by solar radiation producing photoionization of the exospheric atoms and surface release, a process important to study the Hermean evolution. Planets like Mars and Venus, with an atmosphere but without a global internal magnetic field, interact with the Sun at the atmospheric upper boundary, mainly through charge exchange with the solar wind, through photoionization and collecting the planetary components in the solar wind (pick up ions). The comets have the same kind of interaction, while the Moon and the asteroids experience the direct impact of the solar wind on the surface.

In conclusion, investigating the Sun-Earth interaction is fundamental for human activities, but also studying Sun-planets interaction is important in the frame of the present and past evolution of the Solar System. Furthermore, the comparison with different scenarios could help to understand the past and the future of our planet.

The variability of solar irradiance and its effect on the Earth’s environment

The Sun’s outputs change on several spatial and temporal scales.

The radiative variability seems largely due to the evolution of the magnetic field on the solar surface and to its rotation with the Sun, relative to a fixed observer. The particulate variability results indirectly from changes in the heliospheric magnetic field, which modulates the galactic cosmic ray flux, and directly from changes in the solar plasma outflow due to solar magnetic activity. The variability of the average X-ray and EUV radiative outputs, particle and wind energy fluxes drive both space weather and geomagnetic storms, although carrying at most 0.01% of the solar energy output. Solar variability gives us insight into the physics of our star but also tells us about the variations of the various forms of energy input into our environment. There are also claims that it can affect the Earth’s climate, and even lead to ice ages.

2.6.6 Spectroscopic diagnostics and atomic physics

Spectroscopy is a fundamental tool of Astrophysics, over most of the electromagnetic range, and is the stimulus for atomic physics studies. Laboratory experiments not always suffice, since astrophysical conditions cannot be reproduced there and, in fact, typically astrophysical spectra help to identify new spectral lines. The Sun, being the most intense source, is the prime target for astrophysical spectroscopy. Several lines (in most spectral ranges) still await correct identification and explanation in the context of atomic physics.

2.7 The solar system

Our knowledge of the solar system has exploded in the past four decades as interplanetary probes have provided close-up views of all the planets, as well as of a diverse collection of satellites, rings, asteroids and comets. Earth-orbiting telescopes have provided an unprecedented view of the solar system, often at wavelengths not accessible from the Earth's surface. Together with this increased knowledge, numerous additional questions have arisen, as we attempt to explain the complexity and diversity that we observe on each newly visited world. The increased spatial and spectral resolution of the observations, along with in situ measurements of atmospheres, surface materials, and magnetospheres, has shown that each body is unique, and is the result of the different combination of physical, chemical, and dynamical processes that formed it and shaped it, as well as of its initial composition. Although each planet, satellite and minor body is now recognised to be very different from its neighbours, yet there are broad systematic trends and similarities that are clues to the collective history that the solar system has undergone.

2.7.1 Origin and evolution of planets, satellites and minor bodies

Starting from the first conceptions about the Universe, in which essentially only the planets visible to the naked eye were present, astronomy has progressed to a stage in which the amount of data available concerning the solar system looks overwhelming; however, basic questions like:

- How did our own solar system form?
- What processes marked the initial stages of planet and satellite formation?
- How long did it take to the gas giant Jupiter to form, and how different from that of Jupiter and Saturn was the formation of the ice giants, Uranus and Neptune?
- How did the impactor flux decay during the solar system's youth, and in what way did this decline influence the timing of life's emergence on Earth?
- What is the history of volatile compounds, especially water, across the solar system?
- What is the nature of organic material in the solar system and how did this matter evolve?
- What global mechanisms affect the evolution of volatiles on planetary bodies?
- Why do the past evolutions of the terrestrial planets differ so

dramatically?
- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?
- How common are planetary systems around other stars?
- Do any of them resemble ours?
- Is there life beyond Earth?

still lack complete and satisfactory answers. In order to formulate the correct answers, we have to substantially deepen our knowledge of the solar system as a whole as well as of its individual members.

The solar system we see today is the result of the complex interaction of physical, chemical, geological, and dynamical processes that have shaped the planets and other bodies. Many of those processes operated most intensely early in the solar system history, as the Sun and planets formed from an interstellar cloud of dust and gas, 4.6 billion years ago.

The first billion years after the initial phases was a violent period as the planets accreted from planetesimals through mutual collisions. The Solar System was characterized in its primordial phases by a relatively high degree of mixing. The distinction between inner and outer part of the Solar System is mainly due to the different temperatures at which they formed: the giant planets formed in a region where, since the beginning, ice played an important role and the original nebular gas was preserved, while the terrestrial planets formed in a region in which the gas had already been lost, having negligible effects on the overall evolution. The fully formed planets subsequently cleared their orbital zones of most of the leftover debris from the process of planet formation, perturbing the orbits of small bodies until the latter either impacted one of the major bodies (Sun and planets), or were ejected out to interstellar space.

In fact, the present-day solar system is a much quieter place, although all or most of the initial processes continue on a lesser scale today. The recent understanding and characterization of the regions of slow chaos within the reservoirs of minor bodies (the main asteroid belt and the trans-Neptunian belt), once thought to be stable over the age of the solar system, is the key to explain the widespread presence of small bodies in planet crossing orbits throughout the planetary region.

2.7.2 The outer planets

The detailed mechanisms of formation of the planets in the outer solar system are still not well understood, as several different hypotheses are being evaluated and analyzed. The gas giants Jupiter and Saturn accreted a significant amount of gas directly from the protosolar nebula after accumulating solid cores of about 5±15 Earth masses. However, the possibility of gas instability on the protosolar disk has been also proposed; this hypothesis cannot be completely ruled out, due to the discoveries of extra solar planets, some of them unexpectedly large and close to their star. In the first hypothesis, as the core grows larger, more and more nebular gas is captured in its sphere of influence, until a large and massive envelope is formed; at this time a rapid accretion phase begins. The second scenario assumes that giant planets are formed by gravitational instabilities in a massive solar nebula with solar chemical composition and mass far larger than the present masses of the giant planets. The solid core is formed through sedimentation of solid/vaporized material onto the centre of the structure, or else by capture of solid planetesimals. A key issue is then the a posteriori formation of a core.

Given this debate, it is becoming of paramount importance to determine the size of the cores of Jupiter and Saturn. When, where, and how Jupiter formed, as well as the evolution of its orbit after the formation, is likely to have played a key role in the formation of the other planets in our system, including the Earth.

A more precise determination of Jupiter's structure and composition will help us to understand where and how Jupiter formed and whether giant planet migration occurred in our own solar system. A study of heat transport in the interior and the atmosphere will help us to understand how "hot Jupiters" contract early in their history. The measurement of latitudinal temperature variations will yield a better view of how the solar heat flux is absorbed and redistributed over the planet, and will allow us to generalize how stellar heat fluxes are distributed within extrasolar planets.

An additional topic concerning Jupiter is the study of its satellite system. Among Jupiter's 39 known satellites, 31 are irregulars. The eight regular satellites consist of four large moons and four smaller ones. The regular satellites exhibit a negative gradient in the average densities, when moving from Jupiter outward. This is similar to what is found in the solar system where ice is increasing going outward. Moreover, the three inner Galilean satellites (Io, Europa and Ganymede) are locked in a peculiar orbital resonance that makes available a substantial quantity of energy through tidal dissipation, leading to the volcanism on Io, and to the possible presence of liquid water, underneath a substantial ice crust, on Europa.

2.7.3 The inner planets and the Moon

The inner planets provide a unique opportunity to study the processes that lead to habitable worlds. Venus, Mercury, Mars, and the Moon hold clues to different aspects of the origin of the planets and habitable environments in the inner solar system. They have undergone substantial processing of their surfaces after their formation, because of endogenous processes for those that are geologically active, and anyway because of the continuous bombardment of asteroids and in comets in planet crossing orbits.

The Moon and Mercury preserve records of past events that are largely erased on Earth and Venus. In many ways, Venus is Earth's twin in the solar system, and provides a natural laboratory for understanding the evolution of Earth-like planets and their atmospheres, including how Earth's atmosphere might change in the future. Mars shows evidence for substantial climate change, which could reflect processes that influenced all of the inner planets.

Exploration of the inner solar system is vital to understand how Earth-like planets form and evolve and how habitable planets may arise throughout the galaxy. Understanding processes on a planetary scale — volcanism, tectonics, impact bombardment, evolution of atmosphere and magnetosphere, and development and evolution of life — requires a comparative study of the planets closest to Earth in order to know the effects associated with size and distance from the Sun, composition, and type of dissipation of internal energy over time. A comparison of the inner planets shows the importance of a large moon in making the Earth unique and perhaps uniquely suitable for life.

One of the great advances of geosciences has been to recognize that the present-day Earth represents just one step in a progression of changes driven by a complex set of interrelated planetary factors. Coupled with this recognition is the revelation that Earth's atmosphere and biosphere are fragile entities easily perturbed by planetary-scale processes. Much remains to be learned from the other terrestrial planets, where similar processes have produced vastly different results.

Even though the Moon has been extensively studied, there are many domains of lunar science wherein data are still insufficient or interpretations are ambiguous or controversial. In the first period of its life the Moon underwent extensive differentiation processes. The possibility to differentiate a small body like the Moon is strongly related to its formation history. Our knowledge of planetary formation has shown the importance of the role of large planetesimals; the origin of the Moon has been attributed to a Mars-sized impact on the Earth. In the hypothesis of a very hot primordial phase, global melting occurred (magma ocean model), resulting in a complex and heterogeneous crust. Having undergone heavy meteoritic bombardment, these complex crustal rocks occur both as small fragments, eventually re-accreted to form breccias, and as bedrock outcrops as observed by remote sensing (as, for example, the central peaks of large impact craters).

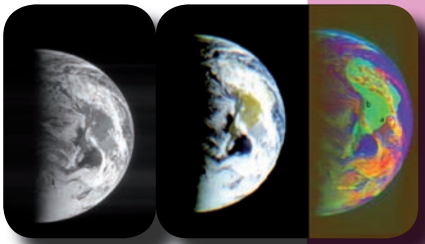


Figure 2.7.1 Left: the Earth as seen by the ROSETTA navigation camera and by the VIS channel of the VIRTIS instrument. Centre: the standard RGB image. Right: the same picture stretched. The outline of South America is fairly evident, as well as a large could coverage. Central America is barely visible at the top of the figure.

We already have samples of some solar system bodies (either by in-situ collection, as for lunar samples, or by delivery from space in the form of meteorites, some of them known to have come from planets or minor bodies), and there are missions to collect more that will cover a wider range of primitive and processed materials. Plans for both collection around the Earth (e.g. with stratospheric balloon flights or on the Space Station) and in-situ, e.g. Mars lander in the framework of the ESA's Aurora Program, are already in place. In situ measurements and sampling would improve our understanding of the potential habitability of Mars, its tectonic, magmatic, and hydrologic evolution as well as geochemical cycles of biological relevance.

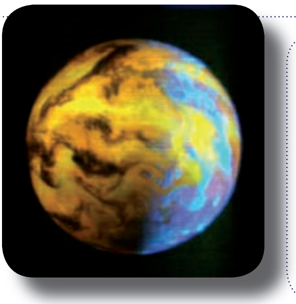


Figure 2.7.2a Three-color image of the Earth with the infrared channel of VIRTIS at wavelengths 1613 nm, 4039 nm and 4936 nm. The Earth emission on the night side is evident.

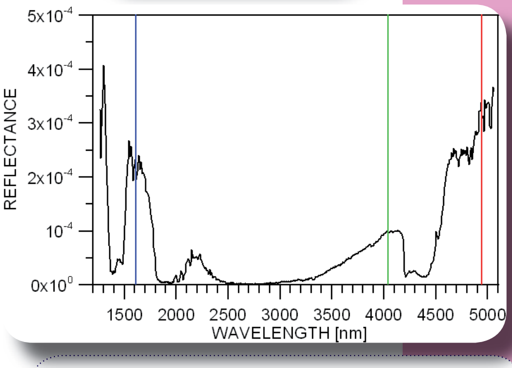


Figure 2.7.2b Spectrum of the Earth in the infrared. The coloured lines indicate the wavelength used to obtain the RGB image at left.

Sample return would give scientists an unprecedented opportunity to obtain, directly in their laboratories, detailed information about the composition and history of the source body and about the conditions prevalent during the formation of the Solar System. Cosmo-chemical studies of dust grains and meteorites obtained from space are extremely important in the understanding of the Solar System formation and evolution.

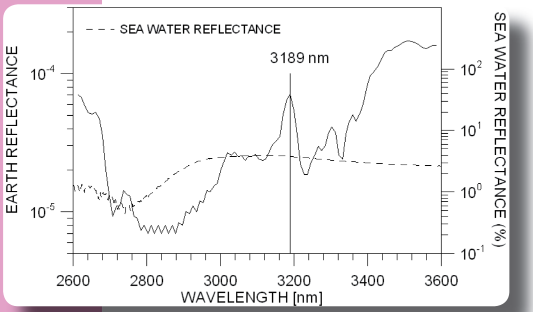


Figure 2.7.3 Characteristic spectrum of the green area in the right panel of Fig. 2.7.1 with the sea water reflectance superimposed

2.7.4 The minor bodies

Further important targets for in situ space missions are of course comets and asteroids. Although reprocessed by impacts and fragmentation throughout the solar system history, these bodies are the residues of the accretion of the planets, and in fact represent samples of the proto-planetary material at various distances from the Sun. Most of them can be considered truly primitive in the sense that they have not been substantially heated or otherwise changed in a chemical or physical sense since the time of their formation. Moreover, they can be considered as reservoirs of organic matter, which are the raw materials for the origin of life.

As researchers survey the primitive bodies and planets of the solar system, they find compelling evidence not only of the preservation of ancient organic matter but also of the formation and destruction of organic molecules in modern environments. While most of the asteroidal material in the inner solar system probably comes from the asteroid belt, the formation regions of long and short period comets cover a much wider orbital range in the outer planetary region, so that the study of these bodies is likely to reveal a wide diversity of compositions and evolutionary histories.

As already said, many aspects of the Solar System formation scenario described at the beginning are still not understood, starting from its basic chronology: in what order, and on what orbits did the planets form? It is quite possible that, in the phases immediately after the formation, the planetary orbits differed significantly from the current ones, and that therefore the network of mean motion and secular resonances covering the planetary region was likewise very different. As a consequence, the ways in which the various populations of small bodies (asteroids, comets, trans-Neptunian objects) would have subsequently evolved would change drastically. In this field chaotic dynamics is dominant, and a detailed orbital and physical census of the current populations of small bodies will put constraints on the various possible scenarios, and help addressing questions like, for instance, why the Late Heavy Bombardment in the inner solar system, whose remains are most evident in the cratering of the Moon, took place about 3.9 Gyr ago and not much earlier, or what is the total mass of the small bodies outside the orbit of Neptune, and how it is distributed among the trans-Neptunian belt, the scattered disk and the inner and outer Oort cloud.

The orbits of the outer solar system small bodies (trans-Neptunian objects and Oort cloud comets) hold the signature of the gravitational interactions with external perturbation elements (the galactic gravity field, passing stars and molecular clouds), and a significant increase in the detail with which the dynamical structures of these populations are known is likely to lead to a better knowledge of the galactic environment of the Sun.

In recent years, the small bodies populating the immediate neighborhoods of the Earth, the so called Near-Earth Objects (NEOs), have been studied both observationally and theoretically. The reason for this interest, besides the obvious aspects concerning the risk for our ecosystem associated with a potential impact with our planet, is that NEOs are the immediate parent bodies of most meteorites, thus representing the link that allow to associate the latter to the regions of the solar system where they formed. Thus, NEOs can be considered promising targets for space missions. Many of them are accessible with small amounts of delta-V, in some cases comparable even smaller than those necessary to land on the Moon, and the close exploration of the first ones reached by spacecraft is revealing surprising diversities, especially in view of the fact that they are thought to come, in the vast majority, only from some selected regions of the main asteroid belt. Moreover, the fact that they can approach rather closely our planet make them ideal targets for radar studies, that have the potential to greatly improve the knowledge both of their dynamical state and of their physical characteristics.

2.8 The search for extraterrestrial planets and life

The discovery of the first extra-solar planet around 51 Peg in 1995 has enormously boosted the investigations on the frequency of occurrence and the formation of planetary systems around other stars. The ultimate goal is the understanding of the mechanisms of formation and evolution of planets and, in perspective, the discovery of other planets able to host life.

We know from observations that proto-stars are surrounded by disks of gas and dust within which the planets form. Anyway little is still known about the mechanisms governing the formation of the disk around central stars, the agglomeration of micron-size dust particles to kilometer-sized planetary embryos, and the runaway growth of the planetesimals to massive planets (cfr. Sec. 4.4). Moreover the effects of environment and initial conditions on the resulting planetary systems, the causes of planet migration and interaction of the planetary bodies in the disks to form stable planetary systems is far from being fully understood. Such issues will find answer with the progressive improvement in the sensitivity and angular resolution of the astronomical instrumentation.

2.8.1 The discovery

Clearly, the prerequisite for the subsequent detailed physical characterization of exoplanets is the detection. However, the extreme contrast in mass and luminosity between the planets and the parent stars, as well as their small angular separations, make the detection of extra-solar planets particularly challenging. The envisaged (current and future) methods of detection can be broadly classified in different categories exploiting a) dynamical perturbations of the star by the planet during their orbit around the common centre of mass, namely radial velocities, astrometric oscillation of the stars around the barycentre of the system and the timing of arrival of the signal, b) changes in the photometric signal due to the transits of the star disk by the planet and reflected light, c) microlensing of the planet on background objects, both astrometric and photometric, d) direct observation of the planets, e) miscellanea of other effects.

The search for extrasolar planetary systems is well under way with over 170 planets discovered, 18 of which in multiple systems. Such discoveries, performed by indirect methods, i.e. from their effects on the central star, have already revealed important insights: 1) planets are quite common, with roughly 7% of all solar-type stars harbouring a giant planet within 3 AU; 2) the number of planets increases as mass decreases; 3) stars that contain a higher abundance of metals are more likely to host planets; 4) multiple planets are common, often in resonant orbits; 5) the number of planets increases with distance from the star; 6) eccentric orbits are common, with only 10% being nearly circular.

This scenario is strongly limited by observational bias: we have been able to observe so far only gaseous giants similar to Jupiter and Saturn, while very little is known about rocky planets with masses comparable to that of the Earth. The increasing number of planets with smaller mass suggests that planets with masses below 15 Earth masses, currently undetectable, are even more numerous. Moreover, the correlation with heavy elements supports current planet formation theory where rocky planets are more numerous than the gas giants.

Doppler planet searches are expected to discover Jupiter-mass planets orbiting at 4-7 AU, providing the first direct comparison of planets in our Solar System to those orbiting at comparable distances from other stars. Doppler measurements with a precision of 1 m/s would allow detection of planets having mass as low as 10 Earth masses, but most easily if they orbit within 0.1 AU of a solar-mass star, a region that is hotter than the corresponding habitable zone. Earth-mass planets orbiting at roughly 1 AU induce a stellar wobble of only 0.1 m/s, a factor of 10 below the detection threshold of even future Doppler work. Microlens surveys have already started to provide the first detections of Jupiter mass planets, but their role will be limited only to the frequency distribution since lensing events happen only once and the discovered system are too distant (of the order of kpc) for any subsequent detailed study. Astrometric detections provide directly the planetary masses rather than M sin i. Accuracies of the order of 100 μas can in principle provide detections of the massive planets around nearby stars, but only when the accuracies will reach the level of few μas the discovery of planets around stars up to few tens of parsecs will be possible. The forthcoming astrometric missions by ESA and NASA will be milestones in the search for exoplanets.

Direct observations of extrasolar planets, even that of the gaseous ones, is beyond the capabilities of currently available instrumentation, save for a few extreme cases of very young and massive planets at large distances from the central star. Future developments in instrumentation coupled with extreme Adaptive

Optics will allow the direct detections with 8-10 m ground-based telescopes and with some of the space observatories currently in the construction phase (like JWST), but imaging of extra-solar planets over a wide range of parameters requires extremely large ground-based telescopes like OWL or specially designed space instrumentation (TPF or Darwin).

The first detection of rocky planets will be likely achieved using transits by the Kepler mission, currently scheduled for 2008, even though there is a limited chance that this could happen even earlier using other instruments (e.g. Corot) or microlens observations. However, rocky planets discovered by these techniques would be hard to be confirmed as such. If these missions will not be able to observe rocky planets, such an epochal discovery might have to wait for the future generation satellites or the advent of Extremely Large Telescopes.

In any case we expect that the census of gaseous planets will be refined within the next decade, when the systematic discovery will (hopefully) be carried out at various distances from the central stars routinely with several techniques, while for rocky planets it crucially depends on the development of the future space missions and of ELTs.

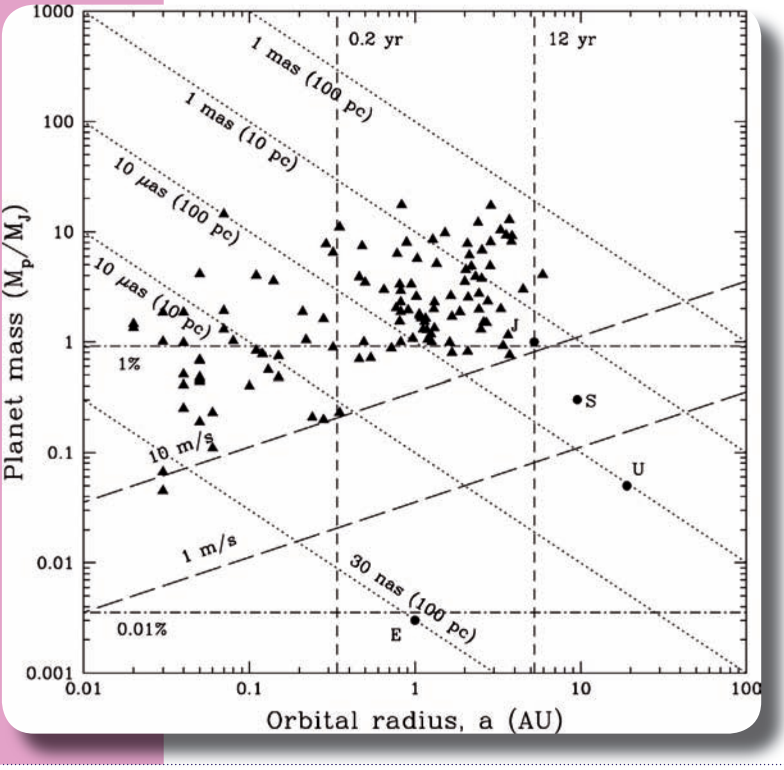


Fig 2.8.1 Detection domains for methods exploiting planet orbital motion, as a function of planet mass and orbital radius, assuming M* = M_. Lines from top left to bottom right show the locus of astrometric signatures of 1 milli-arcsec and 10 micro-arcsec at distances of 10 and 100 pc; a measurement accuracy 3–4 times better would be needed to detect a given signature. Vertical lines show limits corresponding to orbital periods of 0.2 and 12 years, relevant for Gaia (where very short and very long periods cannot be detected) although not for SIM. Lines from top right to bottom left show radial velocities corresponding to K = 10 and K = 1 ms–1; a measurement accuracy 3–4 times better would be needed to detect a given value of K. Horizontal lines indicate photometric detection thresholds for planetary transits, of 1% and 0.01%, corresponding roughly to Jupiter and Earth radius planets respectively (neglecting the effects of orbital inclination, which will diminish the probability of observing a transit as a increases). The positions of Earth (E), Jupiter (J), Saturn (S) and Uranus (U) are shown, as are the lower limits on the masses of known planetary systems as of December 2004 (triangles). (Photo courtesy ESA-ESO Working Groups report, chaired by M. Perryman and O. Hainaut. Garching, Germany: Space Telescope-European Coordination Facility, 2005. "Published by ESA and ESO")

2.8.2 Planet Characterization, Habitability and Search for Life

The first direct detection of the atmosphere of a giant hot planet orbiting a star outside our solar system has been performed by HST when the planet passed in front of its parent star, allowing to see light from the star filtered through the planet’s atmosphere. This unique observation has demonstrated that, under fortunate conditions, it is possible to measure the chemical composition of exoplanets atmospheres even nowadays.

In general, however, the characterization of the atmospheres requires challenging, direct observations of very faint objects in the glow of bright stars (contrasts larger 108). Direct imaging allows, in addition to detection, the determination of the orbital parameters, low-resolution spectroscopy provides information about the presence and composition of the atmospheres, and polarization gives hints on the structure of their atmospheres and the presence of dust. Finally, light curves might provide the planet period of rotation around its own axis, information about the presence of satellites and rings, or even about the presence of clouds and possible structures on the surface. Again, if we reasonably expect to characterize gaseous giants with the instrumentations already envisaged, the direct observations of rocky planets, the only ones able of host life, require a leap toward a new generation of ground- and space-based instrumentation.

2.8.3 Astrobiology

The increasing knowledge of the evolution of our solar system and the discovery of extra-solar systems different from the solar one, have opened a number of questions on the origin of life and on conditions that may allow its evolution.

The determination of the habitability conditions, for instance the presence of liquid water and energy sources able to sustain metabolism, that are not necessarily associated with a single specific environment, will be important to identify potential habitable planets in the Solar and in other systems. Solar system itself may present such conditions in sites other than Earth, and mechanisms of evolution of habitable environments through the Solar systems have to be studied.

In other systems the search for habitable planets will be concentrated on rocky planets in low-eccentricity orbits around Sun-like stars at about 1 AU distance. The extension and position of the habitable zone depend on the star luminosity and age, on the planet atmosphere and on possible internal heat sources. The possible presence of life can be inferred by the detection of life-related compounds like O2 and O3, which anyway are difficult to detect. In order to answer the fundamental question on the origin of life is crucial to understand in which conditions life may be originated, controlled and sustained, and in particular how this occurs if pre-biotic material is brought in from elsewhere. The influence of early planetary environment, including the high energy radiation from the parent young star may be essential for the onset and survival of life. The study of the evolution of pre-biotic material in solar system, subjected to radiation from the young Sun, is a task that will be pursued in the next decade. At the same time the feedback of the organic material on chemistry of planetary atmospheres is an important issue.

This area of astrobiology needs a high level of multidisciplinary know-how, including astrophysics, biology, chemistry, biophysics, and geology, and requires a joint effort of theory, observations, computer simulations and laboratory experiments.

2.8.4 Modeling extrasolar planetary systems

The theory of the formation and evolution of planetary system is currently being stretched from its previous emphasis on the solar system, which obviously implies a number of constraints on model parameters, to the current need to explain the variety of systems that are being discovered and to predict those that will be discovered when substantial advancements in the detection techniques will relax at least in part the biases affecting current searches.

In the foreseeable future modeling will have to span a parameter space much large than today. Large numerical simulations of the evolution of proto-planetary disks, of the accretion of planetesimals onto planets and giant planet cores, and of the dynamics and thermodynamics of the accreting gas in the growing giant gaseous planets will have to be carried out, requiring substantially larger computing resources than those needed until recently, due to the vastity of the formation scenarios to be explored.

A related problem is that of the dynamical evolution of these systems. Here again, a paradigm shift is taking place: when only our planetary system was known, the main problem was to be able to show the stability of the solar system over about 10 Gy in the hierarchical sense (i.e., whether the planets would remain on nearly circular, nearly coplanar orbits without interchange of relative distance from the Sun); the wide variety of orbital configurations found in extrasolar systems makes the study of the hierarchical stability a much more complex issue. For example, orbital resonances are practically absent in our planetary system, while being not infrequent in the satellite systems of the giant planets; on the other hand, resonances seem to be frequent in extra-solar systems, and much theoretical and numerical work is being done to explain this phenomenon.

2.9 The violent universe

2.9.1 Probing Black holes and compact objects

Black holes (BH) are among the most fascinating astrophysical objects. They are fully characterized by only three parameters: mass, angular momentum per unit mass (a=J/M) and electric charge. This is the so-called "black hole no hair theorem". All information other than mass, electric charge and angular momentum is lost inside the event horizon, and is therefore not accessible to external observers. Astrophysical BHs are even simpler, since their charge is expected to be zero in basically all situations of astrophysical interest.

Despite much progress in the search for BHs over the last three decades, it is mainly through the mass argument (i.e. a mass larger than the maximum possible neutron star mass) that the sources have been, and still are, identified as BHs. Incontrovertible evidence for an event horizon is still missing. However, direct observations of effects related to the presence of the horizon are expected to be possible in the near future, though limited to the super-massive black hole (SMBH) at the centre of the Milky Way, through mm VLBI observations of the BH shadow. The most precise observations performed up to now resolve regions of the size of the Earth orbit at the Galactic centre. An improvement by a factor of ~10 is needed to truly resolve the SMBH horizon. To probe the horizons in stellar SMBHs several other methods have been proposed. A promising method relies upon radiatively inefficient flows (ADAF-type) in compact objects accreting at low rate. In the presence of a hard surface (such as that of a neutron star), the internal energy stored in the flow is inevitably released and radiated away at the star surface. On the contrary, if the accretion flow crosses an event horizon, the internal energy is carried into the black hole and hardly radiated away. ADAF-type models predict power law spectra with energy index >–1, followed by a knee above 50 keV. On the other hand, such a knee is not expected for neutron stars. Therefore, high sensitivity high-energy observations can be used discriminate between radiatively inefficient flows on BHs and neutron stars.

As X-rays come from regions very close to the BH, they provide an almost unique chance of observing strong-field effects, in which General Relativity (GR) should play a crucial role in strongly modifying the profiles of emission lines, the brightest of them being usually the fluorescent iron Ka line. Kinematics and Special/General relativistic effects are predicted to result in a broad and skewed profile, as shown in Figs. 2.9.1 and 2.9.2. A large collecting area (of the order of the square meter at 6 keV), coupled with at least moderate energy resolution, is required to search for relativistic lines in a sizeable sample (a few hundreds) of both galactic and extragalactic sources.

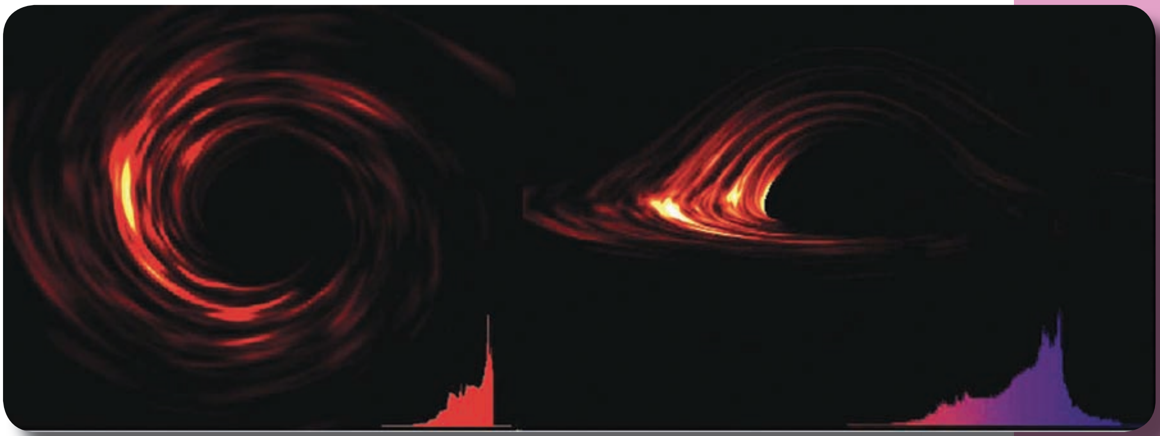


Figure 2.9.1 X-ray view of an accretion disk (Armitage & Reynolds 2003). View of the disk as seen by a distant observer at an inclination angle of 30° (left) and 80° (right). The inset in each panel shows the corresponding Iron K-shell spectral line profile convolved with the typical resolution of an X-ray calorimeter. Adapted from NASA/TP-2005-212784

Detailed observations of iron line profiles allows one to measure the angular momentum per unit mass, since the inner stable orbit has a radius which depends on a=J/M. For a maximally rotating BH this radius is about six times smaller than for a non-rotating BH. This means that line profiles emitted by matter around a rotating BH are more relativistically distorted because matter feels a stronger field than around a non-rotating BH. Furthermore, if the line emission is produced within a relatively small `hot spot’ on the accretion disc around the BH, then the mass can be estimated, assuming Keplerian disc rotation, by determining the orbital period and the spot location from the line amplitude and energy.

In addition to iron line spectroscopy, X-ray polarimetry could also be used to probe strong-field GR effects. In AGNs, a rotation with time of the polarization angle of the Compton Reflection component (produced with the iron line) is in fact expected and, more generally, a time--dependent polarization angle would be a clear signature of the presence of strong field GR effects. Analogously, a rotation with energy of the polarization angle of the thermal disc component is expected in BH X-ray binaries.

Binary compact objects

Double Neutron Star Binaries are a real laboratory for Gravitation Physics. The discovery of PSR1913+16 in 1975 provided the first evidence of gravitational radiation. PSR0737-3039, the first double pulsar, discovered in 2004, resulted in a much better laboratory for high density matter and GR. Data allowed for the determination of all the geometrical parameters of the system and for the measurement of 5 of the so-called Post Keplerian parameters (namely parameters that quantify the deviation from Kepler Laws). All together these results have yielded more extensive tests of GR than those derived in 30 years of observation of PSRJ1913+16. Further order of magnitude improvements of these tests are expected from the monitoring of the system on a timescale of a decade. While Double Neutron Star binaries are the best laboratories for tests of GR, White Dwarf-Pulsar binaries in close orbits are the most promising targets for constraining alternative theories of Gravity. In a few more years of observations of one of these systems, PSR J1141-6545, will allow us to impose better constraints than those recently obtained from the observations in the solar system, as performed by the Cassini spacecraft. The high sensitivity monitoring of the already known relativistic pulsars, as well as extensive surveys aimed at discovering new such systems are of the highest relevance. The new planned surveys will also have the capability of unveiling a putative Pulsar orbiting a BH: such a system may probe relativistic gravity with a discriminating power surpassing all other methodologies.

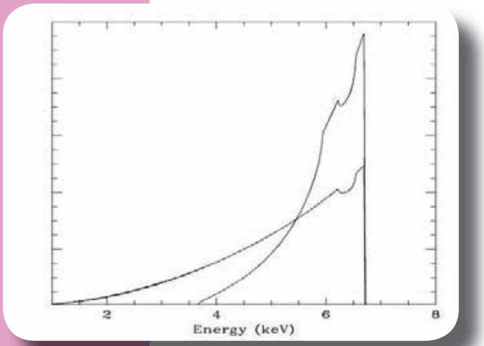


Fig. 2.9.2 Iron line profiles from a non--rotating and a maximally rotating BH. In the latter case, the emission extends to much lower energies

Gravitational waves from binary compact objects

BH binaries are the ideal laboratory to probe GR in strong, relativistic conditions. By tracking the phase and amplitude of gravitational waves (GWs) along the phases of spiral-in, merging, and ring-down, one can extract extremely precise information about the stress-energy tensor. Binary waveforms depend, on the most general case, on 17 parameters, and, in principle, high signal-to-noise GW detections can provide measurements with unprecedented accuracy. As an example, binary mass, chirp mass, and reduced mass can be measured to a few parts in 105 with space interferometers. Compact binaries (NS-NS, NS-BH and BH-BH), and massive black hole binaries (MBHBs) fall in two different GW frequency domains, and will be targeted by both ground and space based interferometers. Coalescing NS-NS and NS-BH binaries are primary sources of high frequency gravitational radiation for ground based interferometers. The rate at which such events take place is highly uncertain for NS-NS binaries and completely unknown for stellar mass BH-NS systems. If short GRBs (see section 2.9.4) originate from coalescing binaries, then an alternative, more direct ways of measuring the rate of GW event could be obtained. Early estimates based on SWIFT observations indicate that the expected rate can be higher than that inferred from relativistic binary pulsars in our galaxy.

The possibility that deformed fast spinning neutron stars produce long lasting high frequency GW signals detectable with present or next generation ground based interferometers has received a great deal of attention in recent years. The two main scenarios involve old neutron stars in low mass x-ray binary systems, which are spun up to millisecond spin periods by accretion torques, and newborn fast spinning magnetars (see section 2.9.2).

If SMBH were common in the past as they are today, and if galaxies merge as implied by hierarchical clustering models of structure formation (see Section 2.2), then MBHBs must have been formed in large numbers during the cosmic history. MBHBs in the mass range 105-107 Msun are among the best targets for spaceborne interferometers, while high precision timing over a sample of some tens of millisecond radio pulsars (the so-called Pulsar Timing Array) can make a direct detection of the GW background at nanoHz frequencies, most likely generated by SMBH in galaxy cores. Detection of GW from MBHBs is interesting for two reasons: first, it will probe in situ strong gravity in the non-linear relativistic regime; second, for astronomy and cosmology, GWs are a complementary mean, with respect to electromagnetic observations, of investigating the cosmic evolution of structures, such as galaxy interactions and mergers, and the demography of SMBH.

Theoretical predictions for the mechanisms of angular momentum loss, driving the evolution of low-mass close binaries (CBs) containing compact objects include magnetic braking, gravitational radiation and, for CVs also mass loss due Nova explosions. The current observational evidence of their efficiency relies on the measured orbital period distribution only. The detection of GW from CBs with double and single degenerates will provide first observational support to the theory and will allow the identification of a large and hidden population of degenerate ultra-short period binaries, which are thought to be the link to type SNIa progenitors.

2.9.2 Matter under extreme conditions

Neutron stars are ideal laboratories to study matter in extreme conditions (extreme densities, extreme magnetic fields), not reachable in ground-based laboratories.

Crucial insights on the equation of state and other properties of matter at nuclear densities can be derived from the following measurements. If the highest frequency Quasi-Periodic Oscillations (QPOs) in the X-ray flux of accreting neutron stars corresponds to the frequency of motion of matter close to the star surface, then an upper limit on the neutron star radius can be inferred, therefore constraining the equation of state. This technique has already been applied to QPO data obtained with XTE but its full potential can only be exploited through higher throughput (large collecting area and band extended to higher energies) studies addressing the signal shape, its energy dependence and harmonic content in much greater detail. Direct information on the redshift at the neutron star surface can be obtained from faint ion spectral lines originated on the surface itself. Detections of such lines (in particular lines from Fe XXVI, Fe XXV and O VIII) have been reported in the past but again a systematic study waits for a much higher throughput X-ray observatory. Combined with the neutron star spin period inferred from pulsations and/or burst oscillations, the lines' profile obtained in this way would yield measurements of the neutron star mass and radius. High precision pulsar timing is already providing us with the most precise determinations of the masses of neutron stars. Furthermore, a decade of accurate timing radio observations of the Double Pulsar system J0737-3039 will enable the first measurement of its moment of inertia, in addition to the mass and the spin rate, and hence of the neutron star radius with enough accuracy for ruling out 90% of the proposed equations of state for nuclear matter.

Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) hold the potential of unveiling a new emission regime, in which the bulk of the emitted radiation results from the dissipation of an exceptionally high magnetic field, as expected in magnetars. There are by now different lines of evidence supporting the view that SGRs and AXPs host neutron stars with magnetic field strengths of at least 1014-1015 Gauss. Direct evidence for a magnetic field strength in the expected range would also come from the detection of proton cyclotron lines in the phase-resolved X-ray spectra of these sources. Another evidence would come from phase and energy resolved polarimetry of SGRs that would show both proton cyclotron resonances and vacuum polarization resonances. The extension of the investigation of the recently discovered very hard component to higher energies could shed some light on the phenomenology of the magnetosphere in such extreme fields. High throughput instrumentation with good spectral resolution would be ideally suited to reach this goal. If AXPs and SGRs in our galaxy are mainly persistent sources, then their number must be very limited and presently available samples (a total of about 10 sources) should not be far from being complete. Searches in nearby galaxies could substantially enlarge the sample. On the other hand, if most AXPs and SGRs are transient sources, then sensitive all sky monitors are the best instruments to discover and study larger samples of these objects in our Galaxy. On the other hand, SGRs are known to emit giant flares during which enormous amounts of energy (up to 1047 ergs) are emitted in the initial subsecond-long spike. These events likely arise from sudden large-scale rearrangements of the extremely intense magnetic fields of these magnetars, possibly triggered by a major fracturing of the neutron star crust. Only three such flares have been observed so far from SGRs in our galaxy and the LMC, implying recurrence times of order of tens of years. An intense giant flare (such as the SGR 1806-20 2004 Dec 27 event) occurring in a galaxy at tens of Mpc distance would appear as a short GRB (see section 2.9.4). Therefore giant flares from SGRs might constitute a subclass of Short GRB.

The study of isolated neutron stars (not powered by accretion and therefore offering in principle a much ''cleaner'' environment), can also be useful to probe the properties of matter in extreme conditions. The main tool in this respect is provided by X-ray observations of the thermal emission from the star's surface, which is affected by the internal structure and evolution, as well as by the composition and magnetization of the star's atmosphere. High resolution, time resolved spectroscopy over a broad energy range is essential to properly identify lines and other spectral features (that can thus provide a gravitational redshift) and to derive the neutron star radius and surface temperature distribution, while spectrum and phase resolved polarimetry could test vacuum birefringence predicted by Quantum Electrodynamics.

Quantum Chromodynamics predicts that matter in extreme conditions could be in the form of a Quark-Gluon Plasma. It has been speculated that, due to accretion, Neutron Stars could temporarily be in this state before they collapse to a BH. The time spent by the star in this state depends on the properties of the Quark-Gluon Plasma. If this transition to Quark-Gluon Plasma occurs, then there should be in Nature neutron stars more compact than could be expected on the basis of any equation of state for ordinary matter. Quark stars of this type would provide an unprecedented test bench for fundamental physics.

2.9.3 Physics of accretion and ejection

The dominant mechanism responsible for the energization of both stellar type BH and SMBH is most likely accretion onto the central object. However, the processes through which gravitational energy in the accretion flow is converted into radiation are all but understood, and therefore subject of intense debate.

The standard Shakura & Sunyaev optically thick and geometrically thin α-disc is still widely adopted for many practical purposes, though it is likely to be too simple to describe the complex observed phenomenology. This solution does not describe correctly the regimes of high and very low accretion rates, which, on the other hand, are highly interesting cases. Recently, much attention is being devoted to the investigation of the transport of angular momentum in accretion discs through magnetic turbulence, and through the so-called magneto-rotational instability. These investigations also aim at understanding the temporal evolution of magneto-hydrodynamic warps, or the excitation of various kinds of oscillation modes and waves in accretion discs. Although analytical studies can still provide invaluable progress in these research fields, it is clear that numerical simulations are necessary to quantify the importance of the several physical effects generated in the non-linear evolution of the astrophysical scenarios mentioned above. In addition, GR effects are also important in the vicinity of BHs, and they can modify existing Newtonian models both quantitatively and qualitatively. With the numerical tools currently available, it is now possible to move beyond the simple search for stationary or quasi-stationary solutions, while putting some of the original ideas of the pioneering works (such as Shakura-Sunyaev model) on a more quantitative level.

There is wide consensus on the fact that the observed X-ray emission is due to Comptonization of soft (optical-UV) seed photons from the accretion disk by a population of hot (109 K) thermal electrons. Modeling the observed X-ray spectra with a proper Comptonization model would provide key information on the system geometry and physical status of the accretion flow (tempe-

rature and optical depth of the hot electrons). In order to make a significant advance in this field, a combination of theoretical and observational efforts is needed. On the observational side more sensitive X-ray measurements, extending up to the energies where the spectra show a cutoff (tens or hundreds of keV), are needed, together with optical/UV and X-ray simultaneous monitoring. On the theoretical side, among many open questions, we stress the need to understand the reasons why systems with a stellar mass BH show noticeable differences with their bigger counterparts, despite the similarity in the physics of accretion that should be the same for both classes of objects.
Accretion onto neutron stars in X-ray binaries and white dwarfs in CVs provides a wealth of information about phenomena that are related to the presence of a “hard” stellar surface and of a stable magnetic field anchored to the star. Such phenomena require an understanding of boundary layer physics, accretion torques, magnetospheric and column accretion, radiative transfer and resonant cyclotron scattering in strong magnetic fields, unstable thermonuclear burning of freshly accreted material in the star’s surface layer.

An important problem that remains currently unsolved is the observation that, despite the fact that all galaxies host a SMBH in their central region, most of them do not appear to be currently active. The most striking case is that of our own Galaxy, whose BH at the Galactic Center has luminosity about ten orders of magnitude lower than the Eddington limit for a BH of its mass (i.e. 2.6×106 solar masses). XMM and Chandra observations showed that the emission exhibits two different states. In the quiescent state, weak X-ray emission appears to originate in an extended area around the BH, evidence for hot accreting gas in the environment of Sgr A*. Sgr A* itself displays X-ray flares which occur about once per day, during which the emission rises by factors up to 100 for several tens of minutes. The short rise-and-decay times of the flares suggests that the radiation must originate in a region within 10 Schwarzschild radii from the BH. Both the quiescent and the flaring states have been modeled in terms of radiatively inefficient accretion predicting a very hard spectrum, peaking around 100 keV. High sensitivity hard X-rays instruments in the 10-100 keV band are required to confirm this hypothesis. Interestingly, there is evidence that the BH in our own galaxy was much more active a few hundred years ago. Evidence relies on Sgr B2, a molecular cloud at a projected distance from Sgr A* of about 100 pc, which in X-rays shows a pure reflection spectrum, with apparently no illuminating source being present in the field. It is then possible that Sgr B2 is echoing a past activity of Sgr A*. A polarimetric measurement would definitely confirm that the illumination is coming from Sgr A* (from the polarization angle), and help estimating the true distance of Sgr B2 (from the degree of polarization) and the epoch when the BH was active. 3 mm VLBI observations show a resolved source coincident with Sgr A*. Future studies will be aimed at detecting possible deviations from circular symmetry, which are theoretically predicted for a rotating accretion disk-BH system.

Another common feature of stellar size BH and SMBHs is the ejection of both winds and jets moving at relativistic speed. The presence of jets might be a key element to understand how the central engine works. While magneto-hydrodynamic processes are widely recognized to be involved in the collimation and acceleration of jets, the specific mechanisms of launching and fueling are not known in detail. Moreover, we still do not know whether the jets are mainly made of leptons (an electron-positron plasma), hadrons (a proton-electron plasma), or rather by Poynting flux (electromagnetic fields). Observational advances in the understanding of these phenomena rely on multi-wavelength and polarization observations. The highest angular resolution is obtained with mm VLBI, thus giving the most detailed view. The measure of the jet diameter can provide information on the size of the region where the jet is formed and initially accelerated near the SMBH. According to current models, the twisted magnetic field lines are anchored in the inner part of the rotating accretion disk. The last stable orbit then determines the minimum jet width. Present mm-VLBI provides a resolution of 15 RS but in the near future the resolution can be significantly improved, thus allowing a direct test of whether BH rotation plays a role in jet formation.

According to Unified schemes the different classes of AGNs can be explained in terms of different viewing angles between the observer and the central source. Blazars represents quite a peculiar case, in which the jet is seen nearly face on. Blazars are extremely interesting also because they possess a prominent high energy emission: 40% of all gamma ray sources detected by EGRET belong to the Blazar class and several Blazars have been detected at TeV energies by Cherenkov telescopes. This clearly indicates that particle acceleration must taking place in these sources. In the near future GLAST will extend the study of Blazars to much fainter sources, providing samples hundreds of time more numerous than those of EGRET, which will be used to discriminate between different models for the acceleration of the jets in AGN: details of the spectra and temporal variability depends on the jet composition. As different energy bands in these variable systems test different emission components and jet scales, simultaneous observations across the whole electromagnetic spectrum (from radio waves to gamma-rays) are of paramount importance and should be pushed toward achieving higher sensitivity and spatial resolution across the spectrum.

In stellar size BHs episodes of ejection are likely associated to particular source states as defined by spectral and time-variability properties; variations at hard X-ray energies in particular, appear to be correlated with the presence of jets. Therefore a broadband sensitive instrumentation as well as an efficient continuous monitoring of the sources is needed.

Massive outflows at non-relativistic or trans-relativistic speeds are also common. The mass ejection from the most extreme AGNs can be prominent, close to the Eddington accretion rate. The velocities could be as high as 10-30% of the speed of light. These outflows are usually highly ionized and are investigated through both high ionization UV and X-ray lines. The mechanism for the launching of the outflow is largely an open issue, and presumably will require an intensive theoretical effort and some innovative ideas. On the observational side, the most relevant information is still missing: the geometric, kinematics and ionization structure of the flow, needed to determine the rate at which matter is ejected and the associated kinetic energy, cannot be probed in sufficient detail with present instruments. High spectral resolution, high sensitivity instruments are necessary to exploit the diagnostic capabilities of the iron absorption lines in the X-ray band.

AGN winds and jets can propagate in the ISM, ICM and IGM. Because of their large total energy, relativistic jets might play a crucial role in the energy balance of the media through which they propagate, as discussed in more detail in Chapter 2.2. The interaction of these large-scale ejections with the surrounding medium is of crucial importance for groups and clusters of galaxies. In these large, approximately virialized structures, phenomena of strong interactions between radio galaxy jets and the ICM are clearly observed in the form of bubbles and cavities, as well as in the form of particle acceleration to supra-thermal energies and related emissions.

2.9.4 Gamma Ray Bursts: the most powerful cosmic explosions after the Big Bang

Gamma Ray Bursts (GRBs) are short (0.1-100 seconds) bursts of gamma-rays produced during the collapse of a very massive star or during the merger of two collapsed objects. The distance to the host galaxies of these events and their intrinsic luminosities could be inferred only after the observations carried out with BeppoSAX in 1997, some 30 years after the discovery of GRBs.

If isotropic, the energy emitted in the prompt gamma-ray phase is found to correspond to a luminosity ~1054 erg/s, making GRBs the biggest cosmic explosions after the Big Bang. GRBs are the most extreme special relativistic macroscopic objects in the universe, producing expanding shells of material moving with bulk Lorentz factors of order 100-1000. The related complex phenomenology can be explained in terms of creation of a fireball, due to the enormous initial energetic input and a transformation of the internal energy of this fireball into kinetic energy of expanding plasma. Part of this kinetic energy is later converted into accelerated particles, through mechanisms that are subjects of active investigation, and then into radiation, the so-called GRB.

The scenario described above branches into several of the hottest problems of 21st century astrophysics:

- Understanding the GRB itself implies that we understand: the formation of a hot fireball, special and general relativity, particle acceleration processes, relativistic collisionless shocks, jet formation and collimation, particle acceleration, accretion processes, radiation mechanisms.
- GRBs emerge from regions of active star formation in galaxies. GRB being associated to massive stars can be used to investigate the star formation rate, and the initial mass function as a function of redshift (see Chapter 2). Furthermore, they can be used as “lighthouses” to investigate the ISM of their host galaxies (metal abundances, dynamics, gas ionization, dust content, see Chapter 3).
- The reionization epoch. Because GRBs are so bright, they could be a suitable tool to probe the so-called Dark Age of the Universe (see Chapter 2).
- The fate of the baryons. GRB can be used as lighthouses to light up the so called “oxygen forest”, thereby allowing us to map the web of dark matter induced filamentary structure of the Universe and possibly find the X-ray signal corresponding

to the presence of a warm medium of ordinary matter, that is believed to hide the so-called missing baryons (Chapter 2).

- Fundamental physics. GRBs can be used to constrain exotic effects of violation of fundamental symmetries such as the Lorentz invariance, possibly deriving from the phenomenology of some theories of quantum gravity.

Although items 2, 3 and 4 and 5 are discussed in Sections 1, 2, and 3, it is worth recalling some recent findings that make GRBs extremely interesting cosmological tools. SWIFT will likely provide a significant sample of GRBs at $z>5$ (so far the farthest GRB has been discovered by SWIFT at $z=6.29$), that can be used to trace star formation, re-ionization and metal enrichment in high redshift galaxies. Furthermore, it must be mentioned the possibility, derived from recently identified correlations between observables, that GRBs may work as standard candles, thereby allowing us to get an independent estimate of the cosmological parameters. In the following we focus on item 1.

The energy involved in GRB explosions is huge and it is released in a small region. Therefore, a quasi-thermal equilibrium (at relativistic temperatures) between matter and radiation is reached, with the formation of electron-positron pairs accelerated to relativistic speeds by the high internal pressure. This is a fireball. The presence of even a small amount of baryons makes the fireball opaque to Thomson scattering, so that the internal energy of the plasma is gradually transformed into kinetic energy of the fireball, which therefore accelerates until it reaches a coasting phase. At some point the fireball eventually becomes transparent. If the central engine works intermittently, the expanding fireball can contain inhomogeneities induced by shells moving with slightly different Lorentz factors. The occasional interaction between faster and slower shells is responsible for the formation of internal shocks and is expected to give rise to the observed temporal variability of the GRB emission. The whole fireball also interacts with the surrounding interstellar medium in the host galaxy, thereby snowplowing material and forming the external shock. Particle acceleration at these shocks and the following related radiative processes are seen to be responsible for the GRB and its afterglow emission. Though the general picture is rather well defined, there are numerous aspects of the processes of acceleration and radiation that are considered as hot topics for the theoretical research in the field.

One of the greatest unknowns in GRB science is the nature of the progenitor, though fortunately the general guidelines illustrated above can be discussed without specific assumptions on the nature of the progenitor.

There are mainly three proposals with respect to the type of progenitor:

- the merging of two compact objects forming a BH surrounded by some accreting torus;
- the core collapse of a very massive star (hypernova);
- the formation of a BH from a rapidly spinning but decelerating neutron star left over from a previous supernova explosion (supranova).

For all the three scenarios, the central engine could be very similar: a fast spinning BH surrounded by a very dense torus. If so, energy should be made available in the form of neutrinos, accretion of the material in the torus onto the BH, rotation of both the torus and the black hole.

The evidence collected so far (X--ray lines, location in host galaxies, association with SN events) indicates that while short GRBs may be generated in the merging of two compact objects, long GRBs are most likely associated with the death of a massive star. However, the connection between the explosion of the star, the formation of the central engine and the development of the fireball producing the GRB remains subject of investigation. The collapsar model, so far the most successful scenario, predicts that the explosion of the star is driven by the same event that produces a GRB fireball. However, in this scenario a pre-explosion wind is needed to evacuate the external layers of the star (that would quench the fireball expansion), and little evidence for such winds has been found so far. Alternatively, the supranova model predicts that a SN takes place days to months before the GRB, evacuating the environment before the GRB event. In the cases where the GRB-SN association has been observed more convincingly (GRB980425, GRB030329, GRB031203 and GRB060218) the burst and the SN event seem to be basically simultaneous. In order to distinguish among competing models measurements of the GRB local environment and of the connection between the SN and the GRB would be crucial. Estimates of the amount of close material and its composition (metals) would shed light on the history of the pre-ejected material. Short-lived absorption features and variable column densities would flag the presence of a nearby absorber affected by the burst prompt emission and early afterglow. Emission features yield information on the kinematics of the ejection, abundances, and location of the reprocessing medium. High resolution, low energy spectra of X-ray afterglows are necessary to extract the relevant information from these features.

Independent of what the progenitor is, there seems to be a large consensus on the fact that GRBs are the birth cry of a spinning BH. However, its formation and the primary energy source (rotational, electromagnetic) are still debated. One crucial piece of information is the total energy budget. Taking into account the collimation angle of the jet, it appears that the energy content of different bursts is universal, ~1051 erg, so that the efficiency in converting the total energy into high-energy radiation, as well as the fireball baryon loading, should also be universal. In the collapsar scenario, where the fireball has to propagate through the stellar interior, this is unlikely to happen. On the other hand, if the fireball is magnetically dominated, rather than matter dominated, a high degree of polarization of the GRB radiation might arise and polarization measurements at early times could be of crucial importance.

In the *internal* shock scenario the colliding shells are both relativistic, and after the collision, the merged shell is still relativistic. The liberated energy is therefore a small fraction of the initial one. The efficiency of transformation of bulk kinetic energy into radiation is therefore small. On the other hand, efficient external shocks should produce the afterglow. Thus the afterglow should be more energetic than the prompt emission, contrary to what is currently observed. Observations of the early afterglow, where most of the energy is in X-rays, are being carried out with SWIFT, while observations in the almost unexplored MeV-GeV band are expected to come soon from the planned gamma-ray observatories.

Synchrotron emission appears to be the most likely emission mechanism of the afterglow at low frequencies (radio, optical and X-rays). However, the hardness of the spectrum seems to disagree with the predicted synchrotron-limiting slope. A better knowledge of the temporal evolution of the spectrum in the prompt phase, requiring large area gamma-ray detectors, will allow us to make progress on this issue. Some relevant insights should also be provided by GLAST. Synchrotron emission should accompanied by an inverse Compton component in the X-ray band. For GRBs at low to moderate redshifts, an extension of the measured afterglow spectra up to 50-100 keV (where the Compton component should dominate) would be crucial to test emission mechanisms.

Finally, the phenomenon of X-Ray Flashes (XRF) should be mentioned. XRFs represent a new class of GRBs discovered by BeppoSAX having a spectrum much softer than that of long GRBs, with peak energy equal or smaller than a few tens of keV. While the origin of XRF is still debated, unfortunately SWIFT is not best suited instrument for studying such events, having a low energy threshold of about 15 keV. Conversely, to clarify the nature of XRFs observations extending down the 1 keV region are needed.

2.9.5 The origin of Cosmic Rays

During the pioneering experiments of 19th century on electrostatic phenomena, scientists noticed the puzzling phenomenon of discharge of the gold leaves of electroscopes in the absence of external action. This indicated that there was some sort of ionization taking place in the air inside the electroscope, eventually leading to the electric discharge of the system. In 1912, V. Hess performed his pioneering first balloon flights that showed that this ionizing radiation, usually thought to be coming from the Earth surface, was in fact coming from outer space. This mysterious radiation was given the name of Cosmic Rays. Experiments aimed at unveiling the origin of Cosmic Rays proliferated and while their technical potential improved, people understood that this radiation was in fact made of charged particles (east-west effect), with energies that were higher and higher when measured with better and better experimental setups.

Much time and many experiments had to be done before we reached our most recent understanding of this phenomenon: cosmic rays are extremely energetic charged particles, with energy that ranges between 106 eV and more than 1020 eV. At the lowest energies their origin is related to and/or affected by phenomena taking place in the Earth-Sun surroundings. At energies of a hundred billion eV, cosmic rays start being generated in distant sources inside our Galaxy. At these energies their flux at the Earth exceeds ~100 particles per square meter per second. At larger energies, their number decreases rapidly, and at the highest energies that we have measurements at, corresponding to ~1020 eV, the flux corresponds to roughly one particle per square km per century! Such energy is only a few orders of magnitude below that corresponding to the so-called Grand Unification of Forces, where scientists expect that all fundamental forces but gravity unify in a single type of interaction.

The existence of cosmic rays forces us to envision new, quite violent places in the Universe in which Nature manages to transform other forms of energy to extremely energetic sub-nuclear particles, far from being in thermal balance with their surroundings. The investigation of the processes of particle acceleration in astrophysical environments has been mentioned many times in this document, to stress the fact that it is absolutely central to a variety of non-thermal phenomena, from GRBs to AGNs, from clusters of galaxies to supernovae.

There is growing evidence that the bulk of cosmic rays are accelerated to their very high energies during the final stages of the life of massive stars, when these explode in the form of supernovae, roughly once every 100 years in our Galaxy. These cosmic explosions eject several solar masses of material into the interstellar medium, enriching it with heavy elements, such as Iron. They proceed outwards from the explosion at supersonic speeds and therefore form strong shock waves that propagate outwards and heat up the circum-stellar gas. At the same time, the shock front energizes a small fraction of this gas to large supra-thermal energies. These few very energetic particles will become Cosmic Rays, although a solid proof that this is at the basis of the Galactic cosmic rays is still missing. The relevant acceleration process, called diffusive shock acceleration and put in its present form in the 70's, is built upon an idea originally put forward in 1949 by Enrico Fermi. Recent investigations of this physical process are revealing new fascinating aspects of it and fostering further application of the underlying physics to situations in which we have evidence that shocks are moving with relativistic speeds, as in Gamma Ray Bursts. These recent investigations are showing to us that the process of acceleration may be even more efficient than was thought in the past and could lead in fact to a bunch of new fascinating phenomena:

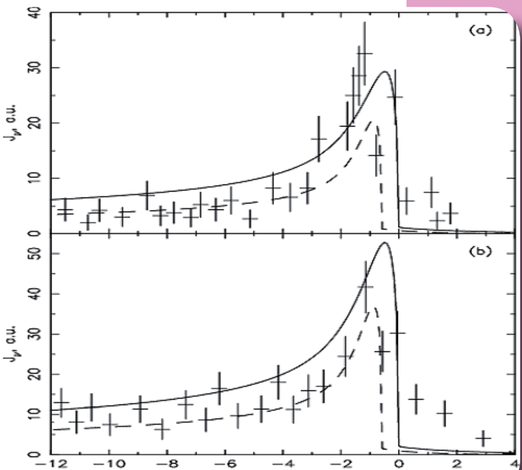


Fig. 2.9.3 brightness profile of the X-ray emission of SNRs for different values of the magnetic field in the shock region.

1. Shocks in SNRs are expected to be strongly modified by the dynamical reaction of the accelerated particles, which in turn

changes the spectra of cosmic rays.

2. The accelerated particles may generate by themselves the level of magnetic turbulence necessary for their scattering (streaming instability). If further investigations will confirm current expectations, SNRs should be found to accelerate cosmic rays up to ~2 ×107 GeV (for protons) and ~4 ×108 GeV (for iron nuclei). This effect might have been discovered recently through Chandra observations of the thickness of the X-ray rims around the SN shock. These observations (see Fig. 2.9.3) show that the brightness profile is consistent with magnetic fields a few hundred times larger than the ISM field (solid lines).

These studies are part of what is known as the non-linear theory of particle acceleration at shock fronts, which is accumulating an impressive amount of indirect confirmations from observations. Future, high angular resolution X-ray measurements, together with gamma ray observations of the remnants are the avenues to pursue in order to get to an unambiguous identification of the sources of cosmic rays and of the processes involved in their acceleration and propagation.

On their way from the sources to the Earth, cosmic rays interact with the gas and magnetic field in the interstellar medium, providing a glow of diffuse radio emission, X-ray radiation and gamma rays that we observe from the Earth. The observation of these radiations allows us to achieve a better understanding of the processes involved in the acceleration of cosmic rays and the random wandering that takes cosmic rays from their sources to Earth through diffusion in the magnetic field. During their journey, cosmic rays also ionize part of the medium that they cross, thereby allowing the regulation of the rate of formation of stars in the Galaxy. The ionization of neutral media affects the interplay of gas and magnetic fields, in particular in dense molecular clouds, where most stars form. The gravitational collapse that leads to the formation of stars happens with a rate that is regulated by the strength and structure of magnetic fields and by the gas itself that will end up in the star. Cosmic rays are the thermostat of all these complex phenomena. In a way, Cosmic Rays contribute to form those stars that will in turn return their energy to cosmic rays after their death. The death of these stars also returns to outer space those heavy elements and in particular those iron and carbon nuclei that are so fundamental for the development of life. The interactions of these high-energy bullets hitting the interstellar medium induce spallation of heavy nuclei. This very important process pollutes the Galaxy with light elements such as Boron and Lithium that are very poor in the primordial soup that emerged from the Big Bang and that can be found in the Galaxy mainly as a result of the presence of cosmic rays and their interactions with the Galaxy. The measurements of the abundances of these elements, as well as of the positrons which are by-products of the same interactions, are precious to understand the processes responsible for diffusion in the Galaxy. Despite much indirect evidence that cosmic rays are accelerated in supernova remnants, observations at present can only confirm that electrons are energized at these locations. This evidence is obtained through multifrequency observations of the shocks that are responsible for the acceleration. During the acceleration, electrons lose some of their energy through synchrotron emission and inverse Compton scattering. Both these processes result in the emission of X-rays in addition to radio and gamma ray emission, all from the shock region. Unfortunately, most particles observed at the Earth as cosmic rays are nuclei rather than electrons.

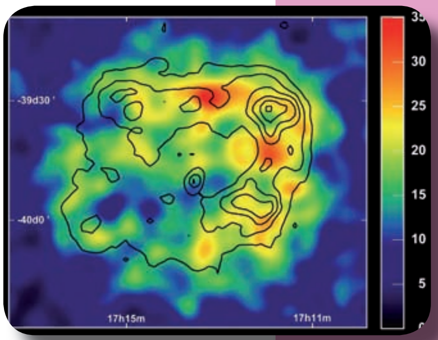


Fig.2.9.4 Image of the SNR G347.3-0.5 obtained by HESS in the TeV domain. It is very well correlated with the X-ray (ASCA) image

The smoking gun, which is still missing in order to claim the discovery of the sources of cosmic rays, is the detection of high-energy gamma radiation that could be uniquely interpreted as the interaction of protons in the supernova environment. Clearly this association of gamma rays with the acceleration and interaction of nuclei is made easier by the availability of multifrequency observations of supernova remnants. Very recent measurements carried out through the HESS Cherenkov telescope may represent the first evidence of such feature. The TeV structure of RXJ1713.7-3946 (see figure 2.9.4) is well consistent with the X-ray structure seen by ASCA, showing that these are sites of extremely efficient high energy particle acceleration.

A large contribution from energetic electrons through inverse Compton scattering is possible. However, because of the high density likely to exist in the north-west rim, p0-decays following proton-proton interactions could give a significant contribution. In order to disentangle the different contributions one needs accurate multi-band spatially resolved spectroscopy, which will be possible in this SNR using Cherenkov telescopes (like HESS with the improved quality image of the full configuration, MAGIC, VERI-

TAS and future instruments), coupled with X-ray imaging. Imaging in the hardest possible X-ray band is desirable because in most SNRs one needs to separate thermal and non-thermal emission. Gamma ray telescopes such as GLAST will play a fundamental role in this program. Also space resolved X-ray Polarimetry of the remnant can significantly contribute to this separation. It is worth noticing that both the interactions of cosmic rays close to their sources and in the interstellar medium also unavoidably lead to the production of the elusive neutrinos. The detection of these neutrinos will represent a great challenge for astrophysics in the next century: experiments of km3 size are being built in order to open this new observational window.

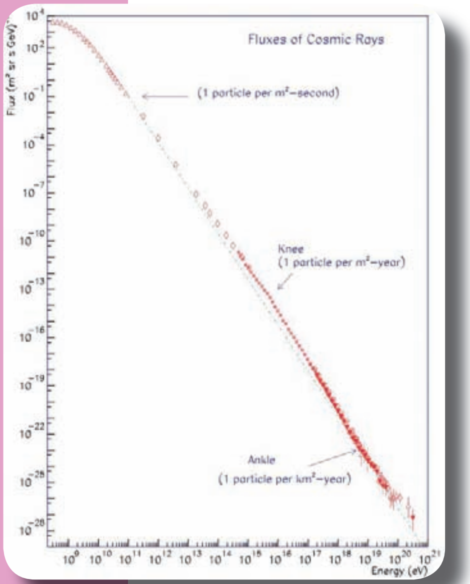


Fig. 2.9.5 The spectrum of Cosmic Rays.

As visible in Fig. 2.9.5, at energies of roughly 3´1015 eV the observed spectrum of cosmic rays shows a feature, known as the knee. The mystery of this feature has been haunting scientists for decades but we are finally starting to have a clue from the most recent observations, mainly from KASCADE (and previous observations carried out with EAS-TOP). These showed that the knee might be due to the effect of superposing the spectra associated with different chemical elements present in cosmic rays, each accelerated to its own maximum energy. According with this picture, cosmic rays would gradually become heavier when their energy increases.

While the energy of the particles increases, their trajectories in the galactic magnetic field suffer increasingly less bending: at energies around 1018 eV, we expect that a transition takes place from cosmic rays predominantly accelerated within the Galaxy to the so-called ultra high energy cosmic rays (UHECRs) that must be accelerated in extragalactic distant sources. Two main theoretical frameworks have been put forward for the transition, the ankle and the dip, which can be most effectively tested by measuring the chemical composition in the energy region between 1017 eV and 1019 eV (the results of KASCADE-GRANDE will be crucial in this respect).

The propagation over cosmological distances opens new questions of unprecedented interest: for protons with sufficiently high energy, the scattering with the photons in the cosmic microwave background gives rise to photopion production (pions appear in the final state). In 1966 two Russian scientists, Zatsepin and Kuzmin and an American scientist, Greisen, predicted independently that this particle physics interaction would cause the appearance of a feature in the spectrum of cosmic rays (the GZK feature), a flux suppression, which became thereafter the Holy Grail of Cosmic Ray Physics. This feature still remains unambiguously observed but incoming data from the Pierre Auger Observatory are expected to clarify this topic. The detailed study of the GZK break (if confirmed) and the possible extension of these measurements to two further decades of energy would open a window on many other aspects of this investigation, such as the ambitious measurement of the spectrum of cosmic rays from a single source, which would really start what we could call “Ultra High Energy Cosmic Ray Astronomy”. For this an experiment with an extremely large detection area is necessary. After the era, it seems reasonable to think that the only way to further improve the performances is to build space-borne instrumentation.

Several fascinating hypotheses have been put forward to explain how Nature generates UHECRs. It is likely that powerful astrophysical objects such as super-massive BHs are their factories. On the other hand, it is possible that at these extreme energies we might be seeing the remnants of the Big Bang itself: during the inflationary period following the Big Bang, very massive particles are generated, whose lifetime can exceed the current age of the universe. These particles may follow and in fact drive the formation of the gravitationally bound objects in the universe, playing the role of dark matter. Eventually and seldom they decay and their end products might be what we observe in the form of ultra high energy cosmic rays. The basic recipe to distinguish between these two possibilities is to proceed to an accurate measurement of both the spectrum of UHECRs and their chemical composition. Both tasks, at the extreme energies of interest turn out to be very challenging but are nevertheless being pursued.

PART 3. MAJOR PROJECTS

Introduction

Following the scientific outline of the most challenging scientific questions for the next decade, we analyze in this Section the ongoing and future projects that will address these items.

First, for each of the major scientific questions, we list the observational techniques or theoretical approaches that can address or give an important contribution to the solution of the problem, and, the ongoing or future projects, facilities or instruments that can be used for this purpose. This exercise is done making use of a “Questions/Project Matrix” tool, which is presented in Section 3.2.

We then focus on the projects that are more relevant for the Italian community, and provide in Sect. 4.3 in the form of a list of tables (one for each project) a synthetic description of their status, impact on the scientific questions, timeline and involvement of the Italian community. For many of these projects, we also provide a short recommendation with the aim of improving the competitiveness and of optimizing the scientific exploitation. This information will be used to prepare strategic roadmaps in Part 6.

Two important caveats are worth mentioning at this stage.

First, such list includes all the projects that can give a substantial contribution to solve the major “big questions”. This list must not be intended as exhaustive of all projects in which INAF scientists are or may be involved, nor of those that are being discussed within the astrophysical community.
On one side, it must be stressed that, beside the large projects quoted here, it is important to support all those scientific and technological projects, small in size but with important scientific return.
On the other side, this list cannot be exhaustive because in scientific research the investigation or even the solution of a problem continuously generates more complex and fascinating questions. We thus expect that in the coming decade new and unforeseen concepts and projects will be proposed. Such projects and their scientific potential will have to be evaluated in the strategic context laid out by this plan and its future updates.

Second, theoretical astrophysics may seem under-represented within the present approach because it is rarely organized in large scale collaborations or coordinated projects. On the contrary: theoretical astrophysics is a major priority for Italian research, as it is highlighted in Part 2 and Part 6.

In the following, the projects are grouped into three broad categories according to their current status, as follows:

1. On going projects: the current facilities and experiments which are delivering scientific results today.
2. The projects and facilities not yet operational but that have passed some “no-return” point and that will enter a scientific operations stage within the next few years. They are printed in blue.
3. New, major projects that are discussed or evaluated for the long term future. These includes phase-A studies and new ideas. For the reasons described above, we restrict our analysis only to few major big projects or broad ideas, and print them in red.

3.1. Associating hot scientific questions and projects: the “Questions/Projects” Matrix

Starting from the scientific themes of Part 2, the methodology to significantly advance in each field was identified, and used to build a “Questions/Projects” Matrix listing the projects that will address the issues. The Matrix is presented as a set of tables, one for each of the nine broad science themes, which contain the title of the scientific theme, the methods and the corresponding projects. Also listed are the top priority projects that hold the promise to allow a major breakthrough in the listed scientific themes.

3.1.1. Geometry and the fundamental nature of the Universe

Hot topics	Methods	Projects	Top Priorities
1.1) Testing inflaction			
Foregrounds and cosmological parameters	Measure E mode polarization and T-E correlation, CMB spectral measurements.	WMAP Planck, CMBpol, Bpol-like mission	
The primordial gravitational waves and their B mode polarization	Measure B-mode polarization at a level of 0.1microK	WMAP, Planck, suborbital experiments, SPORT, CMBpol (BE probe), Bpol-like mission	Bpol-like mission
1.2) The nature of Dark Matter		Experiments for WIMPs, GLAST	
1.3) The enigma of dark energy			
Geometrical tests: SNIa/GRB/Core collapse	Deep wide field imaging O-NIR	HST, CFHT, UKIDSS, SWIFT, VLT, LBC, VST, VISTA, LSST, 3sq-deg, SNAP/JDEM, Dune	Wide photometric surveys from space, 3sq-deg
Geometrical tests: Galaxy power spectra	Wide field, 100-1000 deg2 surveys, with spectroscopic or photometric redshifts	SLOAN, CFHT, UKIDSS, LBT/LBC, VST, LSST, 3sq-deg, space-based large FoV telescope, SKA	LBC and VST large galaxy surveys
Weak lensing surveys	Wide field, 100-1000 deg2 surveys, with spectroscopic or photometric redshifts	SLOAN, CFHT, UKIDSS, LBT/LBC, VST, LSST, 3sq-deg, space-based large FoV telescope	Wide photometric surveys from space
Secular motion of Ly forest	High resolution spectroscopy of QSO	ELT-CODEX	
Dynamical tests: Evolution of the mass and correlation function of galaxy clusters, evolution of the gas fraction within clusters of galaxies.	Wide field X-ray surveys, ~10000deg2 a few arcsec resolution, Radio & mm SZ surveys.	Planck, other SZ surveys, ALMA, WFXT	
1.4) Fundamental physics			

Hot topics	Methods	Projects	Top Priorities
Tests for quantum gravity models: search for violation of Lorenz invariance	GRB high energy msec structure; GRB polarimetry	GLAST	
	Theoretical models, simulations	High performance computing	

Fig. 3.1.1 Working @ Planck LFI Instrument

3.1.2. The formation and evolution of the structure in the Universe

Hot topics	**Methods**	**Projects**	**Top Priorities**
2.1) The first luminous objects in the Universe			
Direct detection of the first metal-free stars, SN, GRB and QSOs.	Wide field ultra-deep surveys in IR and X-rays, sub-arcsec resolution, FIR and mm surveys	JWST, VISTA, Herschel, ALMA, XEUS, ELT. Swift+VLT, post Swift	JWST, ELT, Swift/VLT
Observation of the redshifted 21cm line emission against the CMB.	Low frequency radio surveys	LOFAR, SKA	SKA
2.2) Birth and evolution of galaxies and SMBHs			
	Theoretical models, N-body simulations, hydrodynamic simulations	High performance computing	
The galaxy and SMBH mass & luminosity functions. SMBH complete census. High-z galaxies and QSOs.	Deep IR/OUV/X-ray surveys, search for obscured AGN making the peak of the CXB, Galaxy stellar and dynamical masses with better statistics and extended to higher z	Spitzer, VLT, XMM, LBT/LBC, Lucifer, LBTI, VLT2nd-Gen, Herschel, VST, VISTA, ALMA, JWST, NIR wide field, ELT, XEUS, WFXT, Simbol-X	VLT, LBT, Herschel, Hard X-rays, wide field
AGN and SN feedbacks, physics of feedback	High resolution spectroscopy of local, to high-z galaxies, (sub)mm high spatial resolution spectroscopy, X-ray, Radio high angular resolution imaging.	VLT SPIFFI, SINFONI, VLBI, Chandra, LBT/Lucifer, ALMA, ELT, SKA	VLT, LBT/Lucifer ALMA, SKA
The evolution of the star-formation rate and of the nuclear accretion.	Deep Wide surveys in IR/O-UV/X-rays, Radio, mm and far-IR.	LBT/LBC, VLT, XMM, APEX, VST, VISTA, Herschel, ALMA, SKA, NIR wide field, 3sq-deg, WFXT	VLT, LBT/LBC/Lucifer, ALMA, SKA, 3sq-deg
The evolution of the clustering and of the bias, the correlation of galaxy activity with the environment.	Wide surveys in IR/O-UV/X-rays, Radio, mm and far-IR.	LBT/LBC, VLT, XMM, APEX, VST, VISTA, Herschel, ALMA, SKA, NIR wide field, 3sq-deg, WFXT	LBT/LBC VST +3sq-deg

Hot topics	**Methods**	**Projects**	**Top Priorities**
The assembly of SMBH, spheroids and disks in galaxy halos	Multi-band sub-arcsec imaging	HST, Chandra, VLT-active opt, APEX, JWST, AO, LBT, LBTI, VLTI, ALMA, ELT, XEUS	
Cosmic chemical evolution	Modeling including stellar evolution, SN rates and yields, in- & out-flows IMF, SFR(z)	High performance computing	
2.3) The fate of baryons			
The Lyman-alpha forest	High resolution spectroscopy in UV/opt	VLT/UVES, VLT-2ndGen, WSO	
Detection and characterization of the warm IGM	high resolution spectroscopy in UV/X-rays	FUSE, Chandra, XMM, future X-ray gratings, calorimeters, post-FUSE	Future X-ray gratings, calorimeters
The Hot ICM, probing the virial radius, internal motions and non thermal emission	X-ray wide field, arcsec imaging X-ray high energy coverage	XMM, Chandra, GLAST, LOFAR, WFXT, XEUS/ ConX Simbol-X, SKA	WFXT, Simbol-X, GLAST, SKA
Chemical evolution of ICM/IGM	Abundances of clusters in X-rays both in emission (wide-field imaging) and absorption (high-resolution spectroscopy).	Chandra, XMM, FUSE, VLT, WFXT, New X-ray calorimeters, gratings, ELT	WFXT, New X-ray calorimeters, gratings,

3.1.3 The history of the Galaxy and of nearby galaxies

Hot topics	**Methods**	**Projects**	**Top Priorities**
3.1) Stellar populations			
	UV/Optical/near-IR photometry of resolved stellar populations in our and Nearby Galaxy;	HST,VLT, TNG, VLT-Hawk-I, VST, LBC, GAIA, VISTA, JWST, WSO	LBC,VST,GAIA
3.2) Stellar Clusters			
Physical parameters from C-M diagrams	Deep, high resolution photometry	HST,VLT, TNG, VLT-Hawk-I, VST, LBC, GAIA, VISTA, JWST, WSO	LBC,VST,GAIA
Dynamical History and its influence on their stellar populations	N-body theoretical models coupled with stellar evolutionary models	High performance computing	
The distance of Stellar clusters	Astrometry of loose and dense fields	HST, GAIA, WSO	GAIA
3.3) Star formation history and chemical evolution of local galaxies			
Chemical evolution of the Milky Way	O-UV-IR high-resolution spectroscopy of stars and nebulae.	TNG/SARG,VLT/FLAMES, CRIRES, next generation UV satellite, COS,ELT,WSO	Next generation UV satellites, ELT
Physical parameters, structure	Continuum FIR/mm/radio.	APEX, SRT, ALMA, SKA	ALMA,SKA
Chemical evolution of external galaxies	Photometry and Medium/high resolution spectroscopy of both low and high-z galaxies. Mm observations: morphology and kinematics of molecular gas, HII regions.	VST, LBT/LBC, VLT/SINFONI,FLAMES, LBT/Lucifer, ALMA, LBT-MODS, VLT-XShooter, SKA, ELT	
	Deep narrow-band X-ray imaging with high spatial resolution	Chandra, XEUS	

Hot topics	Methods	Projects	Top Priorities
The ISM of the Galaxy vs. that of external galaxies	O-NIR high resolution spectroscopy. Wide range of spatial scales; Wide field O-NIR photometry	VLT, APEX, LBT, ALMA, SRT, VISTA, SKA, Large single dish sub-mm.	
	Modelling including stellar evolution. SN rates and yields, in- & out-flows IMF	High performance computing.	

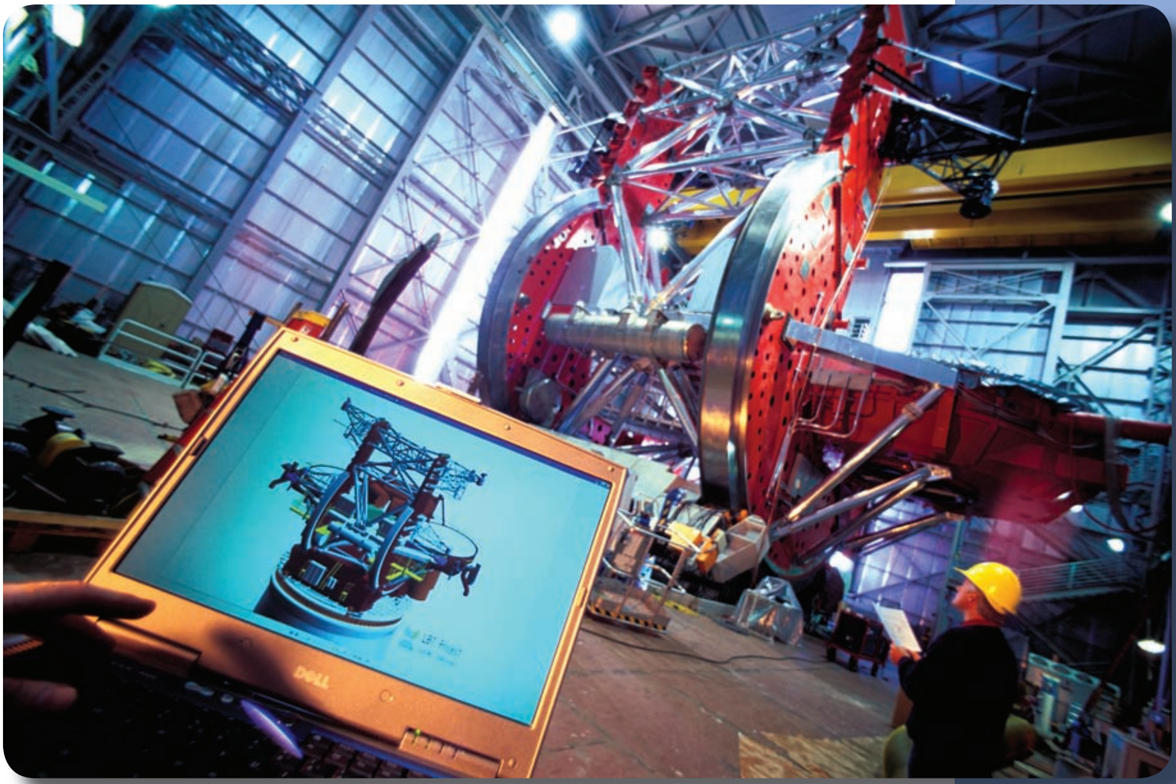


Fig. 3.1.2 The Large Binocular Telescope - LBT

3.1.4 The birth of stars in the nearby and in the far Universe

Hot topics	**Methods**	**Projects**	**Top Priorities**
4.1) ISM			
	O-NIR-mm and radio spectroscopy. Astrophysics laboratory, Continuum FIR/mm/radio	VLT, Spitzer, APEX, IRAM Chandra, XMM, LBT, JWST, Herschel, Planck ALMA, SRT (100GHz), SKA, Large single dish sub-mm	Hershel/ALMA SKA
4.2) Stellar birth			
	High and low resolution IR/mm/radio spectroscopy. IR-radio imaging/spectroscopy. X-ray and Gamma-ray spectroscopy	VLT, VLTI, Spitzer, APEX VLBI, Chandra, XMM, LBT, JWST, LBTI Herschel, ALMA, SRT, GRI, SKA, VLTI-2nd generation, Simbol-X, XEUS	Hershel/ALMA SKA + X-rays, AO/interferometry, LBT/VLTI
4.3) Accretion disks			
	O-IR high-resolution continuum (scattered), and polarization.	VLT, VLTI, LBT, JWST, LBTI, VLTI-2nd generation	ALMA SKA,X-rays, AO/interferometry, LBT/VLTI
Disk structure and properties	NIR, FIR-mm emission (AO, Interferometry). Spectroscopy: dust properties.	VLT, VLTI, LBT, LBTI, JWST, Herschel, VLTI-2nd generation, FIR interferometry	JWST, VLTI, FIR Interferometry
accretion/wind/inner disk	opt/ir high res spec	VLT, LBT	
outer disk: chemistry, structure	mm Spectroscopy: molecular gas, high angular resolution	APEX, Herschel, ALMA, SRT, SKA, Large single dish sub-mm	Herschel, ALMA, SKA
disk-star interaction	X-ray spectroscopy, optical photometry over long time series	VLT/LBT, VISTA, Chandra, XMM, GRI	
4.4) Planet formation			
	IR imaging and spectroscopy high spectra and spatial res mm/radio high resolution	VLT, LBT, VLTI, AO, JWST, Spitzer, Herschel, ALMA, VLTI-2nd generation, FIR Interferometry, SKA	As above +SKA

Hot topics	Methods	Projects	Top Priorities
4.5) High mass stars			
	High angular res observations UV/optical/ir spectroscopy X-ray low-res spectroscopy radio/mm high resolution spec/cont FIR/mm wide area surveys	VLT, LBT, VLTI, AO, Spitzer, Herschel, ALMA, APEX, SRT, VLBI, Chandra, XMM, next gen UV satellite, SKA, VLTI-2nd generation, FIR interferometry, Large single dish sub-mm	As above
4.6) Feedback processes and jets			
	O-NIR high resolution spectroscopy & imaging. X-ray imaging. Infrared spectroscopy/imaging. High resolution mm molecular line spectroscopy	VLT, VLTI, AO, VLBI, Spitzer, LBT, LBTI, Herschel, ALMA, SRT, Chandra, XMM, SKA, VLTI-2nd generation, FIR interferometry, Large single dish sub-mm	VLTI, ALMA, SKA
4.7) The Initial Mass Function			
	High spatial resolution and wide field optical and NIR imaging. X-ray surveys. O-NIR multi object spectroscopy. High resolution mm spectroscopy.	VLT, LBT, Vista, JWST, GAIA, Spitzer, Herschel, ALMA, APEX, Chandra, XMM, SKA	Large area surveys (VLT, LBT), GAIA
4.8) First stars and low metallicity environments			
	Optical and NIR imaging/spectroscopy. FIR and millimeter/radio imaging and spectroscopy.	VLT, LBT, JWST, Herschel, ALMA, LOFAR, SKA, Large single dish sub-mm	ALMA, SKA

3.1.5 The life cycle of stars

Hot topics	**Methods**	**Projects**	**Top priorities**
5.1) Life on the main sequence			
Stellar structure	Space- + ground-based seismic data, High-resolution spectroscopy. Accurate stellar parameters (temperatures, distances, etc.)	VLT UVES, FEROS, Giraffe, TNG/SARG other high-resolution spectrographs,. LBT, Possible use for small telescopes. COROT, GAIA, Cosmic Vision photometric missions.	High spectral resolution. GAIA Cosmic Vision, photometric mission
Chemical analysis	O-NIR high-resolution optical spectroscopy. Currently limited to our Galaxy, in the future extension to external galaxies	VLT UVES and Giraffe, TNG/SARG. LBT, GAIA, TNG/Giano, ELT(s).	See above, more challenging, large throughput.
Large-scale population studies and summary chemical analysis	Astrometry, low-resolution spectroscopy, photometric surveys	HST, GAIA, large scale ground-based surveys (LBT/LBC, VST, VISTA), VLT, VLT2ndGen, Next UV mission	HST + large field. UV imaging and high -spectral resolution spectroscopy.
Computation of atmospheres, general theoretical work	High-performance computing		
5.2) The outer stellar atmospheres	X-ray imaging and spectral observations	XMM, Chandra, Simbol-X, future X-ray telescopes high X-ray spectral resolution (XEUS, smaller missions)	High resolution X-ray spectroscopy
5.3) The structure of the Sun and the Sun as a star			

Hot topics	**Methods**	**Projects**	**Top priorities**
Solar structure (interior)	Constrain dynamo in polar regions higher L modes detection, g modes detection Extension of helioseismology to the polar regions, high resolution (0.1 arcsec) optical imaging. Synoptic time-series, turbulence effects Solar neutrino flux measurements	SOHO/MDI, GONG, BISON, Solar Orbiter (SOLO), ATST, EST, solar neutrino experiments	Participation in the exploitation of ground based networks + SOHO. SOLO. ATST/EST
5.4) Exploding stars and their remnants			
Exploding stars: observations of explosion	Fast-response O-NIR spectrophotometry. Neutrinos	VLT, VLT X-shooter, LBT Lucifer, MODS, 2- mid-size robotic telescopes, UV spectrophotometry, LVD	mid-size robotic tel., VLT/X-shooter LBT/Lucifer
Exploding stars: asymmetries of explosion and interaction with the CSM and ISM	Spectro-polarimetry, UV-opt-IR high-resolution spectroscopy, Radio and X-ray observations	VLT/FORS UVES, CRIRES, -- VLBI, APEX, Chandra, XMM, SRT, ALMA, WSO, COS	VLT,WSO, X-rays, ALMA, VLBI
Exploding stars: discovery of new nearby and distant SN	All-sky variability monitoring with high angular and temporal resolution.	SWIFT, VST, LBC, SNAP/JDEM, PanStarrs, LSST, 3sq-deg, Antartica, X-ASM	VST,LBC,SNAP/JDEM,3sq-deg
Exploding stars: nucleosynthesis	UV/Opt/IR spectroscopy of explosions and SNR, X and Gamma-ray spectroscopy to detect nucleosynthesis yields	VLT, TNG, LBT, XMM, INTEGRAL, GRI, Simbol-X, WSO	
Exploding stars: theoretical modeling	last evolutionary phases, physics of the explosion, ejecta hydrodynamics	High performance computing	
Intermediate and low mass stars (PN, WD)	High-resolution 3D spectroscopy	IFU, Fabry-Perot (VLT instruments)	

Hot topics	Methods	Projects	Top priorities
Production of complex molecules and dust	Mm and Infrared spectroscopy.	VLT, Spitzer, APEX, VLBI, LBT, Herschel, ALMA, SRT,	

3.1.6 Solar, interplanetary and magnetospheric physics

Hot topics	Methods	Projects	Top Priorities
6.1) The Sun as a Rosetta stone: what can we learn about stellar activity observing the sun			
	EUV: high angular resolution, full disk monitoring. XUV and X-ray: arcsec resolution. Multi-band full disk photometry. E/DE ~ 1000 X-ray spectroscopy in the 0.1 - 10 keV band.	SOHO, GOES/SXI, Solar B, SDO, Stereo, Solar Orbiter	Solar B, SOLO
6.2) Magnetic field generation, dissipation, and removal from the solar surface			
	High resolution spectro-polarimetry Wide field, sub-arcsec imaging. O-UV-NIR full Stokes profile. High spectral (mA) and temporal (few s) resolution. EUV polarimetry of the extended corona	SOHO/MDI, DST, ENO, Magneto-Optical-Filters (MOFs), IBIS + Solar B, SDO, ATST/EST, Antarctic telescopes, Solar Orbiter, SPINOR, High Performance Computing	O-NIR band spectroscopy and polarimetry. ATST/EST
6.3) Geating of the solar outer atmosphere, coronal explosive events and other plasma phenomena			
	UV to hard X-ray 0.1arcsec imaging. Spectroscopy to 1 km/sec resolution. Time resolution < 1 sec. High resolution optical-NIR spectro-polarimetry. Medium resolution spectroscopy (E/DE ~ 1000) in 0.1 - 10 keV band.	SOHO, ENO, DST, TRACE, MOF, Coronas, RHESSI, Solar B, SDO, Stereo, Solar Orbiter, Solar Probe ATST/EST, IBIS + SPINOR, High Performance Computing	O-NIR band spectroscopy and polarimetry. ATST/EST

Hot topics	Methods	Projects	Top Priorities
6.4) Solar wind			
Originating regions and acceleration mechanisms. Chemical composition and waves, in situ.	EUV spectroscopy of polar regions. Exploration near the Sun and out-of-ecliptic. In situ measurements of B field and turbulence. Ionic spectrometry (p+, e- and alphas, dE/E~5%, dt~20ms)	SOHO, Ulysses, Solar Orbiter, Solar Probe	SOLO
6.5) Interaction with Earth and other planets			
Geomagnetic and magnetospheric phenomena Solar variability	In situ, also multipoint, plasma and magnetic field measurements. Magnetospheric, ionospheric, auroral and geomagnetic measurements. Multi-band photometry of full solar disk. Synoptic solar time-series, ground and space cosmic ray measurements	SOHO, SOLIS, PSPT, GOES/SXI, ACE, GOES, Cluster, Double Star, Ground magnetometer arrays, SuperDARN radars, All-sky cameras. Network of CR detectors, SVIRCO Solar B, SDO, Stereo SWARM, Bepi Colombo, Solar Orbiter, TIMED and similar future missions	SOLO, BepiColombo
6.6) Spectroscopic diagnostic and atomic physics			
	Multi-band High resolution spectroscopy, including X-rays		

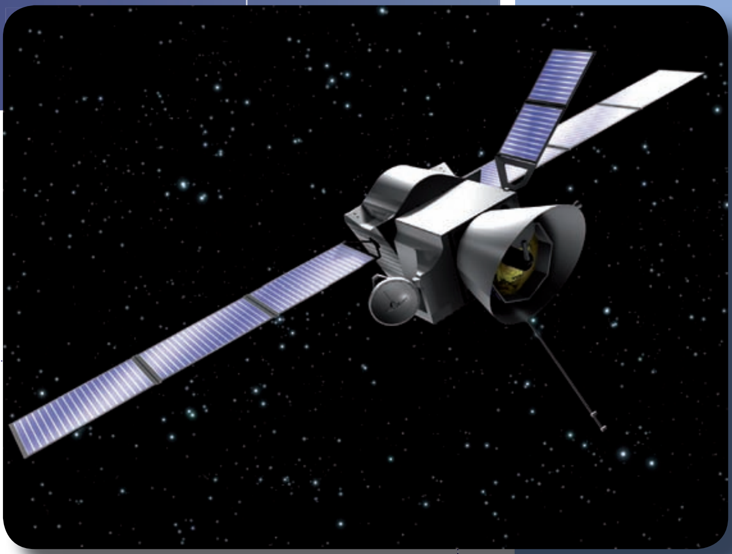


Fig. 3.1.3 An artist's impression of the MCS comprising the two orbiters and the transfer module of the BepiColombo mission. Visible in this view are, from front to back: the Mercury Magnetospheric Orbiter (MMO) surrounded by the Sunshield; the Mercury Planetary Orbiter with its solar panel deployed; and the Mercury Transfer Module with the two solar array wings deployed. (ESA)

3.1.7 The solar system

Hot topics	**Methods**	**Projects**	**Top Priorities**
7.1) The outer planets			
	In situ exploration of Jupiter and Saturn.	Cassini, Juno, Jupiter exploration and Europa Lander Cosmic Vision, Herschel	Exploitation of Cassini data. Collaboration to US missions on Jovian system.
7.2) Inner planets			
	In situ exploration of the Moon, Mercury, Venus, Mars	Venus Express, Mars Express, BepiColombo, future ASI/ESA-Lunar mission, ExoMars (Aurora programme) Herschel	Exploitation of ME/VE. BepiColombo and ExoMars
7.3) The minor bodies			
Discovery and characterization	Physical and astrometric observations of comets, asteroids, trans-neptunian objects and NEOs Wide-field surveys.	TNG, Pan-STARRS, VST, LBT, GAIA, SRT, ALMA, LSST, 3sqdeg, Herschel	VST, LBT, mid-size tel.
In situ exploration	In situ exploration of asteroids, comets and NEOs	Rosetta, dedicated space mission to a NEO (ESA, ASI/CNES)	Rosetta, future ESA/ASI/CNES mission

3.1.8 The search for extraterrestrial planets and life

Hot topics	**Methods**	**Projects**	**Top Priorities**
8.1) Discovery of exoplanets			
Radial velocities	High resolution spectroscopy (delta(v)<<1m/s) over long time baseline	HARPS, TNG/SARG, Coralie, TNG/Giano	Giano
Astrometric oscillations	Interferometry accuracy 100-1 micro-arcsec timing. mm/cm wave astrometry	VLTI, LBTI, GAIA, ALMA, SIM, SKA	GAIA VLTI/LBTI

Hot topics	**Methods**	**Projects**	**Top Priorities**
Transit of stars by planets	Wide-field accurate photometry (to better than 0.01 mag) over long time baseline from ground and space	VST, COROT, Kepler, nearly dedicated 2m tel.	VST, access to Corot
Microlensing of planets on background objects	Wide field accurate photometry (to better than 0.01 mag) over long time baseline on small telescopes	MACHO, MOA, MICROFUN, VST, nearly dedicated 2m tel	VST, access to Corot
Direct detection of forming planets	AO-aided differential imaging, low-resolution spectroscopy and polarimetry on 8m class telescopes, Diffraction limit imaging & spectroscopy from space	NACO, LBT/Lucifer, VLT/Sphere, JWST, ALMA	VLT/Sphere
8.2) Characterization			
	Diffraction limited UV, opt and IR differential imaging, spectroscopy and polarimetry from ground and space	HST, Spitzer, VLT/Sphere, ELT	VLT/Sphere ELT
	Astrometric oscillations: interferometry accuracy 100-1 mas	LBTI, VLTI, ALMA, LOFAR, SKA	
	NIR interferometric spectroscopy	Life-finder Darwin, TPF	
8.3) Astrobiology	Laboratory studies		
Astrobiological observations (complex molecules)	mm.radio, optical and NIR spectroscopy and imaging	APEX, SRT, ALMA, SKA, ELT	

3.1.9 The violent Universe

Hot topics	Methods	Projects	Top Priorities
9.1) Probing Black holes and compact objects			
Resolving/imaging the event horizon of the BH at the Galactic Center. High energy emission from the Galactic Center	mm/infrared/X-ray interferometry, hard X-ray imaging	VLBI, mmVLBI, SRT100GHz, VLT/Gravity Maxim (NASA), INTEGRAL HESS, Magic, GLAST, Simbol-X, GRI	mmVLBI. high throughput X-ray missions together with smaller but dedicated missions (Polarization, high-energy, Simbol-X).
Relativistically distorted lines from solar-masses BH and SMBH to constrain BH mass and spin	High throughput spectroscopy of the 6.4 keV line, polarimetry, high energy X-ray observations	XMM, XEUS, Con-X, dedicated missions (Polarization, Simbol-X)	high throughput X-ray missions, smaller but dedicated missions (Polarization, high-energy, Simbol-X).
Gravitational waves from merging BH probing BH metric through gravitational waves.	Ground-based and space-based interferometers	LIGO, VIRGO, LISA	Space based interferometers
Binary pulsars	Single dish radio telescopes	SRT, Parkes	SRT, w/o dedicated instrument
9.2) Ultra-dense matter, neutron stars equation of state. Ultra-strong magnetic fields			
	High throughput X-ray spectroscopy and timing. High resolution spectroscopy, polarimetry	XMM, XEUS, Con-X, newRXTE, All sky monitors, New dedicated X ray instrument	
9.3) Physics of accretion and ejection in both galactic and extragalactic objects			
	X-ray high spatial/spectral resolution observations. X-ray/gamma-ray high energy observations	Chandra, XEUS, Con-X, Simbol-X, GRI, GLAST, AGILE, HESS Magic	Gamma/TeV astronomy GLAST, AGILE, TeV experiments.
9.4) Gamma Ray Burst			
	Fast pointing opt/NIR and X-ray observatories, gamma-ray observations, X-ray localization and characterization of the prompt event.	Swift, REM, AGILE, GLAST, postSwift	(AGILE, GLAST)

Hot topics	Methods	Projects	Top Priorities
GRBs as cosmology tools.	Fast pointing, high spectral resolutions gratings, calorimeters	Chandra, VLT/UVES, VLT/X-shooter, post-Swift,	VLT
GRB and Blazars constraints to fundamental physics	High-energy observations of GRB with accurate timing. Polarimetry. Limits on IR background	GLAST, AGILE, XEUS, HESS Magic	GLAST, TeV experiments
9.5) The origin of cosmic rays			
Galactic bulk	TeV/X-ray observations	HESS, Magic, GLAST, Simbol-X 5@5 Magic2, Veritas, XEUS	new TeV and X ray experiments
CR of ultra-high energy	CR arrays, space-borne UHECR experiment	Auger, Kascade-Grande, LOFAR, Space-borne UHECR experiment	Auger

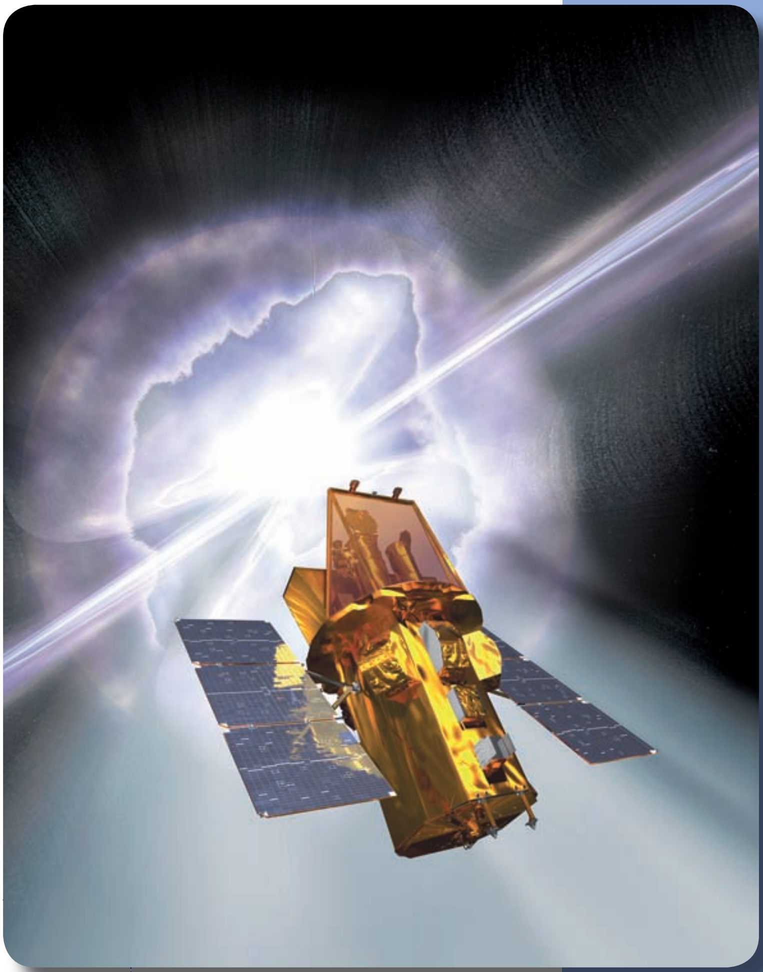


Fig. 3.1.4 An artist's impression of the Swift Gamma-Ray Burst Mission (NASA)

3.2 Specific projects

We describe in this section the projects that have been discussed above, and for which the Italian involvement or interest is high. For each project we provide a short description of the scientific impact, timeline, involvement and expertise and overall momentum. We also list the possible risks connected with the project, the cost (including both the overall contribution provided by Italy and the support that INAF should guarantee to the fulfill the goals of the project) and we conclude wit a short highlight of the strategic priority for the project itself.

3.2.1 Ongoing projects

TNG	Telescopio Nazionale Galileo, 3.5m telescope at the Canary Islands
Scientific impact	TNG has a good record in scientific productivity, at least comparable to similar international facilities. The high efficiency low resolution AMICI NIR spectrograph and the high resolution optical high precision spectrograph SARG are an excellent asset for a telescope of this class.
Time line	In operation since 2000, a new NIR low/high resolution spectrograph (GIANO) is planned to be operational in 2-3 years
Italian Involvement	Very large (Italian telescope and instruments)
Italian expertise	Very good.
Momentum	Medium. All instruments are still first-light instruments and are in operations since several years.
Risk	Low.
Cost	Cost for operations ~3Meuro/year Cost for the upgrade of the instrumentation (GIANO) a few Meuro
Strategic Priority	Medium. The conversion into a dedicated telescope for high efficiency low resolution NIR and high precision high resolution NIR and optical spectroscopy may transform the TNG in a unique asset for the Italian community.

VLT	
Scientific impact	Due to its multi-instrument capabilities and to the high operational efficiency, VLT is providing world class scientific data for all types of projects, enabling astronomers to address important questions in all fields of astronomy.
Time line	The first VLT unit started operations in 1999. At present, all 8m telescopes are fully operational and the smaller units dedicated to interferometry are being commissioned. In the near future, VST and VISTA will become operational on the Cerro Paranal
Italian Involvement	Italy has contributed to a limited number of first-generation instruments (UVES, VIMOS, FLAMES), and it is currently supporting the development of second-generation new instruments like Sphere and X-Shooter
Italian expertise	A significant fraction of Italian astronomers is actively using VLT data, providing world-class results.
Momentum	Construction of second-generation instruments on the VLT is underway and there may soon be calls for a further round of instrument upgrade studies.
Risk	Very low.
Cost	Italian participation to ESO is provided by the Foreign Minister. INAF support to the data exploitation is relatively small
Strategic Priority	Supporting the scientific use and upgrades of the VLT has to remain one of the priorities of INAF.

HST, Spitzer and Chandra	NASA Great Observatories. Multi-purpose Space Observatories.
Scientific impact	The highest conceivable. These instruments are revolutioning our understanding of the Universe, in nearly all fields of astronomy, and are currently used by astronomers worldwide. They represent the major source of top quality data.
Time line	These satellites are expected to be operational for several years. Science from archival data will remain a priority well ahead 2010.
Italian Involvement	Relatively small through the participation of ESA
Italian expertise	A significant fraction of Italian astronomers are actively using HST and Chandra data, see part4, providing world-class data. Italian activity on Spitzer data is lower, albeit quickly growing
Momentum	Activities are focused on the data analysis and interpretation
Risk	Very low
Cost	INAF support to the data exploitation has a relatively small active cost.
Strategic Priority	Provide high support to the data exploitation

XMM-Newton	ESA cornerstone, X-ray observatory
Scientific impact	Very high, XMM is the X-ray observatory with the highest throughput and state of the art instrumentation. Together with the NASA Great Observatories, Keck and VLT it constitutes one of the major sources of top quality data
Time line	Launched in 1999 XMM extension is currently approved to 2008. It is however expected to provide data until mid of the next decade.
Italian Involvement	Large. X-ray mirrors have been realized by Media Lario and are based on OABrera technological developments. Electronics of the EPIC camera has been realized by Laben with participation of IASF-Bo and IASF-Mi. Calibration of EPIC filters has been obtained by OA-Pa.
Italian expertise	Very good, both on instrument calibration and data analysis and interpretation. Italy obtain about 8% of XMM time each year
Momentum	In full operation
Risk	Very low
Cost	Large investment for the hardware by ASI. Today the cost is small, support for data analysis and EPIC calibration
Strategic Priority	Provide high support to the data exploitation.

INTEGRAL	ESA Hard X and Gamma-ray satellite
Scientific impact	Medium-high. INTEGRAL is providing a new insight into the most violent and exotic objects of the Universe, and it is helping to understand processes such as the formation of new chemical elements and the physics of compact objects (binaries and isolated) in the Galactic bulge and in the Galactic Center.
Time line	On going since 2002, will produce data for several years
Italian Involvement	Large, PIship of the IBIS detector (IASF-Ro), co-I in all the other instruments, contribution to the science center.
Italian expertise	Very good, both in the hardware and in the data analysis and exploitation
Momentum	High. Although data analysis is complex, the effort of the groups involved, and in particular of Italian scientists, is helping INTEGRAL entering a phase of full data exploitation.
Risk	Low
Cost	ASI support for data analysis, INAF support to the community through labour and structures in IASF-MI, IASF-Bo, IASF-Roma.
Strategic Priority	Increase data exploitation.

SWIFT	NASA X-ray satellite with ASI and UK participations, the first of its kind primarly dedicated to the study of GRBs
Scientific impact	The Swift mission aims to investigate the origin, underlying nature and causes of gamma-ray bursts, to classify them and search for new types. The mission will also perform a sensitive survey of the sky in the hard x-ray band.
Time line	Operations on going, extension until 2009 is now being evaluated. Data exploitation will continue for several years, especially from the hard X-ray survey telescope.
Italian Involvement	Italy provides X-ray telescope, Malindi tracking station, and an important support to operations and XRT-SW development from ASDC. The INAF community that uses Swift is mostly concentrated in OABrera, IASF-Mi, OAR, IASF-Pa
Italian expertise	Very large
Momentum	Swift is in full operation and there is wide interest and experience on GRB. BAT data analysis is complex. Data exploitation from the whole community should be increased.
Risk	Low
Cost	Support to operations from ASI. Scientific exploitation needs a small investment.
Strategic Priority	Support the dissemination and exploitation of the data within the Italian community

VLBI	Noto, Medicina and SRT antennae are part of the European VLBI
Scientific impact	In the past decades the centimeter VLBI project has been one of the top projects of the Italian astrophysical community. To prepare the future, a quantitative and qualitative review of its use from the Italian community is needed.
Time line	Project on going since 80’.
Italian Involvement	Strong involvement with three dedicated radio telescopes and related operations and technical development
Italian expertise	Very good
Momentum	The field is very mature and most of the activity is moving toward higher frequencies.
Risk	Low for the knowledge and technical expertise on the development and operations of cm-wave VLBI. High for the limited mm expertise and for the uncertainties on the suitability of Italian sites for mm observations.
Cost	Maintenance and operation a few MEuros/year. Cost to upgrade the arrays for mmVLBI large (~10Meuro)
Strategic Priority	Keep alive and capitalize the experties within the community. Perform an accurate site testing campaign before allocating resources to upgrades to mm-VLBI. Top priority is the evaluation of the SRT site and –if positive- the development of mm receivers for SRT. Site evaluation and the possible upgrade of Medicina and Noto should be considered as a lower priority.

Italian Small observatories and infrastructures	They include: The network of Italian small telescopes (including the Asiago and Loiano telescopes, see Part 4 for a full list), REM, a robotic telescope based in La Silla, the Croce del Nord, a transit radio-interferometer located near Medicina (Bo), the Trieste solar radio telescope and SVIRCO, part of a mini-network of cosmic rays detectors.
Scientific impact	Some of these facilities have a respectable scientific production. SVIRCO impact is related to cosmic ray role in space weather and climate.
Time line	Most of these projects are on going since several years or decades
Italian Involvement	The Croce del Nord is property of the Bologna University, but operated and maintained by INAF since 2005. All other observatories are operated and maintained by INAF.
Italian expertise	Very good
Momentum	On some of them there quest of observing time exceeds the time available, others are underscheduled.
Risk	Low
Cost	Cost for operations is relatively low but large is the number of dedicated employees
Strategic Priority	Prepare a plan for the rationalization of these facilities in the national and international context. Consider decommissioning of some of the less efficient structures.

HESS & MAGIC	Cherenkov telescopes
Scientific impact	In its 1st 2 years of operation, H.E.S.S. has already had a major impact, including many firsts (first gamma ray image, first galactic plane survey etc.)
Time line	Both HESS and MAGIC are running and producing results. The likely lifetime of the experiments is ~ 10 years.
Italian Involvement	Italian involvement in HESS is low. INFN is deeply involved in MAGIC. INAF scientists are involved in data analysis and interpretation.
Italian expertise	Good, both on science and technology (INFN).
Momentum	Worldwide, and particularly European, momentum in this field is growing.
Risk	Low
Cost	INAF support to the data exploitation has a relatively small active cost
Strategic Priority	Cherenkov telescopes are producing high level science at a relatively low cost. A little investment in this field may guarantee a large pay back.

PIERRE AUGER OBSERVATORY	Cosmic ray telescopes
Scientific impact	Very high, potentially decisive to address the basic questions about the nature of Ultra High Energy Cosmic Rays.
Time line	Auger South has recently started to collect data, full scientific return will be available after few years of data acquisition.
Italian Involvement	Within INAF, it is low but highly competitive, at IFSI-TO, OA-FI, IFSI-PA. INFN is a major participant to the construction and operation of Auger
Italian expertise	Expertise in the data analysis is very high, expertise in data analysis and interpretation is quickly growing.
Momentum	High
Risk	Very low.
Cost	INAF support to the data exploitation would have a relatively small active cost
Strategic Priority	

Cassini/Huygens	NASA/ESA/ASI Mission to Saturn system
Scientific impact	Cassini and its Titan lander Huygens have made many fundamental discoveries about Saturn, its rings and moons.
Time line	On going. Will continue till 2010, but data exploitation will continue for several years
Italian Involvement	ASI has significantly contributed to both Cassini and Huygens, in particular with the PI of the HASI instrument and of the radar.
Italian expertise	Italian researchers are very active in the modeling of the formation and evolution of the entire Saturnian system.
Momentum	The mission is intensively producing data and the Italian community is very active.
Risk	Low.
Cost	ASI support to operations and data analysis. Contribution to science exploitation has a low cost.
Strategic Priority	Support data analysis and long term exploitation of the data.

Mars Express	ESA Remote Sensing Mars Exploration Project
Scientific Impact	Mars Express will help answer fundamental questions about the geology, atmosphere, surface and sub-surface environment, history of water and potential for life on Mars.
Time Line	Launch took place on June 2, 2003. The primary science mission started on December 25, 2003, and ended on November 30, 2005. The mission has now been extended until the end of October 2007.

Mars Express	ESA Remote Sensing Mars Exploration Project
Italian Involvement	Two of the seven remote sensing have been developed under Italian leadership, while two more see a significant Italian hardware contribution. In particular, the PI of MARSIS, the low-frequency radar for subsurface and ionosphere sounding is from University' La Sapienza; INAF-IFSI is the PI of PFS, the 1.2-45 micron spectrometer devoted to the study of the composition of the Martian atmosphere; INAF-IFSI is the supervisor of the visible channel of OMEGA, the visible and infrared mapping spectrometer and is the responsible of Italian contribution to ASPERA-3, which measures ions, electrons and energetic neutral atoms in the outer atmosphere.
Italian Expertise	Very large, see above.
Momentum	Good. Although past its primary science phase, it has still the potential for more discoveries.
Risk	Mission is ongoing, and there is no development risk associated.
Cost	ASI currently supports Italian members of science teams for science operations and data analysis.
Strategic Priority	Support data analysis and long term exploitation of the data.

Venus Express	ESA Remote Sensing Venus Exploration Project
Scientific Impact	Venus express will try to answer the following main questions: Why Venus entered in the dramatic runaway greenhouse effect, differently from Earth? What is the mechanism at the basis of its powerful atmospheric superotation with a period of about 4 days in contrast with an essentially no-rotating body? Is there active volcanism? How is the atmosphere-surface and atmosphere-interplanetary space interactions?
Time Line	Launched on November 9 2005, orbital insertion on April 11 2006, Nominal mission started June 2006 and will last until end 2007 or possibly end 2009 in case of extension
Italian Involvement	Two experiments are under Italian leadership (VIRTIS, IASF-INAF and PFS, IFSI-INAF) plus a significant participation in another experiment (ASPERA-4). About 65% of the data coming from the mission are generated by Italian instruments.
Italian Expertise	Very large, see above.
Momentum	Very high
Risk	Low risk, being the instrument fully operative
Cost	Supported by ASI. Additional support needed only for phase E-F, data analysis and support to operations and archive.
Strategic Priority	Conduct the mission to the end of the mission operations, data archive and data analysis.

DAWN	Mission to Ceres and Vesta
Scientific Impact	The goal of the mission is to determine what are the parent bodies of specific meteorites, such as HED; moreover it will give a new insight to the role of size and water in determining the evolution of the planets, providing a bridge between the exploration of the rocky inner solar system and the icy outer solar system.
Time Line	Mission will be launched on mid 2007. This mission is very timely. Its journey in time to understand the conditions at the formation of the solar system provides context for the understanding of the observation of extra solar-planetary systems. The combination of the data gathered by Rosetta mission on asteroids and comets and Dawn, on large minor planet will permit to formulate new theories on the evolution of minor bodies' population in the solar system.
Italian Involvement	High, The VIR spectrometer has Italian leadership (INAF-IFSI)
Italian Expertise	Modeling, data analysis, data compression, data standardization.
Momentum	High
Risk	Low
Cost	Low
Strategic Priority	Consolidation of scientific models on origin and formation of the Solar System.

ROSETTA	Rosetta is an ESA mission launched in 2004 which will rendezvous with the comet Churyumov-Gerasimenko in 2014.
Scientific impact	Comets are the most primitive objects in the solar system and therefore give a unique window into the materials and processes of its early phase.
Time line	The spacecraft is already providing scientific data waiting for its main scientific target in 2014.
Italian Involvement	It is very high, due to the Piship of many instruments.
Italian expertise	Very high, a long standing tradition on the study of comets and in the technological developments
Momentum	The time lag from now to the approach (2014) may be a problem.
Risk	There is a significant risk in landing on the comet's surface, however, the orbiter on its own will provide an important advancement in our understanding of comets
Cost	INAF support to the data exploitation has a relatively small active cost
Strategic Priority	Support the community in cometary science to be ready to use the data as soon as they will arrive.

SOHO	SOlar and Heliospheric Observatory, ESA/NASA Mission
Scientific Impact	Mission devoted to the global study of the Sun, from its interior to the outer heliosphere. Continuous observation of the Sun, due to spacecraft halo orbit around the solar terrestrial Lagrangian point L1. Collected data characterized by high temporal, spatial and spectral resolution.
Time Line	On going. Will continue till 2009, but data exploitation will continue for several years.
Italian Involvement	ASI has significantly contributed to UVCS, providing the spectrometer assembly of the instrument in close cooperation with several Italian solar scientists (Italian CoPI and seven CoI's) and some aerospace factories. Italy is also participating to the maintenance of one of the three European data archives, named SOLAR.
Italian Expertise	Italian researchers are very active in the study of the physical structure and dynamics of both closed and open magnetic structures in the outer solar atmosphere and extended corona. Significant contribution to the inversion and interpretation of helioseismic data collected from space.
Momentum	The mission is intensively producing data and the Italian community is highly active
Risk	Low
Cost	ASI support to operations and data analysis. Contribution to science exploitation has a low cost.
Strategic Priority	Support data analysis and interpretation, as well as long term exploitation of the data.

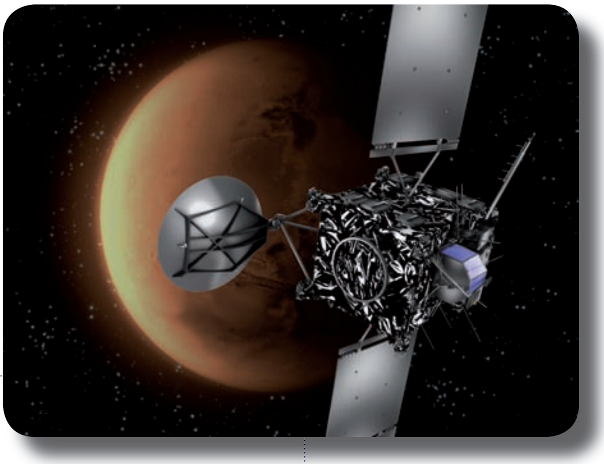


Fig. 3.2.1 Artist's impression of Rosetta at Mars (ESA)

3.2.2 Projects in preparation

CMB Sub-orbital experiments	
Scientific impact	Potentially very high: CMB polarisation, fine structure of temperature anisotropy
Time line	Heritage from previous programs. New ground-based and balloon observations will have time scales of few years.
Italian Involvement	Very high, but needs to be supported to maintain a leading role
Italian expertise	Very high
Momentum	Very high, if projects are properly coordinated with Planck results and timing, and if they are made to act as precursor of a (possible) future mission on CMB B-mode polarisation (technology development for CMB polarisation, polarized foreground exploration).
Risk	Low for ground based measurements, medium for balloon borne. It should be noted, however, that the long tradition and expertise decrease significantly the associated risk.
Cost	Investment of medium size.
Strategic Priority	Constrain B-modes; Develop key technologies; assess feasibility of satellite mission; study foreground contaminations

Planck	ESA satellite dedicated to CMB
Scientific impact	Planck is a cosmology science mission that will provide a map of the Cosmic Microwave Background (CMB) field at high angular resolution, covering at least 95% of the sky over a wide frequency range. The simultaneous mapping of the sky over a wide frequency range will permit separation of the cosmological background from foreground signals and allow investigation of the CMB at an unprecedented level. Planck will also produce a large data base of galactic and extragalactic diffuse emission and point sources for millimeter and microwave astrophysics.
Time line	Planck is to be launched in 2008. It will obtain data that are unique, even after the WMAP experiment.
Italian Involvement	One of the two instruments (LFI) has an Italian PI, and the relevant Data Center is located in Trieste. A large community in Italy is also working in preparation of the scientific data analysis.
Italian expertise	Very high, in all related fields: instrumental, data analysis, theory.
Momentum	Very high, due to large involvement and scientific expertise
Risk	Technical difficulties causing delays to the schedule and costs.
Cost	Scientific exploitation requires an investment of medium size.

Planck	ESA satellite dedicated to CMB
Strategic Priority	Provide maximum support to the scientific exploitation of the data within the Italian community, both during and after the proprietary period.

LBT	LBT is a 8.2m binocular telescope, located in Arizona
Scientific impact	LBT has some peculiar and unique capabilities: the prime focus focal stations (used for wide field imaging), the fully integrated adaptive optics system (through the adaptive secondary mirrors) and the planned interferometric foci.
Time line	It will likely be the last multi purpose telescope of the 10m class. Scientific operations are expected to start in 2007 with wide field imagers, and not earlier than 2008-9 with adaptive optics and nearIR image-spectrographs. The interferometric capabilities will be implemented later.
Italian Involvement	Italy owns 25% of the LBT corporation, and has contributed to the conception, development and construction of the telescope with the mechanical design and construction, the adaptive optics system and the prime focus cameras (LBC)
Italian expertise	Very high, both in the technical aspects and in the expected scientific exploitation of the data.
Momentum	Long standing financial uncertainties and delays have somewhat frustrated the expectations on the projects. LBC is on good track and several groups in Italy are ready to use its data
Risk	There are possible risks of further delay due to management and technical problems. Possible low impact of Italy due to the problematic management and lack of a detailed operations plan to date.
Cost	Management of the Italian participation, support to the operations and scientific exploitation require a large investment (>1-1.5Meuro/year) on top of the contribution for the operations (2 Meuro/year).
Strategic Priority	Focus on observational efficiency and reliability of the Telescope. Maximize scientific return. Develop a plan to improve management and prepare an adequate operations plan for the Italian fraction of the project.

LBC	2 wide field, prime focus cameras for LBT
Scientific impact	The extreme efficiency in the UV and I,Z bands, coupled with the large field of view, make LBC very competitive to address major scientific questions about the formation and evolution of galaxies, the stellar population of our and nearby galaxies and minor objects of the solar system. The amount of observing nights allocated to Italy may be very high in the first years.
Time line	Both cameras will be commissioned within the first months of 2007, and will be the first light instruments of LBT. The only competing instrument is Suprime Camera at Subaru, which is operational since 2004 but is allocated few nights per year.

LBC	2 wide field, prime focus cameras for LBT
Italian Involvement	Both cameras have been entirely built in Italy (OA-RM, OA-FI, OA-PD, OA-TS). Scientific software is also being prepared in Italy (OA-RM). Italian members participate
Italian expertise	Italian astronomers have an excellent record for the execution of galactic and extragalactic surveys.
Momentum	LBC is on good track and several groups in Italy can immediately use its data
Risk	Further delay due to management and technical problems. Possible low impact of Italy on the management issues.
Cost	Scientific exploitation of the data and support to the scientific data center requires a medium-size investment.
Strategic Priority	Focus on the execution of large surveys, within a large Italian collaboration. Support the operational aspects to maximize the efficiency of observations. Increase the Italian involvement in the management of the observatory

VST	VLT Survey Telescope: a 2.5 telescope, to be located at Paranal, dedicated to surveys in the optical domain. The imaging camera Omegacam has a FoV of 1 square degree
Scientific impact	Potentially very important to study the large scale distribution of galaxies at low and intermediate redshifts and the stellar population of our and nearby galaxies.
Time line	The current schedule still depends on the final delivery and commissioning of the mechanical structure, and may suffer from interference from the commissioning of VISTA. Operations are not expected to start before mid-2007
Italian Involvement	Very high, since Italy has led the construction of the telescope and has participated to the construction of the OmegaCam camera.
Italian expertise	Italy has a very good experience in galactic and extragalactic wide field surveys
Momentum	High, but suffers from strong international competing projects
Risk	Further delay would decrease the scientific impact of the data. The commitment of ESO to manage the telescope after commissioning, and the high quality of the Paranal site should guarantee reliable operations. Scientific plans should be revised and upgraded fully involving the Italian community.
Cost	The future cost for the Italian contribution must be of average amount (200-300kE/year) for the management of the data processing facilities.
Strategic Priority	Deliver the instrument as soon as possible. Use the data in a competitive and timely framework.

NIR Interferometry	VLTI, LBT Linc-Nirvana
Scientific impact	VLTI will reach resolutions of ~10mas but will not produce, at least in the near future, real images. Linc-Nirvana, on the other hand, will reach resolutions al least 3 times worse than VLTI, but it will allow direct imaging.
Time line	VLTI is already operating at the VLT and a call for second generation instrument has been issued in 2006.
Italian Involvement	Italian astronomers are involved in AMBER and in the proposals for second generation VLBI instruments. Deep involvement in Linc-Nirvana
Italian expertise	High
Momentum	Medium
Risk	The completion of Linc-Nirvana and its full exploitation require the solution of several technological problems. Scientific programs to fully exploit the resolution that Linc-Nirvana will provide still need to be consolidated. The VLTI full exploitation appears limited to a number of well-focused astrophysical problems. Italian led programs on VLTI represent only a small minority of the total, while most of the programs are carried out by German and French scientists, see Part 4.
Cost	Linc-Nirvana a few MEuro. Smaller investments may be necessary to participate to 2nd generation VLTI project. Support to increase the today small interferometry community should also be foreseen.
Strategic Priority	Complete Linc-Nirvana. A spectroscopic mode would greatly enhance its scientific output. Participate in the development of 2nd generation VLTI instrumentation.

Herschel	The Herschel Space Observatory will be the first space observatory covering the full far infrared and sub-millimeter waveband (60-700 micron
Scientific impact	Herschel will be able to observe dust obscured and cold objects that are invisible to other telescopes and discover how the first galaxies formed.
Time line	It will be launched in 2008, together with Planck.
Italian Involvement	Italy has contributed to the development of the Digital Processing Units and of the on-board software of the three instruments, to the PACS calibration to the HIFI WBS back hand as well as to the Instrument Control Centers of all tree instruments. Italy has a very relevant impact in the galactic programs, leading three GT key programs and one Large Open Time Key Project for the survey of the Galactic plane. The involvement in the extragalactic programs appears to have a lower impact than the Galactic programs.
Italian expertise	There are several groups in Italy that are very active in IR astronomy, both for star—forming regions and for high redshift galaxies and AGNs.
Momentum	Activities are swiftly proceeding throughout Europe, with support also to data processing.

Herschel	The Herschel Space Observatory will be the first space observatory covering the full far infrared and sub-millimeter waveband (60-700 micron
Risk	Technical difficulties are causing delays to the schedule and costs.
Cost	Full scientific exploitation of the data requires an investment of medium size.
Strategic Priority	Increase the support to Italian groups that participate to the preparatory phase, with particular emphasis on those leading large GT and Open Time key programs.

GAIA	Gaia is an ESA cornerstone mission, which aims to create the largest and most precise three dimensional map of our Galaxy
Scientific impact	Gaia will be a milestone in our understanding of early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way Galaxy. It will also provide breakthrough data on asteroids and minor bodies of the solar system.
Time line	Gaia is expected to be launched by 2011-2012.
Italian Involvement	Gaia is fully funded and built by ESA. Italy may have a role in the data analysis process, which is a very challenging task.
Italian expertise	Italy has an excellent track in Galactic astronomy, and in particular a wide experience in astrometry. Activity is planned in OA-TO, OA-BO, OA-RM, OA-CT.
Momentum	The project is quickly acquiring momentum, after the final approval by ESA. The management of the data acquisition process is swiftly starting.
Risk	Possible delays due to complexity of the telescope. Data reduction may be harder than expected
Cost	Scientific exploitation and participation to the data handling consortium require an investment of small-medium size for the next 10-15 years, at last.
Strategic Priority	Absolutely necessary to support the Italian participation to the scientific programs and to the data handling consortium

JWST	The James Webb Space Telescope is an orbiting infrared observatory that will succeed the currently operating Hubble Space Telescope.
Scientific impact	The JWST will be the world leading infrared observatory for the next decade. JWST will be able to examine the first light in the universe and look at how galaxies are formed, the birth of stars and search for protoplanetary systems.
Time line	JWST is expected to be launched in 2013.
Italian Involvement	It is low, with possible chances to increase. Italian institutions do not participate to the hardware development. Few Italian astronomers are involved in the science team of the MIRI spectrograph.

JWST	The James Webb Space Telescope is an orbiting infrared observatory that will succeed the currently operating Hubble Space Telescope.
Italian expertise	The observational expertise at these wavelengths is of excellent quality, but not very diffused. The science addressed by JWST is so important and broad that many Italian astronomers are potentially interested.
Momentum	JWST is the first priority of the US astrophysical program. It has undergone preliminary analysis and technical design studies and is currently in the definition phase. The procurement process of subsystems is well underway. The whole mission is so challenging and expensive that it is still subject to some uncertainty.
Risk	Technological development is necessary, and costs may be much higher than affordable.
Cost	The participation to the scientific exploitation of JWST will have a small—size cost.
Strategic Priority	It is important to support the small Italian groups involved, or any other possible initiative. Support the possibility of being involved in the first light observations or large surveys.

SRT	Sardinia Radio Telescope, 64m antenna
Scientific impact	The telescope may have a significant impact in some key areas such as the development of high frequency single dish and VLBI observations in Italy, assuming that the site and system will be capable of supporting such modes
Time line	Under construction
Italian Involvement	Very high. The project is run by the INAF-Osservatorio Astronomico di Cagliari with the support of other INAF institutes.
Italian expertise	There is a strong expertise in Italy in the various technological aspects of the project, from the antenna design to the receiver and backend as well as the VLBI techniques. There is also a solid expertise in the use of single dish radio telescopes, connected interferometers and VLBI.
Momentum	High. The project is in the critical construction phase, the antenna structure is being erected.
Risk	The most compelling science is expected to be achieved using the high frequency capabilities. There are still uncertainties in the site characterization at these frequencies and the experience in developing high frequency VLBI in Italy is modest.
Cost	High
Strategic Priority	In this long range plan we do not discuss the completion of the telescope itself. It is a priority to ensure the high frequency capabilities of the antenna and its integration in the European VLBI network, provided that the site will allow to efficiently support these type of observations.

LOFAR	Network of low frequency radio telescopes
Scientific impact	Very high. The detection of redshifted HI emission/absorption from the reionization epoch is one of the main scientific goals of the next decade.
Time line	Under construction.
Italian Involvement	Small at the moment. However, plans for the reconversion of the Croce del Nord to one LOFAR station are being considered
Italian expertise	High
Momentum	The scientific goal of the instrument is being reconsidered, mostly to be used as testbed for SKA and to participate in the LOFAR project.
Risk	LOFAR technologies are still challenging, but potentially very important from the scientific point of view
Cost	Operative costs are of medium size. Reconversion to LOFAR technologies of the Croce del Nord is partly covered by external funding (EC and UniBo)
Strategic Priority	Inclusion in the LOFAR network is a very rewarding long term goal

ALMA	ALMA will be the largest and most performing sub-mm interferometer ever built
Scientific impact	ALMA will be the foremost instrument for studying the cool universe, including the relic radiation of the Big Bang, and the molecular gas and dust, the earliest and most distant galaxies and the epoch of the first light in the Universe. It will also look deep into the dust-obscured regions where stars are born to examine the details of star and planet formation. In addition to these two main science drivers the array will make major contributions to many fields of astronomical research.
Time line	The project schedule aims for the first early science observations in 2009/10 and to complete the construction of the whole array by 2012.
Italian Involvement	Industrial involvement in the construction is high due to the European Antenna contract being awarded to a French-Italian-German consortium. A few Italian institutes are involved in the development of the software system and the construction of some components of the correlator.
Italian expertise	Very high in radio interferometry, but the community of users of mm facilities is still small due to the lack of leading mm facilities in the past.
Momentum	The recent signature of the full contracts for the procurement of the antennas and the decision of ESO and NSF to support the full budget for construction and operations marked a non-return point for the project. In Italy the preparation activity is still rather low.
Risk	Management and schedule concerns are small, essentially because of the ESO involvement. A revision of costs has been completed in 2005 and the cost of the revised project should be well constrained now that the most expensive contracts have been signed.

ALMA	ALMA will be the largest and most performing sub-mm interferometer ever built
Cost	Support an European ARC node in Italy and the development of a competitive scientific community requires a medium-size investment.
Strategic Priority	Actively invest in preparing the community to ALMA, in particular through training of young researchers and the use of the APEX and IRAM telescopes. Support an Italian node of the European ALMA Regional Center

GLAST	GLAST is Gamma Ray Large Area Satellite, designed for making observations of celestial gamma-ray sources in the energy band extending from 10 MeV to more than 100 GeV.
Scientific impact	It will lead to major breakthroughs in our understanding of high energy phenomena in the universe
Time line	GLAST will be launched in late 2006-early2007.
Italian Involvement	INFN has done a significant contribution to the mission by building the tracker modules and other hardware. ASDC is deeply involved in the development of software
Italian expertise	High, both on science and technology (INFN in particular).
Momentum	GLAST has an excellent track, and a very active preparation program.
Risk	Low, apart from obvious risks of space missions. Low angular resolution at low energies, where sources emit most of their photons, coupled with large area, may hamper scientific exploitation of low energy data.
Cost	This is the last NASA Great Observatory. ASI/INFN investment is large (several MEuro). INAF investment is necessary only to support the groups actively involved in the scientific exploitation of the mission.
Strategic Priority	It is mandatory to strengthen the involvement of astronomical community.

AGILE	Italian small-size satellite for hard-X and gamma ray astronomy
Scientific impact	High. Gamma-ray imaging with a large Field-of-View. Simultaneous broad-band spectral information 15-45 keV, 30. Microsecond timing. Efficient transient detection and alerts
Time line	Launch by spring 2007
Italian Involvement	Total
Italian expertise	High. Combines expertise of particle physics and High Energy Astrophysics.
Momentum	High.
Risk	Use of low cost technologies. Potential spoiling on some scientific targets by the competition of larger GLAST.

AGILE	Italian small-size satellite for hard-X and gamma ray astronomy
Cost	Total cost for ASI is 50Meuro. Direct contribution by INAF/INFN institutes also of deliverable items with high co-financing in terms of man-power and structures.
Strategic Priority	The full exploitation of the mission requires that the period before the launch of GLAST be used at best. To this purpose it is essential that procedures for data analysis and calibration are developed and tested in advance. The quick data analysis and interpretation is the key for the success of the mission, as well as full exploitation of the X-ray monitor, that it is not present on board of GLAST.

MAGIC2, HESS2	Cherenkov telescopes
Scientific impact	Based on the results that HESS and MAGIC are collecting, the extension to HESS2 and MAGIC2 appear to be a natural step ahead toward improving observational capabilities.
Time line	
Italian Involvement	Mainly limited to INFN, which is one of the major partners of MAGIC. Further partners are being selected for both HESS2 and MAGIC2
Italian expertise	Scientific for both telescopes, also hardware in the case of MAGIC and its extension
Momentum	Worldwide, and particularly European, momentum in this field is growing.
Risk	Low
Cost	
Strategic Priority	Investigate the possibility of direct INAF participation in one of the two projects. Get support in order to enhance the role of the astronomical community in this growing field, also in the perspective of future even more ambitious projects of a similar type.

CTA	Cherenkov Telescope Array
Scientific impact	It would represent a tremendous improvement in our ability to explore the universe in high energy Gamma Rays, leading to an increase by a factor about 30 in the number of sources detected. The threshold for detection is planned to be lowered to about 10 GeV thereby allowing for a substantial overlap with the range of sensitivity of the GLAST telescope.
Time line	Not well defined yet, but it is desirable to have the experiment operating in partial temporal overlap with GLAST.
Italian Involvement	Substantial and still dynamically discussed, both on the scientific side and on the construction side, possibly through the construction of the mirrors.
Italian expertise	Both scientific and in the construction of mirrors

CTA	Cherenkov Telescope Array
Momentum	The situation of gamma ray astronomy in the TeV energy range has deeply changed in the last few years with the operation of the HESS and MAGIC Cherenkov telescopes. The amount of progress made in the field and the general trend is impressive and appears to largely justify future efforts in the direction of making better, more sensitive and lower threshold Cherenkov gamma ray telescopes.
Risk	All partners appear credible and the scientific background extremely solid. The technique has been proven effective by several previous Cherenkov telescopes.
Cost	150 MEuro (<20% possibly from EU. 80% from national funding agencies throughout Europe)
Strategic Priority	Cherenkov telescopes may provide high scientific return with a relatively small investment.

KASKADE-GRANDE	Cosmic ray telescopes
Scientific impact	Very High. Potentially decisive to address the questions about the cosmic ray spectrum and composition in the interval 1016-1018 eV
Time line	KASCADE Grande is taking data since 2004. It will operate for 3-4 more years.
Italian Involvement	The Italian involvement is due to IFSI-TO and Torino University and is highly competitive.
Italian expertise	Very high
Momentum	High
Risk	Absent
Cost	The INAF support can be moderate. At present the INAF support comes from free research funds.
Strategic Priority	

BepiColombo	ESA-JAXA Mission composed by two satellites (MPO and MMO).
Scientific Impact	Mercury is one of the least observed bodies of the solar system. This project wants to address the great scientific interest on Mercury of planetologists, plasma physicists and fundamental physics theoreticians. Such an interdisciplinary effort will be conducted in a time frame of more than 15 years from now.
Time Line	Payload selected, Industrial ITT released, Flight Units due by 2010, launch in 2013, orbit insertion in 2019.

BepiColombo	ESA-JAXA Mission composed by two satellites (MPO and MMO).
Italian Involvement	An unprecedented number of Italian PIs and CoPIs will lead several crucial instruments. On board the MPO satellite, the INAF scientists will lead the three units (VHI, IASF; HRIC, OANA, STC, OAPD) of the Camera Suite Package SYMBIO-SYS (ASI), the Spring Accelerometer ISA (IFSI) as element of the Radio Science Experiment MORE (Uni. RM1), and the neutral and ion particle package SERENA (IFSI). Other participations are related to the UV spectrometer PHEBUS, to the X ray instruments MIXS and SIXS, and to the particle instrument on board the MMO satellite.
Italian Expertise	Very large industrial and laboratory know-how, top-priority scientific capability in carrying necessary research programs, expertise in leading the payload-related programmatic aspects.
Momentum	High, due to the wide Italian participation and international partnerships
Risk	Medium.
Cost	ASI will support hardware development, operations and data analysis. Contribution to science exploitation has a low cost.
Strategic Priority	BepiColombo is an ESA cornerstone and hence its preparation will need a careful and detailed support at highest priority level. Particular care will be devoted to the interpretation of the very preliminary data from the pioneer US mission MESSENGER

Solar B	JAXA/NASA mission with substantial contribution from PPARC
Scientific impact	Entirely devoted to solar observation in Optical, UV, X-ray, and studying photospheric magnetic fields plus the structure and dynamics of various atmospheric levels, from photosphere to corona.
Time line	To be launched at the end of September 2006. Presently on schedule.
Italian Involvement	Moderate: Calibration of parts of XRT, the X-ray telescope, plus planned extensive participation in data analysis, interpretation and theoretical work related to each of the three major instruments (Solar Optical Telescope, Euv Imaging Spectrometer and X-Ray Telescope) and to the atmospheric "layers" they observe: photosphere, chromosphere with transition region and corona
Italian expertise	Quite good and based on past experience of solar space missions
Momentum	Will take the lead from the SOHO mission in the coming years
Risk	The satellite is going to be launched in a few months and most of the cost, supported entirely by ASI, will go into data analysis and interpretation
Cost	Low. Support for data collection, analysis and related studies.

Solar B	JAXA/NASA mission with substantial contribution from PPARC
Strategic Priority	Support data collection, analysis and related studies. The mission will overlap with SOHO and then it will take the lead.

3.2.3 Future projects

B-mode satellite	Possible future satellite to make very deep all-sky CMB polarization measurement.
Scientific impact	Potentially huge if B-mode polarization signature of primordial gravitational waves from inflation will be identified. This would be a direct measure of the energy scale of inflation and potentially the nature of the inflation
Time line	NASA currently funding concept studies and ESA may possibly make AO for phase-A studies for future missions in 2006. ASI involvement is still under evaluation
Italian Involvement	To be determined, but given the strengths in both experimental and theoretical CMB, Italian astronomers could potentially be major players.
Italian expertise	Italy currently has a very high profile in CMB research with Boomerang, Planck.
Momentum	High, would follow on from Planck and Balloon experiments.
Risk	NASA and/ or ESA may decide priorities for science missions lie elsewhere, resulting in slippage in time frame. Primary science could potentially be scooped by earlier ground and balloon experiments (but not at largest angular scales). Significant risk of null result.
Cost	The cost for the Italian contribution must be very high (likely beyond 20 Meuros) to take a significant role.
Strategic Priority	Potentially extremely high, already identified in NASA and ESA long-range planning for 2015-25 timeframe. Priority will depend on results from Planck and of next generation of ground-based experiments.

ELT	A new generation of optical/infrared ground-based telescopes of between 30 and 60 metres in diameter
Scientific impact	Potentially, ELT would revolutionize ground-based astronomy. Although its eventual design would determine overall capability, milli-arc second resolution would be the goal.
Time line	Design studies have started in early 2000s. European plans are now converging on a 30-40m class telescope.
Italian Involvement	Italy is significantly contributing to the technological and scientific definition of the project.
Italian expertise	Very high in key sectors, like adaptive optics.
Momentum	The technical studies are proceeding at a fast pace, also to prepare for FP7 applications. Science cases are being assembled with a large involvement of all European communities

ELT	A new generation of optical/infrared ground-based telescopes of between 30 and 60 metres in diameter
Risk	Technologically challenging. Delay due to fund paucity or to overambitious design might lead Europe to be scooped by US competitors.
Cost	The estimated cost of a European ELT is currently approximately 750M Euros.
Strategic Priority	A key sector where it is mandatory for Italy to have a leading role, both technologically and scientifically. Given the technological challenge and the large investment the management of the project is essential. Preferences should be given enterprises with credible and proven partners

Wide Field Imaging	Space borne missions such as SNAP/JDEM and DUNE, and ground based instrumentation like a 3sqdeg imager
Scientific impact	Very high in all fields of astrophysics
Time line	It can be of a few years for a ground based instrument like the 3sqdeg imager. Mid/end of next decade for a dedicated space mission. NASA will select the first mission of the BE program in 2009.
Italian Involvement	The 3sqdeg imager is an Italian project. There is a small involvement in the SNAP/JDEM project. The involvement in the DUNE project must be defined yet.
Italian expertise	Good for ground based instrumentation
Momentum	Medium
Risk	Medium
Cost	A few MEuro for the 3sqdeg imager.
Strategic Priority	The development of the 3sqdeg imager could be fast and beat the competition of a telescopes fully dedicated to wide field imaging like LSST.

WSO	WSO is a long-standing, Russian-led project to implement a space telescope dedicated to UV high-resolution spectroscopy and diffraction limit imaging.
Scientific impact	The instrument is conceived for providing access to the optical/UV domain, otherwise inaccessible after HST, with consolidated technology and relatively low cost. The scientific interest is certainly vast.
Time line	Present schedule foresee the launch in 2011
Italian Involvement	The involvement of the Italian community might be important to maintain and develop scientific and technological expertise in this wavelength domain.
Italian expertise	Very good on the scientific point of view; interesting opportunities exist on the technological side.
Momentum	The project has received new momentum thanks to its insertion in the Russian Federal Space Program and to a renewed interest of ASI, in Italy.

WSO	WSO is a long-standing, Russian-led project to implement a space telescope dedicated to UV high-resolution spectroscopy and diffraction limit imaging.
Risk	The management of the project, its schedule and the current international support are not fully satisfactory at the moment.
Cost	Present estimate of the Italian investment is of the order of 10 ME. INAF direct contribution might be relatively small-sized.
Strategic Priority	Before considerable investments both in terms of manpower and funds are approved, a number of critical issues should be clarified, such as the Italian contribution and the consortium definition, a detailed management plan and schedule, and the scientific return for the Italian community.

SKA	The SKA is the next generation international radio telescope, designed to have a collecting area of 1 million square meters
Scientific impact	Very high in a large number of astrophysical themes, from cosmology to the formation of planetary systems to tests of fundamental physics
Time line	Construction is currently foreseen to start in the coming decade
Italian Involvement	High. INAF is involved in the definition of the scientific requirements, in developing and testing some of the new technological concepts that will be employed by the instrument. The INAF-IRA is participating in a number of R&D programs which include the refurbishment of the Croce del Nord as a SKA technology testbed.
Italian expertise	High.
Momentum	High.
Risk	There are limited technological risks connected with the new technological developments. The project still needs to identify a funding scheme for its ambitious plans. INAF-IRA takes part to the EU project SKADS, to use the Croce del Nord as a test-bed for SKA technologies.
Cost	High
Strategic Priority	This is the equivalent of ELT for radio astronomy. Participation in this project is mandatory.

Hard X-ray imaging	Simbol-X or similar concept missions
Scientific impact	Open a new window increasing the sensitivity for imaging observations above 10 keV by 3 orders of magnitude with respect to BeppoSAX, INTEGRAL, SWIFT and ASTROE2. This could be the only major X-ray mission to fly within the next decade after Chandra and XMM.
Time line	A joint Italy-France Phase A study for Simbol-X is starting in 2006.

Hard X-ray imaging	Simbol-X or similar concept missions
Italian Involvement	ASI should pay for half of the Simbol-X mission and be responsible for one of the two spacecrafts. OABrera is responsible for the developments of the X-ray optics, while several other INAF observatories and institutes are involved in the support to the phase-A study and in the definition of the scientific requirements.
Italian expertise	Large experience in producing light-weight optics with multilayer coatings capable to produce sharp imaging in the 1-80 keV band. Pioneer both core scientific cases: census of accreting black holes and the sources making the Cosmic X-ray background and non thermal emission and acceleration in cosmic sources.
Momentum	Phase A study just started in France, Pre-Phase study started in Italy
Risk	Medium.
Cost	Cost to completion is about 100MEuro for ASI. Pre-phase A study cost is 200kEuro. For INAF the main cost is related to salary and support of staff involved in the phase A study (about 50 scientists).
Strategic Priority	Provide support for scientists.

High throughput X-ray observatory	The successor of Chandra and XMM-Newton as multi-purpose X-ray observatory For the X-ray community this is the analogous of ELT and SKA.
Scientific impact	Very high for all field from accreting black holes and neutron stars to diffuse plasmas, from the study of the evolving Universe to physics in extreme condition
Time line	Within the framework of ESA CV program. Launch not before the end of next decade
Italian Involvement	At the moment marginal. It must be increased.
Italian expertise	Large experience in producing light-weight mirrors, cryogenic detectors, polarimeters
Momentum	Waiting for ESA CV announcement of opportunity
Risk	Difficult to realize extremely large area (10 square meters) mirrors with good imaging quality and weight ~1/100 of XMM mirrors
Cost	Relatively small for INAF. Support the activities for the preparation of the ESA CV proposal.
Strategic Priority	This is the equivalent of ELT and SKA for X-ray astronomy. Participation is mandatory, provided that the design can fulfill highly demanding requirements and that adequate scientific and technologic return for the Italian community is guaranteed.

Small Mission of X-ray polarimetry	A pathfinder of X-ray polarimetry with respect to the High Throughput X-ray Observatory
Scientific impact	Very High Open a new window increasing the sensitivity time/energy/space resolved polarimetry by 3 orders of magnitude with respect to OSO-8. Probes Deep Physics of X-ray Sources and provides tools to test QED, GR and QG.
Time line	Could be implemented as a part of Chinese Mission HXMT (5years) or be proposed as a national small mission (TBD)
Italian Involvement	Large or total
Italian expertise	Very High, based on a detector completely ideated and developed in Italy and on X-ray optics also developed in Italy
Momentum	Depends on the change of HXMT design or on the issue of a National AOO
Risk	Technical feasibility robust. Astrophysical throughput potentially very high but without any previous data.
Cost	Relatively low for INAF
Strategic Priority	Small/medium size missions can provide breakthroughs in particular areas. X-ray polarimetry is an example.

X-ray mission dedicated to the physics and evolution of LLS and to cosmology with GRBs	Both X-ray wide field imaging and high resolution spectroscopy can be used to investigate the physics of ICM and IGM to carry out cosmological studies with GRBs
Scientific impact	High. The detailed study of the ICM and IGM probably requires a dedicated mission. Wide field imaging with a low background instrument can probe the never observed viral radius regions of galaxy cluster ICM and high resolution spectroscopy can probe the X-ray forest due to warm gas in the filaments and outskirts of galaxy clusters.
Time line	Proposals for a mission dedicated to these themes are planned for the ESA CV program and the next NASA MIDEX program.
Italian Involvement	At the level of PIship for the ESA CV proposal (ESTREMO-WFXT), at the level of important Coship for NASA MIDEX proposals. Technological studies supported by ASI are ongoing
Italian expertise	High. X-ray light-weight mirrors, X-ray all sky monitors, cryogenic detectors
Momentum	Waiting for ESA CV and NASA MIDEX announcements of opportunities
Risk	High
Cost	Relatively low for INAF. Support the activities for the preparation of the ESA CV proposal.

X-ray mission dedicated to the physics and evolution of LLS and to cosmology with GRBs	Both X-ray wide field imaging and high resolution spectroscopy can be used to investigate the physics of ICM and IGM to carry out cosmological studies with GRBs
Strategic Priority	Small/medium size missions can provide breakthroughs in particular areas. INAF should support the activities for the preparation of the ESA CV proposal.

Soft gamma-ray observatory	The successor of INTEGRAL, adopting new technologies like the Laue lenses. The only -ray imager foreseen in the next decade
Scientific impact	Very high. First high throughput collecting optics in soft gamma-rays. Factor of 50 in sensitivity at 100-200 keV. Deep study of single celestial object from 50 to 2000 keV
Time line	In the framework of the ESA CV program. Pre-phase a study for Lau lens and formation flight in parallel with other Mission (e.g. Simbol X)
Italian Involvement	Large for both optics and detectors. Technological studies supported by ASI are ongoing (200+200 KE)
Italian expertise	Strong heritage from INTEGRAL (detectors) and advanced development with Laue lenses and high energy concentrators(up to 200keV).
Momentum	waiting for ESA CV announcement of opportunity
Risk	Medium
Cost	ASI involvement, in case of selection, of ~60 ME, main cost being on ESA side. For INAF the main cost is related to salary of staff involved in the phase A study (about 30 scientists). Support for these scientists should also be provided
Strategic Priority	INAF should support the activities for the preparation of the ESA CV proposal.

Solar Orbiter	ESA Mission (international cooperation prospects under investigation).
Scientific Impact	Ultra high spatial resolution due to the proximity to the Sun (≤0.3 AU). Close up/co-rotation (linking Sun and inner heliosphere). High latitude (40° max) above the equatorial plane (polar processes, fast wind source regions and dynamo mechanisms; observations of CMEs extension in the equatorial plane). Out of Sun-Earth line (multipoint observations of Earth directed ejecta). Combination of remote sensing and in-situ science.
Time Line	Call for letters of intent to provide instrumentation (June 2006). AO release (2007). Launch (2015). Start of Science Phase (2018).

Solar Orbiter	ESA Mission (international cooperation prospects under investigation).
Italian Involvement	The solar and heliospheric community has been considerably involved since the proposal phase and assessment study, and intends to provide a significant contribution to a EUV spectrometer, a UV coronagraph/imager/polarimeter (Italian PI), and an in-situ instrument to detect neutral atoms. Furthermore, in the in-situ solar wind package a Neutral Solar Wind Detector will be proposed (Italian PI), and a significant contribution to the ion particle detector is also foreseen.
Italian Expertise	The scientific community is in a leading position for what concerns both theoretical and numerical studies and for its expertise in space instrumentation concerning UV, XUV, X spectroscopy and imaging, UV and VL coronography, UV and VL coronal spectro-polarimetry, energetic and neutral particle instrumentation design & manufacturing
Momentum	Intense preparatory activity
Risk	Possible mission descoping, if a major cost reduction is not achieved.
Cost	ASI will support hardware development, operations and data analysis. Contribution to science exploitation has a low cost.
Strategic Priority	INAF should support the groups interested in competing for the development of the instrumentation.

SCORE-HERSCHEL	Prototype of the coronagraph for the Solar Orbiter
Scientific Impact	First measurement of the abundance and the outflow velocity of the He component of the solar wind in the outer corona.
Time Line	To be launched in a suborbital flight in early 2007.
Italian Involvement	PI of the instrument SCORE, designed to observe the outer corona, in a sub-orbital flight program (HERSCHEL) approved by NASA and led by the Naval Research Laboratory, US, institution which is responsible for the accompanying instrument EIT, design to obtain
Italian Expertise	Design and development of the first multiwavelength coronagraph which will image for the first time the solar corona in the Helium emission.
Momentum	Crucial for the development of the instrumentation for participating in the future ILWS space missions.
Risk	No specific risk foreseen, except the risk involved in any suborbital rocket flight.
Cost	Low.
Strategic Priority	This is mission is to fly a prototype of the coronagraph of Solar Orbiter, INAF should support the groups that are developing the instrumentation.

ATST/EST	Large Aperture Solar Telescopes (Advanced Technology Solar Telescope – European Solar Telescope)
Scientific Impact	High: The proposed Large Aperture Solar Telescopes (4 m. class) will have broad impact on astronomy, plasma physics, and solar-terrestrial relations by resolving, in space and time, fundamental astrophysical processes on the Sun. These new generation solar telescopes will attack critical aspects of the non-linear dynamical processes governing the highly conducting turbulent solar plasma, coronal heating, solar variability, and crucial in the Sun-Earth connection.
Time Line	ATST first light is expected by 2012. EST first light depends on the optical design (but likely around 2015).
Italian Involvement	ATST: possible participation in the development of a secondary adaptive mirror and a large field 2-D monochromator. EST: to be discussed in a European perspective.
Italian Expertise	High: Italian community will take part in building instruments, observations and data analysis.
Momentum	High: a new class of large aperture solar telescopes is fundamental to address, in the next decade, the open questions in solar science.
Risk	Low
Cost	A medium size investment (a few Meuro) is necessary, depending on the participation level and on the project.
Strategic Priority	High: the involvement of the Italian solar community in a Large Aperture Solar Telescope project is desirable.

EXO-MARS	A roving vehicle on Mars surface with an exobiology payload, possibly also an orbiter
Scientific impact	Possibility to find traces of elementary forms of life on Mars
Time line	Launch in 2011 (2013 if there will be also the orbiter)
Italian Involvement	High (a number of instruments and PIs)
Italian expertise	Long-time involvement in other Mars missions
Momentum	Very high, the mission is approved and in Phase B
Risk	Low
Cost	Low for INAF
Strategic Priority	Support data analysis and long term exploitation of the data; Italy is the leading subscriber, through ASI, of this mission, that is part of the optional Exploration Program of ESA

Moon exploration	Italian participation in a large international collaboration to explore the Moon
Scientific impact	Potentially very high, depending on circumstances that are not known yet

Moon exploration	Italian participation in a large international collaboration to explore the Moon
Time line	2008 onwards
Italian Involvement	Tbd, potentially very high, depending on governmental and ASI decisions
Italian expertise	High (Italian planetology was born with post-Apollo lunar studies)
Momentum	Largely dependent on political decisions
Risk	Low
Cost	Low for INAF
Strategic Priority	Support the relevant community

Exploration of a NEO	Sample return from a primitive near-Earth asteroid, in the framework of ESA Cosmic Vision
Scientific impact	Analyze unprocessed material coming from the accretion zone of the terrestrial planets is fundamental to understand their accretion, and to establish a link between NEOs and meteorites
Time line	Cosmic Vision (2015-2025)
Italian Involvement	Very high
Italian expertise	Excellent
Momentum	Future mission; however, NEOs are important both scientifically and because the prediction/mitigation of their collisions with the Earth is a civil protection issue having a great importance for the society at large
Risk	Technology to be developed for the sampling device
Cost	Same as for other Cosmic Vision missions
Strategic Priority	Support the relevant community in the preparation of the proposal.

Exploration of the Jovian system	Jupiter Exploration Program (first, multiple micro-spacecrafts to explore Europa, then explore the hidden Jovian atmosphere with Jupiter Probes and the surface of Europa with a Europa Lander), in the framework of ESA Cosmic Vision
Scientific impact	Formation and evolution of Jupiter and its satellites; possibility of subsurface liquid water (and life) on Europa
Time line	Cosmic Vision (2015-2025)
Italian Involvement	Potentially very high
Italian expertise	Long experience in modelization and long-time involvement in NASA missions to giant planets
Momentum	Future mission, momentum still to consolidate
Risk	Europe has no RTG (Radioisotope Thermal Generator)

Exploration of the Jovian system	Jupiter Exploration Program (first, multiple micro-spacecrafts to explore Europa, then explore the hidden Jovian atmosphere with Jupiter Probes and the surface of Europa with a Europa Lander), in the framework of ESA Cosmic Vision
Cost	Same as for other Cosmic Vision missions
Strategic Priority	Support the relevant community in the preparation of the proposal.

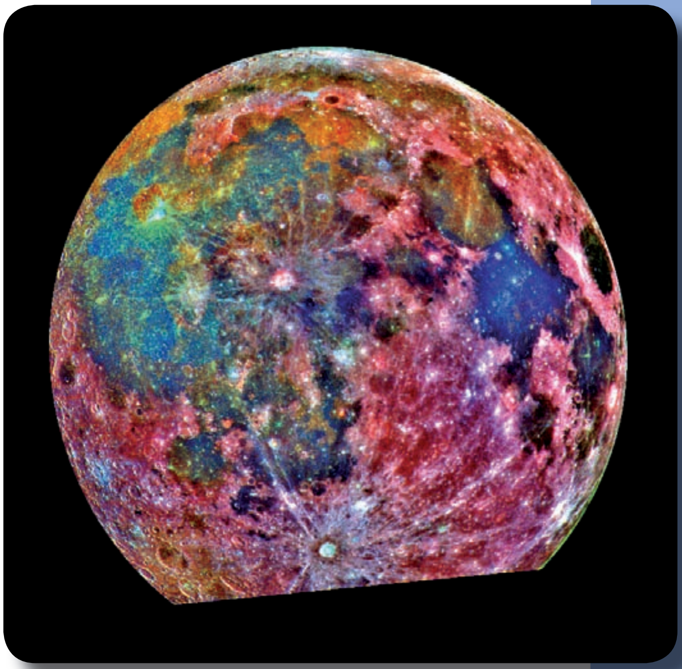


Fig. 3.2.2 Moon - False Color Mosaic - GALILEO Project (JPL)

PART 4: INAF TODAY

Introduction

This part includes a brief description of INAF, its Mission, Organization, Budget, Structures and Personnel. A concise list of the main scientific activities carried out by INAF scientists is presented, along with a summary of its scientific production. This part also includes a short discussion on Italian access to major astrophysical international facilities, and on education.

4.1 Organization

INAF has four main governing bodies:
1. President
2. Administrative council
3. Scientific council
4. Auditors council

INAF is organized in two Departments:
1. Structure's Department
2. Project's Department

4.2 Research structures and personnel

The network of INAF research structures includes the following 19 Observatories and Institutes:

- Osservatorio Astrofisico di Arcetri, Firenze (OA-FI)
- Osservatorio Astronomico di Bologna (OA-BO)
- Osservatorio Astronomico di Brera, Milano (OA-MI)
- Osservatorio Astronomico di Cagliari (OA-CA)
- Osservatorio Astronomico di Capodimonte, Napoli (OA-NA)
- Osservatorio Astrofisico di Catania (OA-CT)
- Osservatorio Astronomico di Padova (OA-PD)
- Osservatorio Astronomico di Palermo "Giuseppe S. Vaiana" (OA-PA)
- Osservatorio Astronomico di Roma (OA-RM)
- Osservatorio Astronomico Collurania di Teramo (OA-TE)
- Osservatorio Astronomico di Torino (OA-TO)
- Osservatorio Astronomico di Trieste (OA-TS)
- Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna (IASF-BO)
- Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano (IASF-MI)
- Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo

(IASF-PA)
- Istituto di Astrofisica Spaziale e Fisica Cosmica di Roma (IASF-RM)
- Istituto di Fisica dello Spazio Interplanetario di Roma (IFSI-RM)
- Istituto di Fisica dello Spazio Interplanetario di Torino (IFSI-TO)
- Istituto di Radioastronomia di Bologna (IRA)

INAF staff includes 521 permanent researchers (summer 2006).

Astronomers and astrophysicists are present in many Universities. In particular astronomy departments are present in the Universities of Padova, Bologna, Roma La Sapienza, Firenze and Como-Insubria. Many other departments of Physics also have groups of research in astronomy.

Researchers with astrophysical background and interests are present in other institutes like INFN, CNR and ENEA. In particular, one of the sections of INFN is dedicated to Astroparticle Physics, which includes gamma-ray, cosmic ray, neutrino astrophysics and gravitational waves. The total number of researchers involved in these projects is ~150.

The total number of researchers of Universities and other institutes associated to INAF is 216, bringing the total number of permanent researchers working in Astronomy and Astrophysics (A&A) within INAF to 737.

The total number of researches with non-permanent positions is ~200, including Ph.D. students, post-docs, fellows, and contractors, bringing the total scientific staff to ~950 researchers. As a comparison, the number of A&A researchers in France is very similar, 950, while it is higher in Germany and UK, 1400 and 1500, respectively.

The other big national institute for fundamental physics (INFN) employs 587 researchers and 221 specialists in technology. It has about 1000 associated in the Universities and other institutes for a total of about 1800 permanent staff members. The total number of researchers and specialist in technology with non-permanent position is ~425, including 38 science oriented post docs, 32 technology oriented post docs, 35 science oriented and 46 technology oriented high level researchers, 93 other fellowships and 135 contracts (Piano Triennale INFN 2006-2008). At least 35 post docs are dedicated to foreign researchers.

The fraction of non-permanent positions with respect to staff members and associated is one fourth for INAF, very similar to that of INFN. However, a large fraction of INFN non-permanent positions is of high level, while the number of similar positions ("Ricercatori a tempo determinato") within INAF is very small. It should also be mentioned that INAF does not have a post doc program for foreign researchers.
The fraction of non-permanent to permanent position within INAF and INFN is significantly smaller than in other countries (e.g. ~50% in UK).

It is interesting to note that today the time spent on average by researchers before getting a permanent position in Italy is similar to that of other countries, about 8-9 years after the Ph.D, about twice than 10-15 year ago. Such increase is due to two main reasons:

1. a reduction of the number of new permanent positions. The total number of new positions in the last five years was 35 for INAF (and 24 for the Universities). An average of 0.37 new positions per institute per year, lower than the rate of retirement. The average age for employment on a permanent position is today very high, 37 years, while the average lifetime of a researcher before retirement is comparably short, about 30 years. Since the total number of staff members is 521 this means that to keep constant this number we would need 17-18 new permanent positions per year, about 1 position per institute per year, that is 2-3 times higher than the recruitment rate from 2000 to 2005. It must be noted that the number of new permanent positions during 2006 will most likely be zero.
2. In the last 10-15 years there has been a strong development of astrophysical infrastructures with Italian involvement (e.g. ESO telescopes, X-ray satellites, planetary missions). As a consequence has become available soft money for contracts from external funding agencies (ASI, MURST/MIUR, etc.). Indeed, in the last three years INAF has directly sponsored only about 10 post docs/year and 10-15 Ph.D. fellowship/year out of a total of about 200 contracts and fellowships. Unfortunately, the level of external funding has decreased strongly in the last 2 years, implying that it would be impossible to simply maintain constant the number of non-permanent positions, which is already deficient with respect to that of other countries.

It appears likely that, if the number of new permanent positions per year is kept constant to the average of the last five/six years, the average time spent on contracts before getting a permanent position will continue to increase although it is difficult to imagine that it can grow further. The consequences will inevitably be that the best young researchers will leave Italy to continue to be active in this area and that those working abroad today will hardly find the chance to reenter tomorrow, both resulting in a huge waste of human and financial resources.

From the analysis of the trends for both non-permanent and permanent positions, it seems clear that lacking a long term recruitment policy there will be a drastic reduction of the number of researchers involved in A&A in Italy, and a consequent reduction of the impact of Italy in this crucial area of fundamental science.

4.2.1 Research activities

The INAF scientific research activity is divided in five macro-areas:

1. Galaxies and Cosmology
2. Stars, stellar populations and interstellar matter
3. The Sun and the solar system
4. Relativistic astrophysics and astroparticles
5. Advanced technologies and instrumentations

The five scientific macro-areas have similar numbers of affiliates but the third, which is significantly smaller.

The research activity is carried out in the 19 structures listed above. The following is a short summary of the main activities characterizing the local structures and should not be considered exhaustive of all activities carried out.

- Observational cosmology: OA-MI, IASF-MI, OA-PD, OA-PD, OA-TS, OA-BO, IRA, IASF-BO, OA-FI, OA-RM, OA-NA.
- Galaxy structure studies: OA-MI, OA-PD, OA-TS.
- Stellar Evolution OA-PD, OA-RM OA-TE.
- Star formation, young stellar objects and interstellar matter: AO-FI, IRA, OA-CA, OA-NA, IASF-RM, OA-CT, OA-PA, OA-RM.
- Stellar population and the evolution of the Galaxy: OA-TO, OA-PD, OA-TS, OA-BO, OA-FI, OA-RM, OA-NA.
- Supernovae and Supernovae Remnants: OA-PD, OA-FI, OA-RM, OA-TE, OA-PA, IFSI-TO

- Stellar activity and astro-sismology: OA-MI, OA-CT e OA-PA.
- Astrometry and preparation of the GAIA mission: OA-TO, OA-BO, OA-RM, OA-TE, OA-NA, OA-PD.
- Solar physics: OA-TO, OA-TS, OA-FI, OA-RM, OA-NA, OA-CT e OA-PA.
- Solar system, planets and minor bodies: OA-TO, OA-PD, IASF-RM, IFSI-RM, AO-RM, OA-CT, OA-NA.
- Magnetospheric and ionospheric phenomena: l'IFSI-RM.
- Geodesy studies through laser ranging and VLBI: IRA, OA-CA.
- Extrasolar planets: OA-PD, OA-NA, OA-CT.
- Observational and theoretical studies of GRB, OA-MI, OA-RM, IASF-RM, IASF-BO, IASF-PA, OA-TS, IFSI-TO
- Multifrequency studies of AGNs: OA-TO, OA-MI, IASF-MI, OA-PD, OA-TS, OA-BO, IRA, OA-FI, OA-RM, IASF-RM.
- Relativistic astrophysics and compact objects: IASF-MI, OA-MI, IASF-BO, IRA, OA-RM, IASF-RM, IASF-PA, OA-CA, OA-FI.
- Astro-particles and Cosmic Rays: IFSI-TO, OA-FI, IASF-PA.
- Radio-astronomy studies and development of instrumentation for radio-observations: IRA, OA-CT.
- Development of instrumentation for space missions: IASF-RM, IASF-BO, IASF-MI, IASF-PA, IFSI-RM, OA-MI and OA-PA.
- Adaptive optics: OA-FI, OA-PD.
- Technologic and scientific studies on optic and infrared interferometry: OA-TO. OA-FI, OA-RM.
- Optic and mechanic technologies: OA-MI, OA-FI, OA-RM, OA-NA.
- Scientific instrument software control OA-TS, OA-PD, IFSI, IASF-RM, IASF-MI, IASF-BO, IFSI-TO
- Data archive management: OA-TS, OA-NA, OA-RM.
- Development of detectors for ground-based optical and infrared astronomy: OA-PD, OA-CT.
- Development of detectors and procedures for ground-based and space-based cosmic ray experiments: IFSI-TO, IFSI-Roma, IASF-PA
- Laboratory astrophysics: OA-NA, OA-CT.
- High performance computing: OA-TO, OA-TS, OA-CT, OA-PA, IASF-PA, OA-CA.

Several of the above listed research activities are carried out in close collaboration with associated scientists working in many Italian Universities.

4.3 Observing facilities

The main Italian observing facilities, including those in advanced stage of construction, are:

1. Telescopio Nazionale Galileo (TNG) Roque de los Muchachos, Canary Island
2. Large Binocular Telescope (LBT) Mount Graham Arizona
3. Sardina Radio Telescope, 64m parabola, San Basilio, Cagliari
4. VLT Survey Telescope (VST) Paranal
5. Noto and Medicina 32m radio-telescopes.
6. Asiago 1.82m telescope
7. Loiano 1.52m telescope
8. Toppo di Castelgrande 1.6m telescope
9. REM 60cm robotic telescope located at La Silla

Since Italy is a key partner of ESO, Italian astronomers have access on competitive basis to all observing facilities of Cerro La Silla and Paranal (Chile).

INAF scientists are deeply involved in the development and exploitation of several space based instruments. ASI has an aggressive program of space exploration and observation (see e.g. the Italian missions BeppoSAX and AGILE). In addition Italy is involved in space missions in the framework of ESA science programs like XMM-Newton, INTEGRAL, Mars Express, Venus Express, Cassini, Rosetta, Planck and Hershel. ASI and Italy have also a long and fruitful collaboration with NASA. Currently, ASI is participating to the NASA MIDEX mission Swift, to the gamma-ray Great Observatory GLAST, to be launched in 2008, to SOHO and to the interplanetary mission Dawn.
See Parts 4 and 6 for more details of observing infrastructures and projects.

4.4 Access to major international facilities

The following table shows the percentage of accepted proposals/targets for some of the major international observing facilities per nation of the proponent scientists, from which it is possible to derive the rank of Italian research in the international context.

GO Programs

	Italy %	UK %	France %	Ger. %	Neth %	CH %	USA %
ESO P74							
UT1	23	9	8	21	2.5	5	2
UT2	13	7	17	13	4	1.5	2.5
UT3	9	20	9	18	3.5	1.5	1.5

	Italy %	**UK %**	**France %**	**Ger. %**	**Neth %**	**CH %**	**USA %**
UT4	4.5	15	12	30	2	4	12.5
VLT P74	12.4	12.8	11.5	20.5	3.0	3.0	9.6
HST 13+14+15	1.3	5.0	1.1	1.3	1.6	0.5	84
Chandra 6+7	3.5	4.0	1.3	3.5	4.0	1.0	78
XMM 3+4+5	8.3						

The table shows that the access to the main ESO telescopes is quantitatively in line with the Italian contribution to ESO, and similar to that of other countries with a strong A&A tradition (UK and France). It should be noted that Germany has an overall access to VLT about twice that of Italy, UK and France. The table also shows that the Italian access to UT3 and UT4 (the telescopes hosting the most innovative instrumentation) is significantly smaller than that to UT1 and UT2 (hosting the first light instrumentation). This can be the consequence of the limited involvement of Italy in the development and construction of the most innovative instrumentation. It should also be noted that while a large amount of funds and effort are devoted by ESO to VLTI, Italian proposals are nearly missing in the area of interferometry, which is largely dominated by French and German scientists.

The access to HST is very limited with an average of 3 proposals (1.3%) per cycle (a similar situation holds for France, Germany and The Netherlands). However, this is significantly smaller than the access of UK to HST, with an average of 10 accepted proposals per cycle (5%).

The access to Chandra time is limited (6-7 accepted proposals per cycle) but in line with that of other European countries with strong X-ray tradition (UK, Germany, The Netherlands). The access to XMM-Newton time is significantly larger with 20-25 accepted proposals per cycle, because this an ESA mission.

The following table gives the number of Treasury, Large and Very Large programs allocated to each country in the past 3/4 years.

Large, Very Large and Treasury Programs

	Italy	UK	France	Ger.	Neth.	CH	USA	Tot
ESO P72-77	4	4	4	8	3	3	0	35
XMM AO 3+4+5	2	0	2	5	0	1	3	15
Chandra AO 6+7+8	1	2	0	0	1	0	20	35
HST cycle 11-15	0	1	0	0	0	0	41	48

Again the number of German-led LP is twice that of the other ESO main contributors, Italy, UK and France. Germany takes an absolute lead on LP on XMM-Newton too. The number of non-US led LP on US large space observatories (HST and Chandra) is very small and UK is the leading European country.

4.5 Funding

The direct INAF budget (the budget directly received by INAF from MIUR) in the last three years has been in the range from 85 to 93 MEuro/year. This includes ordinary funds plus special contributions linked to the financial laws and specific projects (MIUR FIRB). A large fraction of this budget is dedicated to salaries and overheads (between 80 and 90%). As a comparison, the average budget of INFN in the period 2003-2005 is about 280 MEuro/year, a factor 3 larger for a number of researchers 1.5 higher (2.3 including associates and non staff researchers).

In order to make a complete census of the resources Italy is investing for A&A, one should also add:

1. salaries and overheads to support researchers working in the Universities and in other institutes (~20 MEuro/year);
2. Funds allocated by MIUR to academic research in the field of A&A (MIUR PRIN, ~2-3 MEuro/year);
3. Contributions to ESO and ESA scientific programs (~70-80 MEuro/year);
4. A&A ASI scientific programs (10-20 MEuro/year, including support to Astroparticle experiments with INFN PIship);
5. A&A EU structured (PON) and non-structured (e.g. RTN) funds (~5 MEuro/year);
6. A&A regional funds (~a few MEuro/year).

The total of the resources allocated to A&A in Italy is therefore of the order of 200 MEuro/year. INFN enjoys similar external contributions (for example gravitation, Astroparticle and high energy experiments supported by ASI, direct contributions to CERN programs, EU funds).

From the numbers above it is clear that the development and realization of medium/large technological projects for A&A in Italy must rely only on funds external to INAF. Even the funds for basic science are today mostly provided by external bodies. The low level of internal resources that can be allocated to research makes also very difficult to support an aggressive program of technological research and development, which is at the basis of the preparation of proposals for new instrumentation and observational infrastructures and has important fall back on the industry.

4.6 Scientific production

The scientific production of INAF scientists in the international framework is today at the top level: Italy is ranked at the fifth position in the last ISI report for space science, after USA, Germany, UK and France, and before The Netherlands, Canada, Australia etc. The total number of papers published in the 1995-2005 decade is nearly ten thousands, with an average number of citations per paper of 12.6.
(from http://www.incites.com/countries/top20spa.html)
The average cost of each citation is about 16 kEuro, similar to that in France and United States, but higher than in UK (11-15 kEuro). It should be noted however, that both the average cost of the salaries and the funding for research in Italy are significantly smaller than those in these other countries.

The analysis of the papers in the years 2002-2004 with number of citations within the top 3% indicates that the area with the largest impact are the following:

- Cosmic Microwave Background
- X-ray surveys
- Multiwavelength surveys and optical spectroscopic surveys
- Metal abundances in high-z galaxies
- Bulge-BH mass relations
- Dark matter in galaxies
- Properties of field and cluster galaxies
- Hydrodynamic simulations
- Models for the formation of structure in the Universe
- Models for the co-evolution of galaxies and BH

- Stellar evolution
- Star-formation
- Metal poor stars
- Brown dwarf properties
- X-ray active stars
- Supernovae & hypernovae
- Open and globular clusters
- Age and metallicity of the Galactic bulge
- Structure and accretion phenomena in the Galaxy
- Stellar population in nearby galaxies
- Models for the chemical evolution of the Galaxy and of the galaxies
- Distance scale from stellar indicators

- The corona of the Sun and the solar wind
- Laboratory simulations to study the interstellar matter
- NEO and TNO studies
- Dynamic and morphology of asteroids
- Analysis of planetary mission data

- X-ray binaries, BH and neutron stars
- Pulsar surveys, relativistic effects in binary pulsars
- GRB physics and GRB as cosmological tools
- Spectrum and anisotropies of High energy Cosmic Rays
- X-ray emission of AGNs
- Acceleration processes in Jets of radio loud AGNs
- Non thermal emission from clusters of galaxies
- INTEGRAL data analysis

It is interesting to note how the above topics match rather well the hot topics illustrated in part 2.

4.7 Education

The number of new Ph.D. students on A&A in Italy during the last five years is ~40 per year. Most of them are sponsored by the Universities while INAF sponsored on average in the last five years 10-15 fellowships per year. ASI and INFN have sponsored other fellowships dedicated to A&A Ph.D. students.

Compared to other countries the overall number of Ph.D. students per year in Italy is significantly smaller (France about 70, Germany about 65 and UK about 125). This number is also significantly smaller than the number of Ph.D. students in fields related to INFN, the other large Italian institute on fundamental physics (about 185/year between 2001 and 2004, with about 45 fellowship/year sponsored by INFN).

4.8 Other activities

INAF structures and scientists also support and perform several outreach activities through dedicated web sites, dedicated infrastructures and workshops, public lectures and seminars.

Fig. 4.8.1 Astrolab: an outreach interactive museum of the INAF Astronomical Observatory of Rome

INAF structures hosts several important museums.

INAF structures hosts several small telescopes dedicated to teaching and educational purposes.

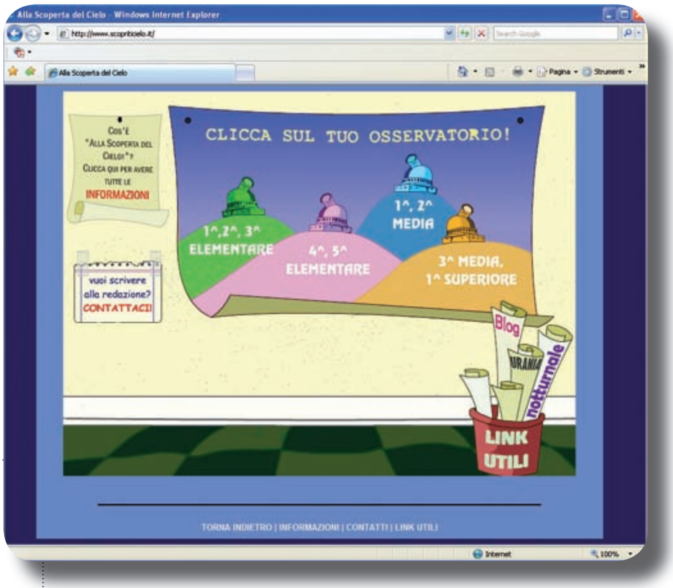


Fig. 4.7.1 Alla Scoperta del Cielo! (Let's Discover the Sky!), a Countrywide INAF project for Schools used every year in more than 500 classrooms.

PART 5: ENABLING TECHNOLOGIES

Introduction

Since Galileo's time the major significant advances in astrophysics have been driven by technological advances. This is mostly true for astrophysics of the XXI century, which has become a "big science".
If our community intends to remain competitive at international level, it must have access to advanced instrumentation and it must participate to the development of state-of-the -art technology.
To this aim an aggressive technology development program must be set up. Such research and development programs must be carried out with a combined effort of astrophysicists with researchers of other disciplines (photonics, particle and nuclear physics, solid-state and material science, cryogenics) and industries.

As recommended in Part 6 the R&D activity at INAF must be driven by science. Considering the limits in the available resources, those technologies that are expected to ensure INAF a leading role in projects of high scientific profile should be privileged. In order to avoid self-referenced activities we propose that they are selected and managed according to the following guidelines.

- A proposed R&D program must not necessarily be linked to a particular project but must be aimed at solving well-recognized astrophysical problems.
- An interaction of R&D team with the science team of each project should be always assured. The modality can vary. The team should be always aware of the state of the art at world-wide level.
- The team should be aware, as well, of other possible projects that can benefit of the technology (if any).
- Results must be submitted to international magazines and presented to international conferences
- The progress of the activity should be monitored and compared with possible applications.

In general, technological advances which involve large collaborations at national and international level should be encouraged. Moreover, fields in which our competence has a high degree of excellence should be supported, and the dispersion in many low-profile projects or duplications of developments in mature technologies avoided.

This activity is the natural candidate to the transfer of technology to other sectors of the Society and, conversely, potentially has the capability of attracting additional funding from external sources. INAF must put a special care in identifying such areas and should focus on building relationships between those who develop the technology and those who may find an industrial application.

5.1 Radio/Microwaves from meter to sub-millimeter wavelengths

Radio waves offer a unique view of the origin of the Universe through the analysis of the CMB. Radio astronomy is also crucial for the analysis of radio photons emitted by relativistic particles, spiraling in magnetic fields and revealing the structure of jets and plasmas around black holes at the center of galaxies. Radio waves are also the best probe for the early stage of star and planetary formation in sites obscured to other wavelengths by deep clouds of dust and gas.

Space radio telescopes, ground large collecting areas together with interferometry techniques are altogether instruments of a continuous improvement in radio astronomy research.

Future CMB experiments on B-mode polarisation or fine structure anisotropy will require instrument sensitivity and control of systematic effects at sub-μK level. Even for E-mode polarisation, to reach the cosmic variance limit up to multiples of 2000 requires an order of magnitude higher sensitivity than Planck. Deep spectroscopic and continuum surveys require the best sensitivities that can be achieved by large collecting areas, which include fast mapping capabilities, high sensitivity detectors and adequate back ends for spectral and continuum analysis.

In recent years, progress in both bolometers and coherent receivers has been remarkable, leading to sensitivities approaching the physical limits (quantum noise) for single detectors. The only viable perspective to push sensitivity beyond such ultimate limit is to build large arrays of N detectors, thus reducing the noise by a factor N1/2. Feed arrays can be placed in the focal plane of telescopes for high resolution observations. Arrays with N up to several thousands can be designed to be simultaneously sensitive to linear polarisation and adequate for deep arcmin T imaging. High sensitivity comes at the cost of higher instrument complexity, involving cryogenically cooled detectors and multiple-beam optics. In addition, new methods will be required to approach the testing of these large arrays with good precision and in an affordable time. Multifrequency arrays are needed to separate foregrounds

for both high precision, fine-scale CMB imaging, or polarisation, possibly with ancillary monitoring at low frequency (< 5 GHz) and high frequency (> 5 THz).
There is a constant push towards higher frequencies, up to the limit of atmospheric windows, since molecular transitions are stronger and more frequent at these wavelengths, interferometric observations provide higher spatial resolution, and thermal emissivity sharply increases with the frequency. On the other side, lower frequency instruments may benefit of new technologies to dramatically increase their sensitivities, opening the possibility to study objects at very high z.

The Italian community has gained high expertise in both radiometer and bolometric detector technologies. Both technologies have rapidly evolved and have contributed to the dramatic recent progress of CMB observations and are optimally employed roughly below and above 100 GHz, respectively. Continued technology development is required in both areas to realize their full potential.

5.1.1 Coherent receivers

Low system noise, large bandwidth, high stability (low 1/f knee frequency) and low dissipation are key features for future high performance radiometers. Active cooling of the front-end (typically to 20K or 4K) will be mandatory to reduce noise temperature. Compact and relatively low cost correlation receivers may be produced in the near future based on monolithic microwave integrated circuit (MMIC) technologies. Arrays of thousands of radiometers may be assembled either as independent channels or in interferometer (feed-less) configuration. Repeatability and ease of testing are strategic guidelines for technology in this area.

Low noise amplifiers today are based on high electron mobility transistors (HEMT) devices. HEMTs display a unique combination of low noise, wide bandwidth, cryogenic operability and low power consumption. Noise figures ~5 times the quantum limit have been achieved. Future amplifiers may be able to exploit antimonide-based MMICs for lower noise and power, now being experimented.

Important technological breakthroughs may come from deeper understanding of 1/f noise, related to the presence of traps in the semiconductor substrate. 1/f noise not only degrades the sensitivity, but it also introduces spurious correlations in the data. To minimise these effects, differential receivers (correlators, pseudo-correlation, Dicke) have to be implemented. If in the future ultra-stable HEMTs will be available, optical beam switching coupled to (very simple) total power designs may provide an optimal choice for low dissipation and low cost arrays with huge number of elements.

5.1.2 Bolometers

Bolometers are successfully used for mm and sub-mm (0.2 to 3mm) astrophysical applications. By reducing physical temperature to very low levels (0.3 to 0.1 K) extreme sensitivity can be obtained (NEP of order 10 –17 W Hz-1/2). Current state-of-the-art bolometer technology combined with multi-stage cryogenic chains allows to approach photon-noise-limited sensitivities.

A breakthrough in bolometer technology has been achieved with the introduction of spider-web bolometers (SWB). These bolometers have better sensitivity due to the reduction of the heat capacity of the absorber. In addition, the web structure reduces the detector mass by two orders of magnitude thus decreasing the bolometer's sensitivity to microphonics. Also, its smaller cross-section reduces the importance of cosmic rays hits. Future application and developments should include the recently introduced PSB, Polarisation Sensitive Bolometers capable of providing adequate linear polarisation isolation out of the same feed element, and TES, Transition Edge Superconducting (TES) temperature sensors. The detectors can be fabricated on a Silicon wafer with an easily scalable and flexible fabrication technology, so that it should be possible to produce large arrays at different frequencies.

Unlike coherent detectors, bolometers are sensitive to radiation from any frequency and direction. Technological research is also crucial on high-efficiency filters, typically rejecting out-of-band radiation at 10-9 level, and must be cooled to avoid parassitic emission towards the bolometers. Coupling of the detector to the telescope represent another technological challenge. This can be achieved with either multimode concentrators, such as Winston cones, or with single-mode corrugated feed horns, preferred also at high frequencies as they ensure better stray-light rejection. Further work is needed to explore extension of bolometers operability at low frequencies, coupling with multiplexers, and arraying technologies. Large antenna-coupled PSB mosaics are being experimented based on monolithic arrays with 1000-3000 channels, and coupled to 3-meter class off-axis telescopes.

5.1.3 Optics and passive components

Low-loss (~0.1 to 0.5dB) wide band (~10% to 30%) front-end elements are crucial elements for future CMB experiments involving large arrays. CMB polarisation sets more stringent optical requirements (typically by an order of magnitude) than T anisotropy, requiring new technical research. Beam patterns will need high symmetry, high side-lobes suppression, low cross-polarisation. For multi-feed arrays it is essential to avoid cross-talk between array elements. For optimum optical coupling one must ensure alignment of feeds array phase centres with telescope focal surface. Very low telescope side-lobe levels (down to -90dB) have been demonstrated, but more stringent limits will be imposed by future sub-μK polarisation arrays. Feed designs optimised for primary illumination and low edge taper include double profiled feeds (DPF). Performances have been demonstrated up to 300 GHz thus covering also bolometer detectors. A key component for radiometric polarisation arrays is the development of new high-efficiency, miniaturized, wide-band, low-loss OMTs. Both symmetric and asymmetric solutions exist and need to be pushed further.

Manufacturing feed arrays with a huge number of elements is a new technological challenge. The cryo operation of the array requires excellent thermal stability and high conductivity at low temperatures. Furthermore, the large number of elements calls for low-risk technology with proper choice of material and manufacturing techniques. Different mechanical approaches exist such as direct machining, electro-erosion or electro-forming, either with independent feeds integrated in a frame or an array generated from a single block.

Horn-less interferometric systems are currently being studied, with hundreds or thousands of coherent receivers, coupled with simple feeds, to synthesize independent beams in the focal plane. These solutions are very promising for the development of large size coherent receivers.
Large receiver arrays require a wide focal plane for the telescope, with good optical correction. Electromagnetic characterization of the optics requires specific tools to be developed, merging electromagnetic analysis in standard optic tools.
Large mm telescopes have very tight surface and pointing requirements. To achieve them, active corrections and advanced metrology are necessary.

5.1.4 Cryogenics

Thermal stability is of crucial importance for CMB measurements because residual thermal fluctuations generated by the active refrigerators can in principle mimic a real sky signal. Future experiments will require very specialized thermal design, to ensure both absolute temperatures and stability. The design of thermal architecture of future instruments will be crucial and will require efficient passive cooling, thermal decoupling, and active cooling chains. Promising cooler technologies for the future include closed-cycle absorption cryo-coolers, mechanical stirling coolers, and dilution coolers to achieve 0.1K levels for bolometers.

Large cooling capacities at intermediate temperatures are required for wide arrays, to provide an effective sink for the last cooling stages and to reduce the noise of the IF MMIC electronics. Dewar design minimizing thermal losses are essential for systems with hundreds of interconnections and wide input windows.

5.1.5 Backend electronics

For coherent receivers, the received signal must be analyzed using a continuum or spectroscopic backend, or recorded for later processing in a VLBI correlator. Receiver arrays produce a large number of wideband signals, requiring a very high total instantaneous data processing capability. At millimeter wavelengths, even continuum observations must be processed in (low resolution) spectroscopic mode, to avoid contamination from molecular line emission.

High speed electronics, especially field programmable gate arrays, provide huge computing power at decreasing costs and total size, with instantaneous bandwidths currently of the order of a few GHz approaching the capabilities of acousto-optic systems. Digital systems can be used to directly process the radio signal, reducing cost and size of multi-channel and wideband radio receivers. Spectrometers based on FFT engines may provide spectral resolutions of thousands to millions of spectral points over these bandwidths, allowing for unbiased searches of molecular transitions, both in the ISM and in absorption at high z.

VLBI requires increasing bandwidth, both for increased sensitivity and for higher frequency spectroscopy. New digital data recording systems exploit the high storage capability of modern media. E-VLBI, using wideband networks, allow for real time VLBI. Goals for the next years are sensitivities around one mJy, spatial resolutions of one marcsec, and real time bandwidths of 2 GBps.

Interferometric instruments at lower frequencies are moving in the direction of big arrays of simple receivers (LOFAR, SKA). These instruments move the complexity from the receiver/antenna to the electronic processing, allowing for very large collecting areas. Adaptive beamforming allows for very fast position switching, and for widely separate targets to be observed simultaneously. Adaptive nulling of selected directions is essential to reduce the impact of man-made interferences. The existing "Croce del Nord" telescope can provide a good test bench for these technologies.

5.2 Ground based Optical Near IR technologies

Some technologic developments that will play a fundamental role in Optical/IR range (e.g. lightweight mirrors, precision shaping and metrology) are increasing their role also in other ranges. Therefore they have been included in Section 10 on Transversal Technologies.

5.2.1 Adaptive optics

Adaptive optics allow in principle the large-collecting-areas, ground-based telescopes to reach angular resolution so far reached only from space, at affordable costs. In perspective, the utility of ELT depends critically from the ability to reach diffraction limit performances, hence from the development effective AO systems. For this reason all major observatories in the world are funding AO developing plans and INAF should strengthen the world leadership in this strategic field.

The results are already very promising in the near IR, but far from being satisfactory. Certainly much is to be done at optical wavelengths. The construction of extreme AO systems is therefore the challenge for the next future of ground based astronomy.

The most promising sectors, in which the perspectives of significant progresses are most promising, are the following:

- very high accuracy Wave Front Sensors, in particular those of the Pyramid type, which allow to reach very high modes, hence better performances
- active secondary mirrors, which apply wavefront corrections (including tip-tilt) with a smaller number of reflections hence ensure higher throughput, lower emissivity, and simpler optical setup.
- mesospheric laser guide stars, artificially created by laser beams to determine the atmospheric turbulence at any direc-

tion in the sky.

- Multi-Conjugate Adaptive Optics, which extends the image compensation for atmospheric turbulence to larger fields of views, with respect to standard normal AO, using several guide stars.

5.2.2 Optical Detectors

The advent of **very-wide field-of-view instruments** with good optical performances and the perspective to correct increasingly large field of view at diffraction limit have vastly increased the need to pave the focal planes with large arrays of detectors. This requires a high degree of integration of analog and digital components that constitute the controller in order o improve compactness and reliability. Some of the most interesting projects foresee a wide field instrumentation.

The making of these wide field (or all sky) instrumentation is based on the development, in a near future, of ASIC circuits to process analog information from CCDs and generate logic signals to networks (likely based on FPGA technology) handling simultaneously hundreds of CCDs.

For imaging instruments like cameras, the use of CMOS Active Pixel Sensors has been a considerable breakthrough with respect to the use of CCDs. CMOS is superior to CCD when applied to high speed applications, as in adaptive optics, star trackers, fast video-rate readout systems. At the moment the relevant difference between CCD and CMOS is the fill factor that, while for CCD is 100 %, for CMOS-APS is still not higher than 60 %, however the use of Hybrid CMOS instead of monolithic ones improve this value to about 100% making them a real competitor with CCDs. Additionally, CMOS has a low fabrication cost and easy foundry access, while the CCD technology is very complex and expensive.

APS sensors offer more integration (more functions on the chip), lower power dissipation (at the chip level), and smaller system size. Additionally, the pixel can be made very small, also as compared to CCD typical pixels even further reducing the size. In summary:

– APS does not require any external driving electronics, and thus avoids the complexity and power consumption of the electronic driver.

– APS has an architecture capable of higher frame rates than CCD, of essential importance whenever fast orbiting S/C with large format cameras are involved

– CMOS is more resistant to high energy radiation than a CCD and thus is suitable in space applications.

High Time Resolution Astrophysics (HTRA) will reach into the largely unexplored time interval from the picosecond to the millisecond. In this new astrophysics domain one can expect to observe several interesting phenomena ranging from laser-intensified spectral lines in planetary atmospheres and peculiar stars like Eta Carinae, to coherent phenomena in pulsars and compact objects. Below the nanosecond limit, one approaches the Heisenberg uncertainty principle limit. Hence, the study of second and higher order correlation functions in the polarization-resolved photon stream goes beyond the traditional way of astronomical instrumentation and opens the truly novel QA, where the 'unexpected' must be expected.

Extremely Large Telescopes will open the possibility of exploiting this novel observational and theoretical approach thanks to their high photon rate in the visible range. Several improvements on existing technology are needed to fully exploit the quantum concepts:

- photon counting detectors: the Single Photon Avalanche Detectors combine the high quantum efficiency of Si with very fast timing. Italy is in a position of particular advantage in this area, of high strategic value.
- photonics components. Coatings, polarizers, beamsplitters, narrow band filters etc. need to be optimized.

5.2.3 NIR Detectors

Detectors for NIR employ an array of photodiodes bounded on a Si multiplexer. Nowadays, multi-million pixel infrared detectors (especially the well proven HgCdTe) are very useful for surveying of cool, weak objects, and for providing diffraction limited images. They are however still quite expensive, limiting the maximum practical sizes of detector mosaics. It is thus crucial to explore technologies for lowering their cost, and to exploit them at their best. They require very fast readout electronics, with extremely low readout noise, due to the limited well size and high background, and there is need and space for performance improvements in this area, although commercial readout systems are available.

Intelligent ideas to improve survey efficiency (like for the past the use of Amici prisms) are necessary for maximizing their scientific return.

5.2.4 IR Spectroscopy

In the near and medium infrared, the luminosity ratio of cold bodies (planets, minor bodies) to the parent star is the most favorable. IR is also the best spectral region to study heavily obscured regions, in galactic cores and star forming regions, and where high z objects are most luminous. For these problems, there is an observational request for ever-increasing spectral resolution. Currently explored techniques range form the traditional Echelle spectrometers, GRISM and immersion gratings, that exploit the high refraction index of the immersing medium (silicon) to increase dispersion for a given grating step, and volume phase holographic dispersing elements.
Imaging spectrometers (currently with a limited number of spatial pixels) are becoming available. There is a need to push the mapping capability for line emission of this class of instruments over wider areas.

5.2.5 Interferometry

For several scientific applications, a spatial resolution higher than that obtained with space telescopes is often required. Such high resolution can be achieved in the infrared only, with baselines of tens to hundreds of meters. Conventional infrared interferometry is a mature technique, and many instruments with a significant Italian participation are now available. They can take advantage of adaptive optics at the collecting telescopes to achieve accurate fringe stabilizations, and to allow for imaging interferometry. Imaging interferometers that can be used to null a particular position and achieve very high sensitivity on the surrounding region are essential for study of planets and protoplanetary regions.
Phase resolved and phase closure interferometers, allowing real imaging at the interferometric spatial resolution, are beginning to appear. Interferometric spectrographs, currently providing spectral resolution up to 10000, allow for accurate study of spectral signatures in these regions.

Intensity Interferometry might even lead to optical intensity VLBI, with sensitivity at least 100 times better than the original Narrabri realization, in the blue-visible spectral region.

5.3 UV

5.3.1 Optics and optical components

Some relevant technologies are available as a heritage of the studies for the UVISS mission. These include the development of Wide Field UV optics and a spectrographs.

Of particular interest are reflecting multilayer mirrors, providing a high efficiency and a narrow band. Filters based on this technique are worthy to be further investigated and developed because they are efficient and can be easily tuned on the desired wavelengths and bandwidths.

5.3.2 Detectors

Detectors play a crucial role for any future UV application. The Italian Community has been involved in the design, study and early development of various space UV missions. This activity has stimulated an intense and active R&D of technologies oriented to this application. The most important was the development of array detectors based on a solar blind, high quantum efficiency, photocathode, an image intensifier and a read-out based on a phosphor, a tapered light guide and a CCD. A continuous improvement of this technology is strategic for the participation with a significant role to future UV missions. A promising evolution is the use of the Advanced Pixel Sensors, providing less noise, faster read-out and higher radiation hardness than CCDs.

Another potentially interesting technique is the use of Diamond as radiation detector, because of their good UV and XUV sensitivity and the possibility to operate them at room temperature. Through a sound R&D activity these devices could move from the pioneering phase to a practical application in experiments.

SiC as a semiconductor has the peculiarity of a high gap. Some prototypes of detectors based on this material have been already manufactured, showing very interesting features. The R&D activity on these detectors should be aimed at realizing Single Photon Avalanche Detectors (SPAD). Since they are sensitive to energies >3.2 eV they should result in fast single photon detectors which are intrinsically solar blind.

5.4 X-Ray

5.4.1 Optics

X-ray optics, since the Einstein revolution, allow to resolve, localize and identify multiple and extended sources and represent a break-through in sensitivity. The development of technology of the optics is opening new important possibilities in high energy astrophysics. In this field Italy, since SAX, XMM and SWIFT, has a role of worldwide excellence that must be preserved and possibly improved also because it matches an excellent role of the Community in terms of proposing new break-through missions.

The development of low weight, high rigidity components, aimed to make feasible future telescopes combining a high throughput (required for spectroscopy, timing and polarimetry) with high angular resolution, is needed to improve the limit sensitivity avoiding confusion, to resolve extended sources and diffuse background. This requires the study of new solutions such as the slumping of Borofloat glass or the development of SiC structure, with a particular attention to the capability to implement cost and time effective large-scale production.
Another important evolution of these applications is the development of wide field optics, based on polynomial profiles. Of particular interest are designs with large area, high angular resolution and short focal length (for a low background), particularly suitable for surveys and for the study of low brightness objects.

Another set of technological developments is in the domain of coatings of telescope shells, mainly aimed to extend the energy band and possibly to provide a more continuous response. A moderate extension of the band of X-ray optics can be achieved by using materials more dense than Au, such as Pt or Ir. A much more effective approach employs a coating of alternate low Z and high Z materials with gradually increasing thickness. This technique, compared with the one-material reflection, allows reflecting the X-rays of the same energy with incidence angles 3-4 times larger and, therefore an increase of the band with the same focal ratio, or an increase of the area with the same focal length. In the hard X-ray range (10-80 keV) the evolution of experiments from collimators to optics allows for a gain of up to 3 orders of magnitude. Recently coatings based on low Z materials, superimposed to the standard multi-layer surfaces have been suggested to improve the reflectivity and avoid gaps at low energies. Due to the high interest of extending the powerful application of optics to the hard X-ray range, while preserving a good coverage down to the soft X-rays, all these developments deserve systematic studies.

At energies above 60-100 keV the multilayer technique is much less effective. The present technique is that of coded masks combined with array detectors. This allows resolving sources but the high background limits the sensitivity. A substantial step forward in sensitivity will be achieved by the development of focussing devices based on an array of crystals oriented in such a way that the Laue diffraction concentrates a parallel beam in a focal spot. In Italy there is an excellent tradition for the design, testing and prototyping of such devices. With the present quality of crystals and with the possibility to foresee payloads of large dimensions (especially with formation flights) Italy can play a leading role in the future evolution of Hard X/Soft gamma-Ray astrophysics. An intense activity of R&D is anyhow needed spanning from the optimisation of the telescope itself (continuum and lines), the development of crystal technology, the alignment methods, the design of suitable detectors (imaging, low noise, polarimetric).

The extension of functionalities of X-ray optics to higher energies requires an adequate availability of beam-line facilities, also in the development phase, to be achieved with a proper extension of international collaborations and a rationalization and an improvement of the existing national facilities.

5.4.2 Detectors

After the age of proportional counters, silicon detectors are since 10 years the basic multipurpose devices in X-ray astronomy. The future evolution in this field is Advanced Pixel Sensors. CCDs have been combined with gratings, opening the field of high resolution spectroscopy. The high resolution spectroscopy, both in emission and absorption, is an important tool to explore the deep physics of X-ray sources but the requirements are there for an improved spectral resolution combine with a much larger collecting area. Cryogenic detectors perform the measurement of the energy of each single photon at sub-kelvin temperatures, with a very low noise. These are not dispersive and can be built in pixel so that can perform spectroscopy of extended sources. The two major classes of cryogenic detectors are Superconducting Tunneling Junction Detectors and Microcalorimeters.

In Italy there is no substantial tradition in the domain of gratings. In the domain of Josephson Junctions devices there is an excellent expertise, but not for applications on X-ray astronomy. Moreover, following a long developmental work in other countries, they have lost their appeal. We identify micro-calorimetry as the strategic technology to be pursued in Italy, within the frame of international collaborations. Two implementations are viable: X-ray micro-calorimeters with resistive sensors based on doped semiconductors and implanted thermistors, and Transition Edge Sensors with squid read out. The latter technique is nowadays more promising and an intense R&D activity is performed in Italy. The goal is to develop arrays for imaging spectroscopy, down to 1eV – 2eV resolution, with multiplexed SQUID read out. A competence in this technique is strategic for an effective participation to future X-ray missions, particularly oriented to Cosmology.

Magnetic micro-calorimeters are a very new interesting evolution that could further improve the energy resolution to levels that cannot be arrived by gratings.

The manufacture and testing of thin, selective filters is important for all the low energy applications and becomes very challenging for the cryogenic detectors.

At higher energies the development of multilayer optics and of Laue lenses requires an adequate investment in improving the capabilities to build arrays of high Z detectors (CdTe, CZT, scintillators read with SDD), to be used by themselves or as building blocks of multiple-interaction. These developments are strategic as well to maintain and improve the capability to develop instruments with coded masks and position sensitive detectors that can play a role complementary to focussing devices to resolve, study and monitor sources on a large filed of view. Si micro-strip detectors can replace proportional counters in wide field or all sky instruments, fundamental for all sky monitoring and for transient/burst detection. Strip or pixel SDD could extend this capability to lower energies, also providing a good spectral resolution. Also the improvement of detectors based on new materials, such as SiC, GaAs, Diamond can be very promising if some present criticalities can be overcome.

Polarimetry is an almost unexplored window of X-ray astronomy. The major limit has been, so far, the instrumental approach. The development, all Italian, of a new device based on the photoelectric effect in a finely subdivided gas detector (MPGD) allows for high sensitivity, time and spectrum resolved polarimetry. The read-out system based on VLSI technology includes all in a chip, inside the detector itself, the Front End Electronics, resulting in a very light and compact device that can be easily harboured in the focal plane of large, multi-purpose telescopes or in small missions more dedicated to polarimetry.
In all these domains there is a sound tradition that must be preserved.

5.5 VHE Gamma Rays

The VHE astronomy, most based on data from Cherenkov telescopes, is one of the fastest sectors of astronomy. The contribution of INAF has been so far negligible. The strategic role of this branch of astronomy suggests that INAF should identify some areas where a hardware contribution to future projects could be realistically achieved in a limited time, starting from the available technologies and capabilities. These could be the development of light, cost effective mirrors, based on technologies developed for ground based large telescopes and for X-ray telescopes. This could also include the study of large area Fresnel Lenses and Cherenkov light sensing technologies, developed for UHECR experiments.

5.6 Cosmic Rays

The existence of major experiments in the phase of extended data acquisition (Kascade Grande, PAO) does not suppress the need for an important R&D activity aimed to improve the efficiency of the system and to improve the calibration both inter-experiment and absolute. The combined exploitation of data from the various detectors to reconstruct the energy, nature and direction of the incoming particle is based on methods that are in continuous improvement. The major issues are related to triggering criteria, and to simulation tools to derive the associated acceptance. The development of the Lateral Trigger Probability for PAO is an example of how much a new method can impact on the performances.

The need for huge detecting surfaces makes strategic the development of detectors (as RPC) or detecting stations with a degree of reliability suitable for a large scale manufacture and unattended operation.

The development of scintillators doped with heavy metals can improve the sensitivity to different neutrino interaction channels in the search for neutrino bursts from gravitational stellar collapse

The technique to detect cosmic rays by radio signals, long time searched and only recently discovered, is another very promising tool for future experiments. In UHE range the air fluorescence is a fundamental complement to the electromagnetic shower and related technologies (lenses, mirrors, detectors, air transparency monitoring) are to be improved.

For space application the development of rugged, radiation hard but sophisticated performances version of the most advanced devices is a key for a competitive participation to future Cosmic Rays Space Missions. This includes silicon strip, silicon drift, transition radiation, straw tubes, scintillating fibres as component of vertex detectors, trackers or calorimeters stages. Taking into account the limited resources, in terms of power and data rates the development of ASIC chip with VLSI technology is substantial to handle data from a very large number of channels.

An evolution of the highest strategic interest is the development of photon detectors based on solid state, that provide high quantum efficiency, fast operation, low power, easy integration with Front End Electronics and no need for High Voltage. This is true in general but in particular for space application

Another technology of potentially high strategic value is that of magnetic analyzers.

The feasibility of an experiment based on the detection from space of fluorescence photons produced in the atmosphere by showers started by Ultra High Energy particles depends on the improvement of new optical components (mainly large area Fresnel lenses), on the development of intelligent and very fast Front End Electronics, based on ASIC chips, capable to handle a large number of pixels of light sensors, on the capability to implement an effective monitoring of atmosphere transparency.

5.7 Technologies for the Planetary System

Technologies for the Study of the Solar System can be grouped into three broad categories:

- Ground based;
- Remote Sensing from an orbiting or flying-by spacecraft;
- In situ.

For the two latter categories the identification of guidelines for the development of new technologies suitable for the time frame envisaged by this Long Term Plan is impaired by the consideration that any major exploratory mission lasts much more than ten years, from its conception to the nominal end of the mission.

5.7.1 Ground based

For ground based studies the involved technologies are the same as for other branches of observational astrophysics.

5.7.2 Remote Sensing from an orbiting or flying-by spacecraft

Thanks to the availability of nanotechnologies, a new interdisciplinary planetary research line has been set up to produce a new generation of instrumentation capable to observe the neutral atom emission from the target surface, and can be applied to increase the scientific knowledge of the space environment in which energetic ions and exospheric neutral gas coexist.
The instruments for future missions can be grouped into two broad categories: low-energy (10eV-5KeV) and medium-high energy (5keV – 200keV) instruments. Given the growing importance of the latter instruments, a significant R&D activity is required to preserve the level of excellence of the Italian community in this field.

Imaging spectroscopy, a field in which Italy is highly qualified, applied to the exploration of the planets of the Solar System has received a huge boost after the success of several recent missions in determining the composition of the surfaces of Solar System bodies, and of their atmospheres, when present. In the future other missions, such as DAWN, BepiColombo, JUNO will carry Hyperspectral imager as part of their payload.
Large steps forward can be imagined in the next years and decades, particularly in the field of detectors and of the miniaturization of electro-optical components.
As far as detectors (both IR and CMOS-APS) are concerned INAF should make a continuous effort in the next years in order to maintain and further improve our level of knowledge and competence in this field to participate to future interplanetary missions.

5.7.3 In situ instrumentation

For planetary exploration the analyses of samples by means of instrumented drills and in situ analytic stations are the key for unambiguous interpretation of the original environment that lead rock formation.
For in situ instrumentations a general requirement is miniaturization. Specifically, miniaturization of visible –infrared imaging spectrometers requires new approach in the instrument design and optimization. Moreover, this new type of very small spectrometer must be very flexible to be accommodated in different part of rovers and drill systems. The design and the solutions adopted for this miniaturized spectrometer must be innovative and robust at the same time, to overcome all the difficulty (movement, illumination system, etc.) and the constraints of system resources. Among the others, a promising route for the instrument miniaturization is the development of a spectrometer based on optical

fibres.

The future exploration of planets will require imaging system able to make a global mapping in 3D allowing to study the morphology of the entire surface or for specific features as for instance the channels on the Jovian icy satellite Europa, that may be the candidate of next planetary missions. Italy is developing a new generation of stereo cameras based on new detectors (Advanced Pixel Sensor) and a light-weight original optical design. Important efforts are needed to develop the software to reconstruct the stereo pairs, to generate the Digital Terrain Model (DTM) and to archive the huge amount of data that will be collected by a mission making the global mapping of a planet.

INAF is very active at international level in the development and realization of systems for the dust and volatile monitoring, thanks to an aggressive R&D program. In particular, various complementary methods have been developed for in situ monitoring of both dust, with sizes down to sub-micrometric scale, and of volatiles, down to trace amounts.

Methods for direct in situ monitoring of solid particles are based on the measurement of light scattered by particles crossing light beams (optical detection), on the detection of the perturbation produced by a grain impinging onto a solid surface (impact detection) and on the measure of the deposited mass through piezoelectric sensors (cumulative detection). A continuous effort of R&D is needed on the following aspects:

- improving sensitivity in order to detect smaller particles at low velocity and/or volatiles in lower amounts;
- investigating other complementary techniques, which may allow selective detection of refractory and organic species;
- pushing miniaturisation of sources, sensors, detection devices and their assemblies, in order to gain flexibility in utilisation and applicability to a larger amount of measurement conditions and environments.

Passive collectors for sample return

The R&D in this field is aimed at identifying materials suitable to collect particles, even at high velocity (hyper-velocity), by minimising damage of particles for an intact collection and subsequent analysis. In this respect the use of “aerogel” (an innovative low-density material) is a frontier approach.
In this field, the main objectives of future R&D are:

- search for new materials, such as multi-layer and piezo-electric films, for combined non-destructive collection and detection of grains;
- coupling of passive collection materials with active detection methods (e.g.: optical detection) in order to obtain an in situ control of collected grains.

Planetary Radiation Analysis

Radiation exposure in space and on the surface of a terrestrial planet like Mars is a significant and serious hazard during any human expedition in space. In order to monitor the radioactivity emissions both during cruise phases and at surface planetary ground level, the possibility to use more active instrumentation, providing a faster response and more information on the composition of the radiation itself, should be investigated. Diamond detectors could result in more compact and flexible dosimeters but still require a significant progress in performances.

On a related topic, the analysis of planetary surfaces is important to predict the fluxes of neutron produced by cosmic rays in upper layers of the soil in order to retrieve information on the effective radiation dose that an astronaut will absorb. X-ray fluorescence spectrometry is a promising technique that could investigate the interior of samples and detect both major and trace elements. This technology can be significantly inproved both by the development of compact excitation sources and the use of room temperature, high Z semiconductor detectors, such as CdTe, which have a good efficiency and resolution for lines from Fe to U.
This in situ X ray investigation will also provide specific information to the future strategy the selection of samples that could be sent back to the Earth.

Electromagnetic (e.m) surveys are, by far, the most suitable tools for planetary geophysical investigations because they are relatively simple and appropriate to be hosted for example on a moving vehicle. These techniques rely on the e.m. parameters of the subsoil and are sensitive to the contrast of conductivity, permittivity and magnetic permeability of the subsurface lithology.
A research line to study the different electrical characteristics of a planetary soil has been set up to investigate and evaluate the performances of multi e.m. detector head integrating in one package a set of sensors for measuring the electromagnetic properties of the soil.

5.8 Technologies for the Sun and Interplanetary Plasma

5.8.1 Ground based optical and near IR solar telescopes

Up to now, the aperture of ground-based solar telescopes has been limited to about 1 meter due to the difficulties in dissipating the collected heat, that also worsen the atmospheric seeing. However, the recent development of efficient AO systems and of appropriate thermal controls, have allowed the design of solar telescopes with large apertures.
Applying AO to solar astronomy is nevertheless a big challenge. Recently, high-order AO systems have allowed solar telescopes to operate at their diffraction limit under a wider range of atmospheric conditions. The present goal is to expand this capability to support large aperture solar telescopes. As discussed in Section 2.1 INAF is already playing a major role in developing such technology: the same kind of expertise could be applied to the development of large solar facilities.

The Italian community has been a leader in the development of 2-D Solar Spectro-polarimetric instrumentation for precision spectroscopy based on interferometric systems like IBIS. The target for the next years is the investigation of optical properties of large aperture etalons and the accurate optical design of a panoramic monochromator for new generation solar telescopes.
The most crucial ingredient in spectro-polarimeters for large solar telescopes is a high-speed, high-sensitivity array detector suitable for polarimetry. With respect to the CCD presently used, CMOS devices have the advantage that auxiliary functions can be integrated on the chip and into each individual pixel, a feature that could be useful for the investigation of solar transient phenomena.

5.8.2 Space remote-sensing and in-situ instruments

The study of the solar corona requires instruments with a large dynamical range at most wavelengths: this represents an important constrain on the selection and development of the detectors for the new. Major limits in the capability of observing key features of the outer corona (e.g. magnetic field, He abundance) and in performing spectro-coronagraphy has led the Italian community to explore new diagnostic methods based on the Hanle effect, EUV Imaging in H, He 304, and OVI 1032-1037 lines. This led to the development of new EUV instrumentation (multilayer mirrors, liquid crystal polarimeters, gratings) in order to provide imaging of the entire ultraviolet corona from the solar limb outwards and the measurements of the polarized ultraviolet coronal emission.

The know-how acquired in the realization of the UVCS/SOHO spectrometer has set the basis to develop the technology for a new generation of coronagraphs. The technology is based on the optimization of the multilayer optics, reflecting both at UV wavelength and in the visible band, in order to achieve multiwavelength capability in a single optical channel. Developments in this field will allow to build compact telescopes, tailored for space missions, capable of observing the full corona in the visible and in the UV.
To measure the magnetic field in the outer corona through the Hanle effect, a space polarimeter should also be developed.

The inner heliosphere environment is currently unexplored. In-situ exploration requires the design of a solar wind plasma analyser with msec sampling, and neutral particles detectors capable of surviving in these extreme environments.

5.9 Transversal Technologies

Some technologies have a particular “transversal” value, since they are not confined to a particular application but have a more general use. It would be useful to organize a good sharing of ideas, know how and, in some cases, equipments in order to obtain significant cost and labour reductions.

5.9.1 VLSI Electronics

The huge increase in the number of pixels is a transversal problem to most of future astronomical instruments. ASIC chips are already present in most of applications including a large number of pixels with parallel readout. The capability to develop chips compliant with the further increase of the focal planes is strategic. The presence of a long lasting tradition in this field suggests that the capability to design and test, in interaction with industries and University Departments, should be preserved and expanded within INAF.

5.9.2 Time definition and distribution

The development of HTRA requires a technological improvement for which Italy is already in a privileged position. There are certainly overlaps between the requirements of the VLBI radio technique with those of the precise time correlation of data from space telescopes, from optical band to gamma-Rays, such that an exchange of experiences could be useful.

5.9.3 Cryogenics

Many devices expected to play a role of frontier in many branches of astrophysics (X, Gamma, IR, CMB, CR) require low or very low temperatures (down to 0.1 - 0.05 °K). An accurate thermal design and analysis will be always a critical factor of quality for any project. The cryostat is a major item and, in some cases, the building block of an instrument. Many experiments, in the past, have failed or have suffered substantial delays because of problems with the cryogenics. The requirements of future experiments result in a major application of passive cooling and in the development of multi-stage coolers, with a reduced or null role of cryogenic liquids. An increase and an effective share of know how in this field is highly recommended.

5.9.4 Light Mirrors

Lightweight mirrors are required for space telescopes that have to resist different gravity conditions still keeping the payload as light as possible. Lightweight, durable and robust materials are also mandatory for the next generation of ground-based gigantic telescopes (e.g. ELT and CTA). Activities are in progress to study and test several composites for such application, e.g. silicon carbide or carbon fibre composites.

A sound and systematic activity in this field is of the highest strategic impact for the future programs of INAF. Italy has already a good know how in the SiC technology involving the manufacture of pre-formed panels based on Si-SIC technique and the development of techniques of coating, super polishing and figuring.

5.9.5 Shaping control and Metrology

Modern telescopes with large mirrors require permanent control of their shape.

This is obtained by mean of Active Optics consisting in applying controlled forces to the primary mirror and in moving the secondary mirror in order to cancel out the errors. Though relatively complex such capability has greatly reduced the risk inherent in designing and building larger telescopes.

The design and realization of ELTs will necessarily require segmented mirrors which need to be co-phased to act as a monolithic mirror.

This approach is being progressively adopted in other domains such as high frequency radio astronomy, high throughput X-ray telescopes, Laue telescopes for gamma-ray imaging.

Metrology both on large and small scales is relevant for a large number of technologies. Due to the large investments of equipments and of labour required the diffusion know-how and the share of some resources should be favoured.

5.9.6 Computer Science

In most fields of astronomy high performance computing is needed for advanced theory, simulations and data analysis. Moreover in some areas (e.g. hydrodynamics or many body dynamics) this is the very crucial technology. INAF should take care that Super Computing Facilities of appropriate power are made available to the teams involved in these fields.

Grid technology enables computing and storage resources around the world to be harnessed easily and efficiently into a single powerful resource. This paradigm, which is not in competition, but rather complementary to the above-mentioned Super Computing Facilities, allows a new approach to the analysis of astrophysical data for all applications which can be run in a coarsely-grained parallel environment.

The Virtual Observatory (VO) is expected to become the new paradigm scientists will use to access and compare data. Waiting for the developments carried out at international level is not sufficient. To remain competitive at international level, our community needs to participate in the international coordination and collaboration aimed at defining standards, developing and deploying tools, systems and organizational structures necessary to use astronomical archives in an integrated and interoperable way.

To allow the community to exploit the wealth of information the new generation of national instrumentation is going to provide, it is very important that at the same time the appropriate data processing procedures/pipelines are developed. No instrument can be considered as commissioned until the related data reduction package is released. This type of processing often does not need special computing resources; rather, appropriate human resources shall be invested in this field.

Control systems

The development of Control System plays a key role in the instruments and ground based telescopes design and implementation. INAF have a long experience in this field both in national and international. An increase and an effective share of know how in this field is highly recommended.

PART 6: A STRATEGIC VIEW

Introduction

This part first present a list of general recommendations, which should be the basis of any strategic view for the future development of INAF. Road-maps for the strategic research areas present within INAF are then presented. The strategic areas considered are: 1) Early Universe studies; 2) Mid and far infrared astronomy; 3) Optical and near infrared astronomy; 4) UV astronomy; 5) Radio and sub-millimeter astronomy; 6) X-ray astronomy; 7) Gamma-ray astronomy and Cosmic Rays; 8) Planetary science; 9) Solar physics; 10) Gravitational waves; 11) High performance computing. For each strategic research area a road-map has been envisaged, putting in full context the scientific goals presented in Part 2 and the scientific projects presented in Part 3.

The road-maps present a set of scientific and technological priorities. Priorities have been assigned according to the scientific relevance of the project, the level of national and INAF involvement, the level of INAF internal resources to be dedicated to the project, the timeframe, the international context (and therefore the level of uniqueness and competition of the project), the quality of the partners, e.g. whether the project is timely to attack a specific hot topic. Such evaluation is extremely difficult. On going projects, as well as projects near completion, should be subject to periodic review to assess their real scientific efficiency with respect to aging. On the other end, it is clearly not sufficient to evaluate the timelines of new projects with respect to today’s hot topics and instrumentation only. Extrapolations should be done about which topics will presumably be solved in the next few years by the present instrumentation and/or by projects today in an advanced status of preparation, and which other will require new approaches and ideas, not to speak about new hot topics not even mentioned in Part 2 and that will likely emerge in the next years. Furthermore, this exercise has to be multi-disciplinary, because new ambitious projects today in preparation may also help in solving problems not included in their core science. As a result, the evaluation of new ideas for the next decades cannot be done out of the full context of the projects today in preparation. This is clearly extremely difficult, and it is therefore subject to an unavoidably large margin of uncertainty.

INAF has inherited four large technological projects (TNG, LBT, VST and SRT) started in frameworks drastically different from the

current ones. LBT, SRT and VST benefited of dedicated funding that turned out to be inadequate for their completion, operation and exploitation. LBT, VST and SRT are expected to produce a high scientific return for the Italian community, but they require a high level of investment for their completion (including development of adequate instrumentation), operation and data analysis. Furthermore, their full exploitation is still subject to significant risks.
The completion of these infrastructures, although not questioned here, should not jeopardize the scientific activities of INAF. Furthermore, the level of support for the future exploitation of these observatories and the development of new instrumentation must be subject to scientific competition with all other INAF projects and therefore appears in the list of priorities given below.

Priorities are summarized in three broad categories: 1) Top priority projects. The level of direct INAF investment needed to support these projects is small, compared to the scientific return. Having only a marginal role in these projects would represent a major setback for a relevant part of the community. 2) Very important projects. These projects are divided according to the level of direct INAF funding required: high (several MEuro/yr); medium (a fraction of MEuro/yr); small (<few hundred kEuro/yr). 3) Other important projects.

Concise recommendations about which should be the major INAF actions are finally given for each project.

6.1 Basic Priorities

Free research should be encouraged, as a priority activity and strategic resource. Free research, not explicitly finalized to a specific large technological or scientific project, is a fundamental resource. It ensures vital lymph to INAF and prompts the generation of new ideas and new projects. Adequate funding (at least several per cent of the INAF budget) for free research must be considered a top priority. In particular, specific funds must be allocated to the support of researchers, students and post docs. This is a necessary condition to retain the level of excellence in Astrophysics reached so far by our community. It must be remarked that new large technological projects should not be started or carried on at the expenses of adequate support to top scientific activities of INAF.

The scientific priority is the most important criterion for the development of new projects. It must be avoided to proceed to the definition of scientific and technological projects only because linked to sites or infrastructures that look politically or economically privileged. It would be advisable to learn from past experience, like (but not limited to) that of the International Space Station (ISS) and of the related projects like EUSO, SPORT, LOBSTER, the original project of XEUS. Sometimes, even large investments turned out to be inadequate to complete such projects, jeopardizing the funding and hiring policies of the Institute, without a strong scientific return. New observation sites, like Antarctica or the Moon, must first be qualified in detail, before discussing the start of any construction project.

The role of INAF within international organizations like ESO, ESA, and the initiatives of the European Community, should be made more active and incisive. In the past, the link between the Italian scientific policy and these organizations has not always been the best. In a few cases, strategic choices to pursue and guide the highest priority technological developments have been missed. This potential problem is particularly serious for the development of future large infrastructures, like ELT or XEUS, for which ESO, ESA are the most natural and reliable partners, and SKA. For such large and complex projects it seems advisable to concentrate the efforts on a few highly qualifying areas, in collaboration with the most reliable partners. Small technological participation in multiple different enterprises should be discouraged, especially if the funding of the projects and credibility of the partners are not deemed adequate after a careful scrutiny. INAF should pursue comprehensive strategies and ensure that the Italian representatives in political boards endorse these positions. At the same time INAF should stimulate and strongly support the Italian groups that respond to announcement of opportunities for participation to large international projects and instrumentation. For example, INAF should support and sponsor the creation of consortia for the development of ground and space based instrumentation with Italian leadership.

Adequate funding for operations of the infrastructures, data management, archive and analysis must be included in the preparation of new projects. To secure the best possible scientific return from new projects, adequate funding for the management of the infrastructure, for their operation, for the maintenance of the present instrumentation and for the development of new instrumentation, must be located and specified in advance. These activities are key components in the development of any projects and the efforts for their planning and fund raising should not be

left to future administrations.
Funds for operations and data analysis should not be cut, even in case of a descoping of the project for financial reasons. It may be preferable to reduce the scientific capability of an instrument, rather then reducing its operation and data exploitation.

Support the organization of "large", "key" and "legacy" programs with Italian PI in international infrastructures. The exploitation of large and modern infrastructures built with participation of the Italian community like VLT, XMM and others, often produces high-level results but it is not optimal. In particular, the number of large/legacy programs with Italian leadership seems not corresponding to the scientific level of Italian A&A. It is therefore a priority to support with dedicated funds and manpower the organization and realization of large programs on these infrastructures. This is strategic, also in view of the new infrastructures with strong Italian involvement that will soon start producing data, such as LBT, VST, Planck, Herschel, SRT, ALMA.

Support an aggressive program of technological research & development. In a situation of limited resources, at least two fundamental requirements must be satisfied in order to participate to the planning and development of new large observational infrastructures. The first, discussed above, is the support for the full scientific exploitation of these infrastructures. The second is the support for strong programs of technologic R&D related to the project. Technological R&D which is in general expensive, must always be justified by a strong scientific requirement. For this reason the limited available resources should be concentrated in the few "core programs" which appear the most promising and for which there is the possibility to acquire the leadership.

Support the exploitation of data archives. Together with realization of large/legacy programs, the best possible exploitation of scientific data already available in archives must be encouraged and supported. Large data archives are today available from both observatories and dedicated missions and projects. Often these archives are interconnected through VO protocols, which ease their comprehensive use. The development of data archives devoted to the main scientific projects with a large Italian involvement (e.g. VST, LBT, GAIA, HERSCHEL) should be pursued, including a support and a close interaction with the ASI Science Data Center. It should be emphasized that while data mining activities have already taken strong roots among the optical, infrared and high energies communities, also interplanetary missions like Cassini, Mars Express, Venus Express etc. produce a large amount of data that sometimes are under-utilized. The analysis and interpretation of archival data from the instruments on board these missions will also have the advantage to train and prepare the community interested in the exploration of the solar system to the data that will be produced by Rosetta and by BepiColombo starting from 2014, the next high priority enterprise of this community together with GAIA.

Stimulate an aggressive outreach policy. A strong initiative in the field of public outreach is a strategic priority of INAF. Planetary missions are particularly well suited to reach a large public and can work as a fly-wheel to promote also the other fields of astrophysical research, which require stronger efforts to increase their intelligibility and therefore visibility toward a large public.

Contact points with fundamental physics. Beside traditional astrophysics and planetology, gravitation, astro-particle and very high energy (GeV, TeV) astrophysics are fields in vigorous development. It is crucial to maintain and develop competences in these border fields between astrophysics and fundamental physics for at least two main reasons. The first is that numerous activities in the framework of astro-particle and cosmology were born in the CNR institutes, and are therefore part of the cultural heritage of today’s INAF. An inadequate support to these components would represent a cultural impoverishment of the Institute. The second reason is that within the international community the interest in these areas connecting physics and astronomy is becoming pre-eminent. INAF is particularly well suited to play a forefront role. It is therefore a priority to maintain and increase the presence in these fields and, at the same time, to strengthen the collaboration with scientists of other institutes in Italy (INFN, CNR, etc) and abroad. To this purposes initiatives should be undertaken, as, for example, the set-up of exchange programs at the level of young scientists and Post Docs and the creation of structures to promote the collaboration in such areas.

Recommendations on Plasma Physics. Universe is mostly made of plasma and, therefore, Plasma Physics plays a fundamental role in several areas of Astrophysics. Understanding the behaviour of several astrophysical objects (e.g. accreting systems, relativistic jets and bipolar proto-stellar flows, winds, supernova remnants etc.), relies on studying the physical effects at play in a plasma as well as the complex interaction among them. If, on one hand, Astrophysics may naturally be organized according to "objects of interest" (the Sun, planets, stars AGN, galaxies, etc.), on the other hand Plasma Physics plays a role getting across the various fields of Astrophysics, because it pertains to many fundamental phenomena, often occurring in astrophysical objects having quite different dimensions and physical regimes. For all these reasons we recommend to maintain and support research in astrophysical plasmas because it is a fundamental tool to understand our Universe.

Recommendation on theoretical research. Most of the times, major scientific discoveries arise from the synergic interaction between observational findings and bright theoretical insights. While theoretical ideas sometimes are driven by the results of new observations, it is also true that some theoretical work has served the scope to start new types of observations. It is important that the support to theoretical research in all areas of astrophysics remains at the highest priority.

Strategic coordination with Universities to create a compact national Astrophysical community. This could to be achieved through a deep integration of research activity and higher education, and realized with several tools, which include joint PhD degrees and mobility staff exchanges between INAF and the Italian Universities. The scope includes forming an integrated nation-wide astrophysical community and attracting new students to the astrophysical research. To this end such integration should be structural and not occasional, in analogy with that -very fruitful- of other institutions (e.g. INFN).

The details of such a close collaboration between Universities and INAF have to be envisaged in a proper convention that takes into account both the autonomy and the different roles, in research and education that law assigns to the two institutions.

6.2 Road-maps

6.2.1 Early Universe

In the past decade the Italian community has achieved an international leadership on early Universe studies thanks to **CMB balloon-borne experiments** and the preparation of the Planck mission. This is a nice example of a very fruitful collaboration between INAF ASI and several Italian Universities.

The highest priorities for the next decade are therefore straightforward and consist in: a) making adequate investments in human and financial resources to fully exploit **Planck** data; b) maintain the leadership on balloon borne experiments by continuing a comprehensive program of finalized experiments that can nicely complement the topics covered by Planck, such as: CMB fluctuations over small angular scales, CMB polarization studies; c) study and prepare a satellite mission dedicated to the detection of B-mode polarization of the CMB.

6.2.2 Mid and Far infrared astronomy

The NASA **Spitzer** satellite is revolutionizing both Galactic and extragalactic astrophysical forefront studies in the 3-70 micron band. The exploitation of the Spitzer archive must be pushed, and support to projects using Spitzer data should be given, also in preparation to the full exploitation of the data that will soon be produced by the **Herschel** satellite. A large fraction of the Herschel time is dedicated to large programs; adequate support must be guaranteed to the Italian community already involved in these programs and to the groups that want to propose new large programs. On longer time scales, the Italian community should participate to **SPICA**, the next large mission for mid to far infrared observations developed by Japan with a strong ESA and European participation, and in the ESA concept for a FIR interferometer in Space in the framework of the CV program.

JWST will be launched in the early years of the next decades, and is expected to become the successor of HST for the near to mid-infrared wavebands. The communities that are involved in its construction will obtain most of the first light results, and the Italian role is very limited. For this reason, despite its outstanding scientific priority, it cannot be a major priority for INAF, albeit it is mandatory to guarantee support to the (small) number of Italian researchers involved and, close and after its launch, provide support for the access to its data.

6.2.3 Optical and near infrared astronomy

In the optical and near—IR domain, the instrumentation of the VLT telescopes will remain the most competitive tool for Italian astronomers in the nearby future.
A top priority for INAF is to act in order to keep **VLT** instrumentation at the top level, in particular supporting the development of new instrumentation, and to ensure a proper exploitation of their capabilities by the Italian community. In this regard it is particu-

larly important to support the participation of Italian scientist to second and further generation instruments like the X-shooter and Sphere.

In parallel, it is also important that the Telescopio Nazionale Galileo (**TNG**) is made more competitive, both through a more intensive use for large surveys or long term projects and through the development of new dedicated instrumentation, as in the case of the recent GIANO project. The continuation of the operation of TNG should be subject to periodic reviews to asses whether its scientific capabilities are commensurate to the investment and to the international competition.

The experience of the very last years has shown that **small telescopes** can produce important scientific results, provided that they have a very clear goal and that they are optimized or highly specialized, and possibly robotized. The network of Italian small telescopes is far from this state. It is necessary to consider the cost-effectiveness and the scientific return of these facilities. The future use of these small telescopes must follow the same rules mentioned above: have a clear scientific goal, a small operational cost and possibly a high degree of automation. Because of their nature, these facilities might attract regional funds, and have a role in educational and outreach activities.

In the mid term, the Large Binocular Telescope (**LBT**) is a major priority for ground-based observational astronomy in the optical and near-IR domains. In the near future, the scientific potential of LBC must be fully exploited through dedicated large surveys, possibly in cooperation with other multiwavelength projects that use facilities as VISTA, XMM, Herschel or eventually ALMA. In the mid term, the scientific return of LBT is related to the development of key technological features, like those of adaptive optics and eventually interferometry. Here, it is important to ensure that such a technological development is driven by a strong scientific interest.

Another major priority of the forthcoming years will be the **GAIA** mission, an ESA cornerstone. GAIA will not only deeply change our understanding of the nature and evolution of the Galaxy but also produce fundamental breakthroughs on our solar system. It is mandatory that INAF supports at any level the Italian participation to this mission, mostly through the support to the science preparation activities and through the involvement in the data analysis process within the European context.

VST is the other mid term project devoted to the execution of large surveys in the optical domain. It is mandatory to ensure a proper scientific return to the large investments done by the Italian community. This can be pursued by a revision and update of the scientific plans based on competitive calls open to the whole Italian community, but still capitalizing the experience of the teams that led the design and construction of the telescope and instrument. A proper support to the huge process of data analysis must also be foreseen.

The public data obtained IR survey telescopes, like **UKIRT** and **VISTA**, will naturally complement those obtained by VST and LBC, and will also allow fundamental studies of the Universe. It is important to support the Italian collaborations that plan to use such data sets.

Interferometry in the near-IR with VLTI and LBTI has, potentially, a large discovery space, by exploring a region of parameter space never explored before. **VLTI** will reach resolutions of ~10mas but will not produce, at least in the near future, real images. The analysis and interpretation of the data requires the knowledge of the source morphology, or a model of it. The full exploitation of VLTI appears therefore limited to a number of well-focused astrophysical problems, pursued by dedicated groups. Participation in the development of second-generation VLTI instruments, which may have real imaging capabilities, will open this area to a broader community. **LBTI (Linc-Nirvana)**, on the other hand, will reach resolutions al least 3 times worse than VLTI, because of the smaller baseline, but the binocular mounting allows Fizeau interferometry and direct imaging (although with a complex PSF). A spectroscopic mode would enhance the scientific output of Linc-Nirvana and would be an instrument with unique capabilities. Scientific programs, representing a breakthrough with a PSF only ~3 times better than that of HST or than that of a diffraction limited 8m telescope, still need to be planned, and their feasibility still need to be verified.

COROT is a project where a relatively small support can provide important returns about the searches of extraterrestrial planet, where the Italian community is very active. Support to such mission should be therefore guaranteed.

On a longer timescale, the future of ground-based astronomy in the optical-NIR domain is tied to the development of the next generation of Extremely Large Telescopes (ELT). The Italian community is already playing a major role in the scientific definition of the European project, as well as in the technological development participating in the ESO-ELT Science and Engineering Working Groups. A full support to such activity is definitely mandatory, both in terms of contribution to research groups as well as in coordinated actions at the highest political levels.

Another future frontier, with potentially big discovery space, is very wide field imaging from both 8m class, ground-based telescopes (e.g. the **3sq-deg** imaging camera) and space-born missions (**SNAP/JDEM**, **DUNE**), focused at the search of high-z SNe, weak lensing surveys and very large area surveys in general.

6.2.4 UV astronomy

Access to the UV wavelengths is currently problematic especially for spectroscopy. At the moment, **HST** guarantees access to low resolution UV spectroscopy through ACS which recently experienced major problems. Even assuming a full success for the fourth servicing mission, planned for 2008, with the installation of COS, it is hardly conceivable that HST will remain fully operational after, 2012-2015. Low resolution spectroscopy is currently provided by Galex while access to far UV is provided up to 2008 by Fuse.
Currently, NASA and ESA do not have plans for any future UV mission, which, as a consequence, cannot be expected before the 2020-2025 timeframe. This will produce a big gap between HST and the next ESA/NASA UV mission. It is important that INAF acts in the international context to explore all possibilities to ensure that the UV window remains open in the future.

In this regard it is important to carefully evaluate the feasibility also of smaller projects, like WSO. The project itself and the Italian contribution are being finalized. Nevertheless, before considerable investments both in terms of manpower and funds are approved, a number of critical issues should be clarified, such as the Italian contribution and the consortium definition, the detailed management plan and schedule, and the scientific return for the Italian community.

6.2.5 Radio and sub-millimeter astronomy

In the past decades the centimeter VLBI project has been one of the top projects of the Italian astrophysical community. Today, to prepare the future, a quantitative and qualitative review of its use from the Italian community is needed. In other European countries, the development of the VLBI toward millimeter wavelength is preceding fast, see for example the Global VLBI Millimeter Array (GVMA) network, coordinated by the Max-Planck-Institute fuer Radioastronomie. The GVMA is today able to provide good quality images in the 3mm band, with an angular resolution of typically 50-70 micro-arcseconds. Furthermore, the GVMA allows spectroscopy in a number of interesting molecules with masing transitions in the 40 and 100 GHz bands. The participation in the GVMA is therefore recommended. In this framework the Italian community has proposed and is building the **SRT**, a large and high technology radio-telescope which may allow to observe at 100 GHz with good aperture efficiency, thanks to its active optics. If this goal is reached, SRT can be the response to the large pressure for high frequency observations, provided that the site is up to the expectations. This sets natural priorities for the radio-astronomical community. First, together with the completion of the SRT antenna, an accurate monitoring campaign to assess the quality of the site for high frequency observation should be performed as soon as possible. If this study is successful, receivers at 40 and 100 GHz should be developed on an aggressive timescale. Should the site result not well suited for high frequency studies, the scientific priority of the project would be reduced, even if the development of more conventional instrumentation would still allow breakthrough studies on a few hot topics, such as the search for binary pulsars and their characterization. Nevertheless, to be competitive with other facilities such as the Parkes radio-telescope, a dedicated instrumentation should be developed, to allow, for example, the search for more compact binaries. Since the investment for the development of dedicated instrumentation (either for high frequency observations or for other kind of observations) and for the maintenance and operation of SRT is high, the possibility to involve international partners in this project should be investigated, as well as the possibility of an upgrade to join the Deep Space Network.

The upgrade for millimeter VLBI of the Noto and Medicina antennae would of course increase the quality of the network, together with the Italian impact on the full project. However, it is not clear weather these sites can efficiently support high-resolution observations, and the upgrade of the two antennae, together with the development of other 40 and 100 GHz receivers, are certainly very expensive. These activities have therefore lower priorities with respect to the completion of SRT and the support for its full exploitation, and, in any case, a comprehensive site testing campaign that demonstrates the feasibility of mm observations from the Italian sites must be carried on before making any decision.

A top priority is the support to the development of **ALMA** also through the support of the Italian node of the European ARC. Particular emphasis should be given to the growth of the extragalactic millimeter community and the synergies between scientific projects with ALMA and other facilities, such as **Herschel/Spitzer**, **JWST** and the national and international optical/infrared telescopes (**VLT/LBT**).

At the other end of the radio spectrum, the long wavelengths, the large project currently being developed by the European Radio-astronomical community is **LOFAR**. This project has certainly a high scientific discovery space. Today, the involvement of the Italian community in LOFAR is only marginal. The participation to the preparation of the hardware, through the development of one or two LOFAR station is in competition with the other projects that the radio-astronomical community wants to carry out, SRT first of all. If both financial and human resources can be found without impacting on the completion and operation of SRT and the development of **SKA**, a participation in the LOFAR project is certainly desirable. For example, a small participation, like the upgrade of part of the Croce del Nord as a LOFAR station, would already be important. LOFAR will also test new technologies to be used for SKA, the next big, planetary-size, radio-astronomy project. SKA has top priority scientific programs, including tests of fundamental physics, formation of first stars and galaxies, formation of planetary systems. INAF-IRA takes part to the EU project SKADS, to use the Croce del Nord as a test-bed for SKA technologies. Maintaining a high level participation in the design and promoting appropriate lobbying to the funding agencies to ensure the construction of SKA is a strategic high priority for INAF. The ambition of SKA is to create a world-class collaboration project, for its complexity and size such a project falls into the same class of ELT, ALMA and large space missions or even beyond. It may be difficult to successfully build and operate such a project without the political, technical and managerial support in a framework of an international organization similar to ESO or ESA. INAF should take a proactive role with the aim that this project is undertaken in a framework that will ensure its final success.

6.2.6 X-ray astronomy

X-ray astronomy has now entered in a phase of full maturity. The access to the X-ray spectrum is guaranteed today by two large observatories, **XMM-Newton** and **Chandra**, launched in 1999 and now in the middle of their lifetime, by **Swift**, a MIDEX NASA mission with significant Italian involvement, by RXTE, another NASA satellite, and by Suzaku (Astro-E2), a Japanese satellite launched on summer 2005 (the Suzaku main instrument failed soon after the launch and the access of the Italian community to Suzaku is anyway limited). The access to the hard X-ray, soft gamma-ray spectrum is guaranteed by **INTEGRAL**.

On short time scales the highest priority is to support the Italian groups already involved in large and legacy programs using Chandra and XMM-Newton, the groups that want to propose new large programs, and those performing multi-band studies using infrared, radio, and optical facilities, together with X-ray and gamma-ray observatories, and generating multiwavelength archives. Unfortunately, no new X-ray mission is today in an advanced phase of preparation, and therefore there is the concrete possibility of a large gap between the end of Chandra, XMM-Newton and Swift operations and the start of a new X-ray observatory. INAF should operate in the national (ASI) and international (ESA, NASA) context to avoid this gap, or make it as short as possible. In this framework, it is particularly important the involvement of Italian scientists in the Simbol-X project, for which a common Italian and French phase A study is starting. Simbol-X will improve the sensitivity in the 10-100 keV band by 2.5-3 orders of magnitude with respect to BeppoSAX, INTEGRAL and Suzaku, opening a new window in astronomy. This is probably the only reliable medium-large X-ray project with a chance to fly within 2015. On longer times scales the highest priority is to support projects in the framework of the ESA Cosmic Vision 2015-2025. In particular, this is, together with the NASA Beyond Einstein program, the only realistic framework in which an **X-ray observatory with a very large collecting area** is envisageable. To fully exploit a large collecting area very good image quality (PSF of the order of a few arcsec or less) and good spectral resolution ($E/\Delta E>1000$) are needed. These requirements are today technologically demanding, but they may be reached in the timeframe of the CV or BE programs. If this should not be the case the scientific case of such a mission, and therefore its priority, would be reduced. INAF, and the Italian scientific community in general, should act to guarantee the maximum possible technological and scientific pay back from the participation to such a mission.

The ESA Cosmic Vision and the NASA SMEX and MIDEX programs can also be possible frameworks for smaller missions, focused on specific scientific goals, in which the Italian community is also interested (e.g. X-ray polarimetry, the physics of the ICM and IGM, nuclear lines in SNR as probes of the synthesis of heavy elements). A mission to tackle the latter topic would be the natural follow-up of INTEGRAL for what concerns the 0.1-1 MeV astronomy.

6.2.7 Gamma ray astronomy and Cosmic rays

The Italian astronomical community is deeply involved in the preparation of **AGILE and GLAST**, in close connection with INFN. AGILE should be launched at the beginning of 2007 and GLAST six months to one year later. Although AGILE has some advantages with respect to GLAST (an X-ray monitor), the much smaller size of the gamma-ray detector implies that this experiment may be competitive with GLAST only if the best exploitation of the data is made possible before the GLAST launching.
This advantage can also be used to best train the community to a) prepare competitive GLAST programs; and b) make full and quick use of the GLAST data. This is also an area in which the synergy between INAF and INFN can and must be made valuable.

The community is also showing a growing interest in **Cherenkov telescopes** as the future of gamma ray astronomy. In fact HESS and MAGIC (the latter with a very relevant INFN involvement) are already producing a mass of data with an impressive amount of discoveries. The Italian astronomical community should enhance the involvement in the future developments in this field (e.g. GAW, HESS2, MAGIC2, CTA). In this sense it is desirable that a tighter scientific connection is established with INFN. An alternative way to detect gamma-rays from the ground is through gamma-ray initiated showers. The sensitivity is in general smaller that Cherenkov telescopes but the large field of view would allow for the search and detection of transient phenomena such as GRB.

In the field of Cosmic Rays, Italian scientists are currently involved in both theoretical studies and experiments like the Pierre Auger Observatory (PAO) and KASCADE-GRANDE. The PAO is currently being built in Argentina, and will become fully operational at its complete size within 2008. A second part of the project is being planned in the northern hemisphere. The Italian community is strongly involved in the construction of Auger South through INFN, though many scientists are part of INAF. INAF should therefore guarantee the support to the people involved in Auger south completion and Auger north design and create the conditions for the best possible exploitation of the upcoming Auger data.

Future developments in this field should be aimed at the construction of a space-borne experiment, along the lines of projects such as EUSO and OWL, and with a strong Italian involvement, in the framework of ESA CV.

6.2.8 Planetary science

The community is today involved in the exploitation of the large amount of data coming from the **Cassini, Mars Express and Venus Express missions**. This is a top priority effort, because, in addition to the obvious importance "per se", it is an excellent training while waiting for the data of the **ROSETTA** mission, the next cornerstone in science of the solar system together with **GAIA**, which will provide breakthroughs data on the minor bodies of the solar system. Furthermore, the largest and best possible exploitation of the Mars Express data is also strategic and propedeutic to the preparation of the ExoMars program, the highest priority of the European community about the exploration of terrestrial planets in the next decade(s). Another top priority is the participation to BepiColombo, a long standing ESA project, whose industrial phase has been recently approved.

The participation of INAF scientists to the NASA mission **DAWN** ensures the access of the Italian community to in situ data of small bodies of the solar system (Ceres and Vesta).

A large interest may also be associated to a **Moon program.** However, the efforts to produce a real breakthrough in this field ought to be very large (similar, say, to the Mars Express program), given the knowledge already reached by past and present mission. A small mission would not achieve this goal. A large mission would naturally involve several international partners, whose interest in this field, and consequent realistic programs, have still to be verified.

Other two planetary missions are discussed in the framework of the ESA Cosmic Vision program, and therefore on longer timescales: a mission dedicated to the "in situ" **exploration of a NEO** and a mission dedicated to the exploration of the **Jovian system**, a natural follow-up of the Cassini mission.

6.2.9 Solar physics

The next future will see the extension of the **SOHO** mission until 2009 and, more important, an unprecedented effort by the international solar and interplanetary community for a global coordination in solar and interplanetary studies within the International Living With a Star (**ILWS**) project. This includes solar missions like SolarB and SDO, heliospheric and magnetospheric missions like Coronas, and dedicated instruments on board Bepi Colombo, and a new class of **large aperture ground-based solar telescopes** like ATST, and EST. The participation of the Italian community to SOHO and the ILWS activities is recommended to remain at the forefront of solar physics while preparing for the next generation of solar instruments, which will take significant time to appear. In particular the most important ESA mission in this context, namely **Solar Orbiter**, is expected to fly not before 2015. The possible participation of Italian Astronomers to the development of an the Ultraviolet Coronagraph and of plasma analyzers for this mission have an high priority and should be actively supported. The **SCORE/HERSCHEL** rocket programme, based on a prototype of this new class of EUV/UV and visible-light coronal instruments, is a path-finder for Solar Orbiter and, and as such, should be supported. As for ground-based instrumentation, it is important that the Italian community contribute to the European organization aimed at defining and co-ordinating ground-based solar research, including design and construction of world-class observing facilities. In this regard, the involvement of Italian community in a Large Aperture Solar Telescope (e.g. ATST, EST) project is vital to ensure Italian solar astronomers a leading role and appropriate access to the research at the forefront of this field.

6.2.10 Gravitational waves

The quest for the detection of gravitational waves is certainly one of the major hot topics for the near future. INFN is deeply involved in both ground-based projects (VIRGO) and space-borne projects (**LISA**) for the detection of low frequency gravitational waves. The involvement of INAF in these projects is today marginal. It is desirable to increase the involvement, especially in the scientific exploitation and interpretation of the data.

6.2.11 High performance computing

Finally it is worth emphasizing the importance in astrophysics of

High Performance Computing, handling and analyzing large databases and the use of GRID for astronomy. INAF already has a preeminent role in these activities: recently it signed a new agreement with CINECA (in Bologna) for the use of the related computer resources and it has an important role in two recently created consortia, COSMOLAB (in Sardinia) and COMETA (in Sicily) which have obtained significant economic resources for high performance computing, databases and Grid. It is of fundamental importance that INAF benefits from the large investments already made and that it maintains its preeminent role in these fields given the larger and larger strategic importance they are gaining.

6.3 Summary of priorities

Priorities are summarized below in three broad priority categories.

6.3.1 Recommendations of top priority projects

The projects listed here represent the major current and future international enterprises, that can give outstanding breakthroughs in the next decade, and on which the Italian community has or can have a leading role. Having only a marginal role in these projects would represent a major setback for a relevant part of the community. The INAF actions toward these projects are mostly to support the involved Italian community, and to guarantee the highest scientific return with a relatively small level of investment, whenever this is possible. The actions recommended in this section should be considered as having the same priority level. INAF should:

- The access of the Italian community to major present and near future international facilities with significant Italian contribution must be guaranteed and possibly increased through a dedicated support. Such facilities are: **VLT, XMM, SOHO, Herschel, GLAST**, **Auger**. Improving the access to other major present international facilities with little Italian involvement, like **HST**, **Chandra**, **Spitzer** and in the future **JWST**, would also be desirable.
- Develop Italian-led **innovative instrumentation for large ground-based telescopes** and in particular actively support the development of next generation **VLT** instruments. Act to keep the VLT instrumentation at the top level.
- Prepare the community to the exploitation of the next large ESO and ESA facilities like **ALMA** and **GAIA**.

- Participate in the development of the future major facilities like **ESO-ELT**, **SKA**, high sensitivity observatories in both **soft and hard X-rays**, provided that a relevant participation of the community to the instrumentation and/or to the science is guaranteed.
- Support the community involved in **Mars-Express**, **Venus-Express** and **ROSETTA** and the preparation of **BepiColombo** and **ExoMars**.
- INAF should act to guarantee the full exploitation of **Planck** data and to maintain the leadership on **CXB sub-orbital experiments**, also in preparation of the participation to a mission dedicated to the detection of the **B mode polarization of the CMB**.

6.3.2 Recommendations for very important projects

Projects requiring high level of funding from INAF

The projects listed in this section are also expected to produce breakthroughs and a very high scientific return for the Italian community, but, on one side they require a high level of investment for their development and operation (several MEuro/year), and, on the other side, their full exploitation is still subject to significant risks.

The three projects discussed below are the largest and most important projects in which INAF is involved today, and the following actions are suggested:

1. Supporting and easing the access of the Italian community to **LBT** for the best exploitation of its scientific capabilities, also with synergic efforts with the other partners, is a first priority. **LBC** should be best exploited through dedicated large/legacy surveys.
2. **TNG** should be made more competitive by focusing its use on a few, large specific programs.
3. Take radical actions to ensure the rapid completion of **VST** and consider with ESO the options for collaboration and support to clear the technical issues that are still outstanding. Support large/legacy surveys, following a critical review and update of the scientific plans, with the involvement of the Italian community at large.
4. Specialize **SRT**, provided that its capability to efficiently reach high frequencies (40-100 GHz) is first demonstrated.

Projects requiring a medium level of funding for INAF

Other projects require a medium level of funding (a fraction of MEuro/year) with potentially large impact on the community. For them the following actions are recommended:

1. Support the exploitation and development of ground and space based **optical and near-IR survey telescopes**.
2. Carefully evaluate science cases for infrared interferometry with **VLTI** and **LBT** before investing significant resources in these projects.
3. Participate in the development of a large ground based solar telescope and the participation to **Solar Orbiter.** Support the scientific activities tied with the program **International Living With a Star**.
4. Support actions aimed at maximizing the access of the Italian Community to the data from Cherenkov telescopes. Investigate the possibility of participation in the development of one new project in this field like **MAGIC2**, **HESS2** in view of a significant involvement in the **Cherenkov Telescope Array.**

Projects requiring a relatively low level of funding from INAF

In addition there are other projects that can produce breakthroughs on specific topics, and do not necessarily require large investments from INAF (less than a few hundred kEuro/year). The following actions are recommended:

1. Support the groups involved in the development and preparation of future Infrared missions and facilities like **ESI-SPICA** and **space interferometers** in the framework of ESA CV and NASA programs.
2. Facilitate the exploitation of **Swift** and **INTEGRAL** data and support the interested community.
3. Support the exploitation of the **AGILE** data, also in preparation to GLAST.
4. Study X-ray and gamma-ray missions capable of achieving breakthroughs in some specific areas like **polarimetry, the physics of the IGM and of the ICM, nucleosynthesis in SNR**.
5. Participate in the planning of the **next generation of Cosmic Ray experiments**, including space-borne experiments if a strong scientific case is made in this sense.
6. Support the exploitation of the data from major planetary missions like **Cassini**, **Mars-Express**, **Venus-Express**, also in preparation to the exploitation of data from ROSETTA. Participate to the definition of a new mission to the **Jovian system** and to

the in situ exploration of a **NEO**, in the framework of the ESA Cosmic Vision program.

6.3.3 Recommendations for other projects

The following actions should be considered:

1. Develop a plan for the optimal use of the **Italian small telescopes** and consider decommission or change of use for those with limited scientific value. Explore cost effective alternatives for programs needing access to these facilities.
2. Participate in the development of **LOFAR**, possibly with the upgrade of the Croce del Nord.
3. Define the Italian contribution to the **WSO** consortium and the return expected for the Italian community. A detailed management plan and schedule should be made public before investing large resources in this program.
4. Consider the possibility to upgrade the Medicina and Noto **VLBI** antennas to mm wavelength, subject to a careful site-testing campaign to demonstrate the possibility of efficient mm observations.
5. Support the exploitation of the data from the **DAWN** mission and explore the opportunity and possibility of a large **Moon exploration** program in the framework of key international partners.
6. Support the small participation in **Solar B.**

Printed in March, 2007
Photographies at pages 4, 6, 8, 10, 12, 185, 186 are
snapshots from INAF Telescopes, Laboratories and
Institutes - © Renato Cerisola - INAF