Tracing the Formation and Evolution of the Giant Planets

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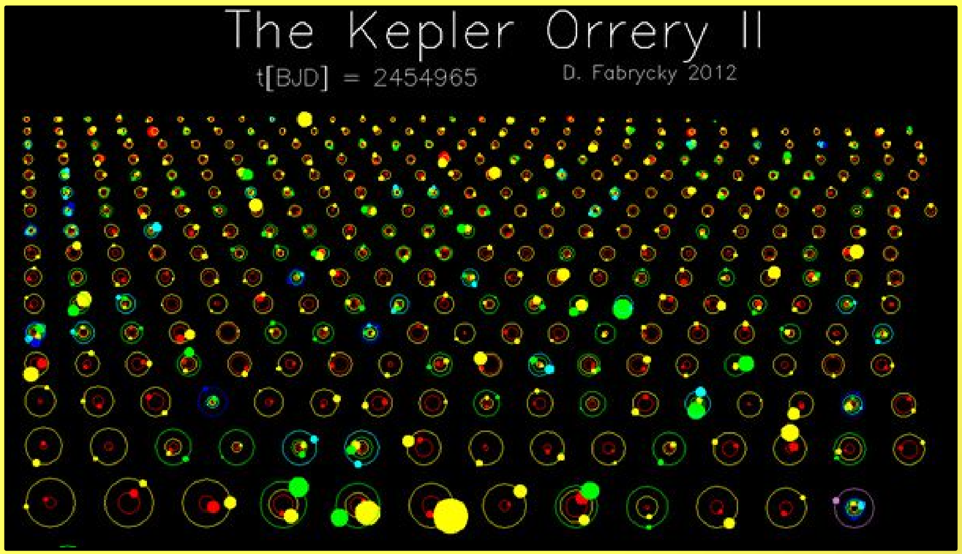
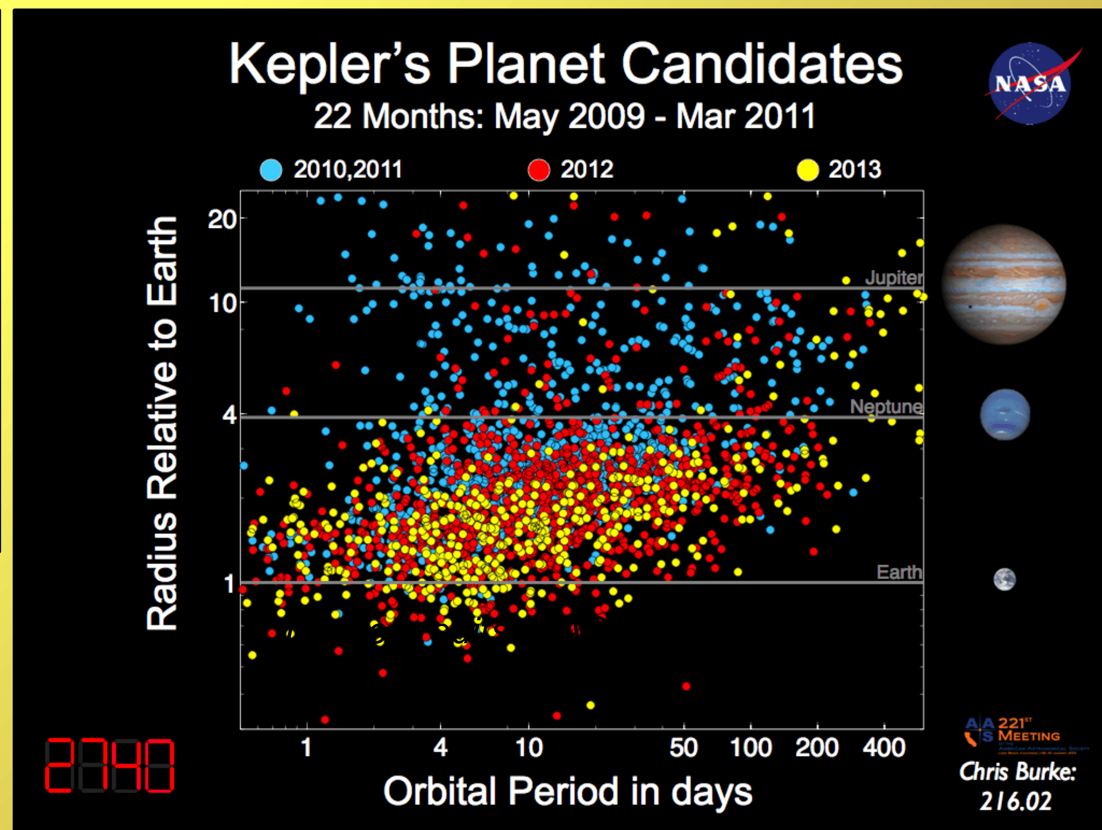
Solar and Extrasolar Giant Planets

As we discover more and more planetary systems through ground-based and space-based observations, we are getting a better understanding of the variety of outcomes of the processes governing planetary formation and evolution.



In order to understand the histories and what processes shaped the present state of the know planetary systems, we need information on their composition.



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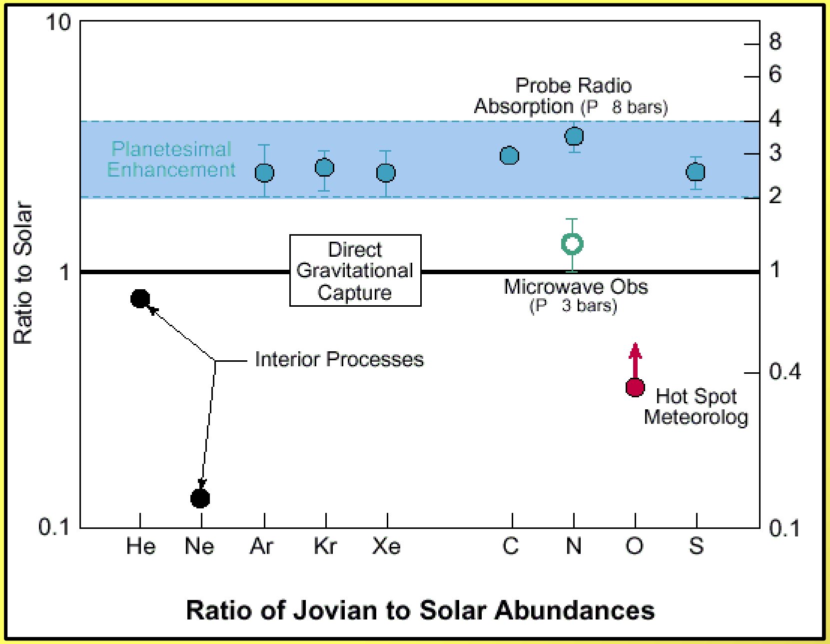
Lessons Learned from the Solar System

The Galileo mission revealed that the **Jovian atmosphere** is characterized by a **factor 3 enhancement of C, N, S and Ar, Kr and Xe** (Owen et al. 1999). Jupiter's bulk composition in enriched (3%-13%) in high-Z elements respect to solar (2%) composition (Lunine et al. 2004).



Elemental abundances (relative to hydrogen) in Jupiter's atmosphere, compared to solar abundances. Figure from Coradini et al. 2011 (updated from Lunine et al. 2004).

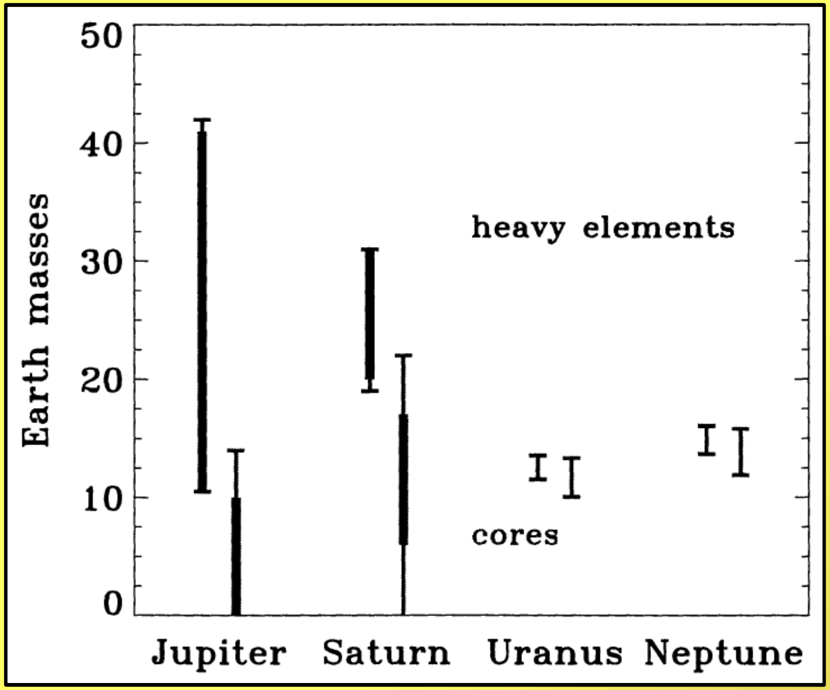
Also the other giant planets of the Solar System have been enriched in high-Z elements, but the **enrichment factor varies from planet to planet and possibly from element to element**.

For, e.g., C/H we have:

- **Saturn: 10.4±0.4** (Fouchet et al. 2009);
- **Uranus & Neptune: 45±20** (Guillot & Gautier 2007).

Formation or Evolution?

It is still an open question whether enrichment is a reflection of the formation mechanism or if it is due to the later evolution of the Solar System.



Abundance of high-Z elements in the giant planets (left bars) and in their cores (right bars). Figure from Guillot & Gladman (2000).

For a long time it was thought that **enrichment** could be used to **assess whether** giant planets **formed by core accretion or gravitational instability** (see e.g. Coradini et al. 2011).

Our **limited understanding of internal processes** (e.g. sinking of high-Z material and the erosion of the core by the convecting mantle) **make it difficult to answer this question** at present **for planets like Jupiter and Saturn** (Helled et al. 2011). However...

Probing the Formation Environment

…**atmospheric enrichment** and composition tells us about the **formation environment** of the giant planets (see e.g. Helled et al. 2011).

Enrichment in noble gases has been suggested to be due to the accretion of nebular gas from a **circumsolar disk** in an advanced (**H and He depleted**) stage of evolution (Guillot & Hueso 2006).

To explain the C (and O,N,S) enrichment of Jupiter, a **late accretion of planetesimals during the capture of the nebular gas** has been suggested (Owen et al 1999; Gautier et al. 2001; Mousis et al. 2012).

Late accretion is a "local" process, i.e. it tracks the region where the giant planet formed.

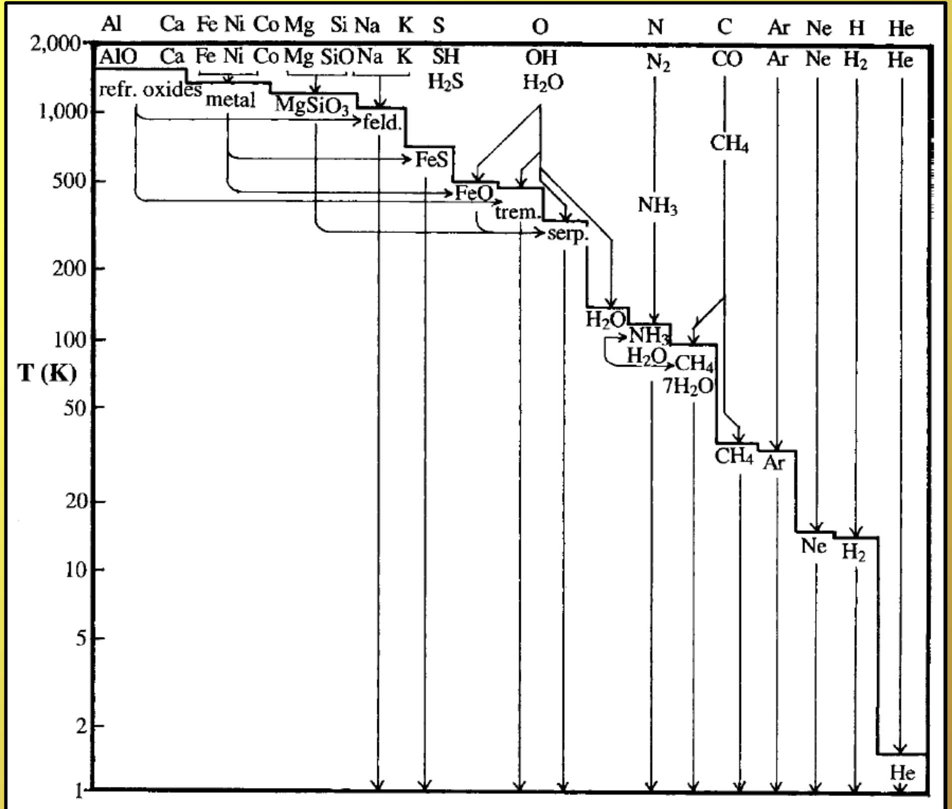
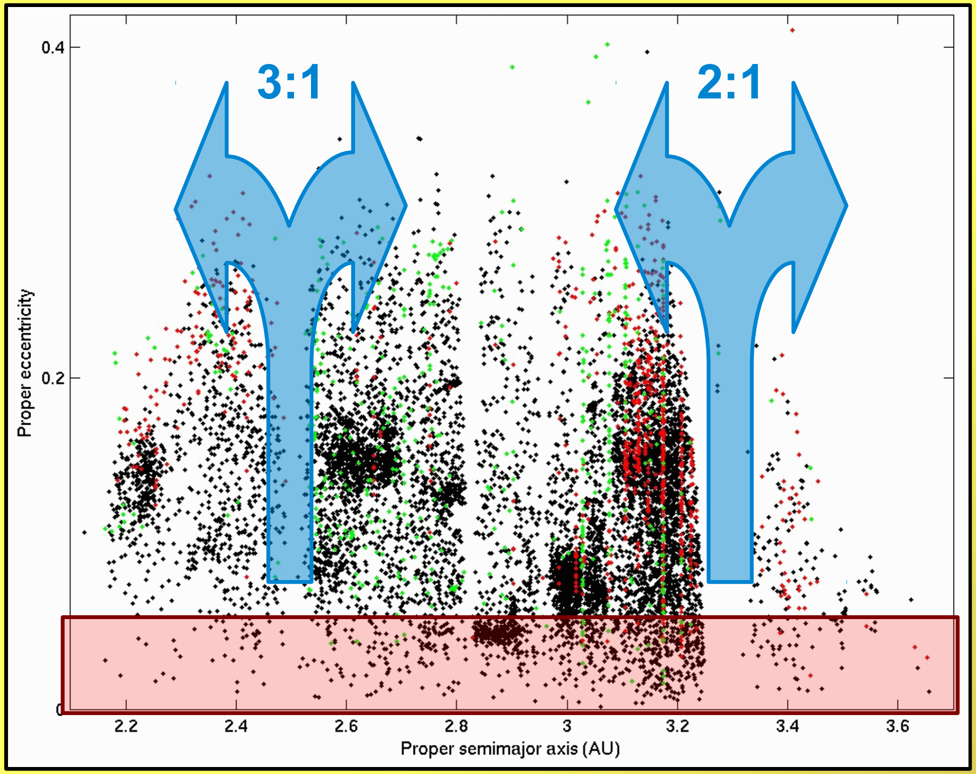


Figure IV.26 Major element flow chart for equilibrium condensation. The sequence of reactions of gases (above the solid line) and condensates (below the solid line) in solar material cooling at equilibrium. A pressure of 10^{-2} bar is assumed.

Condensation sequence of the Solar Nebula from Lewis (1996).

Post-Formation Evolution

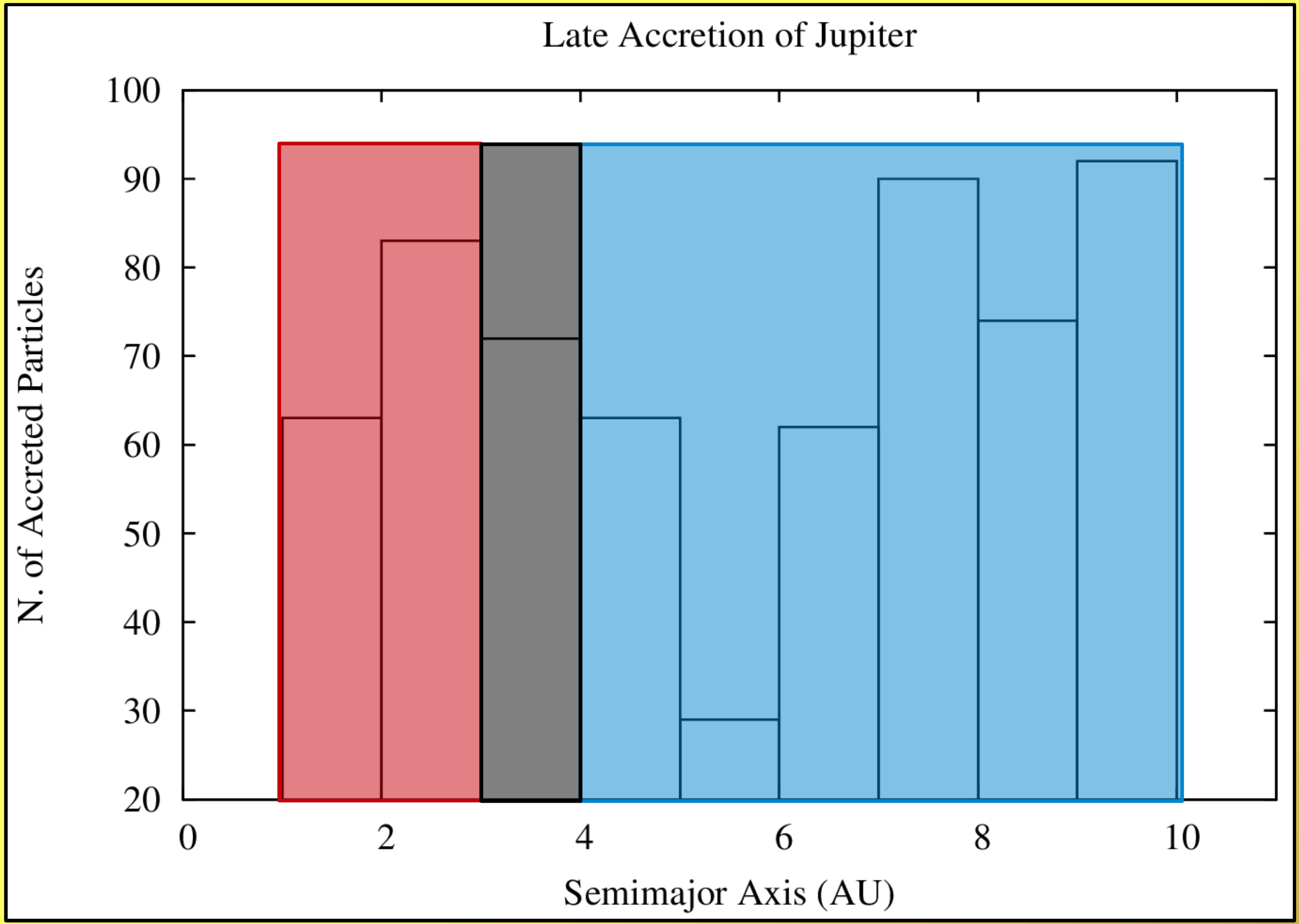
Safronov (1969) originally proposed that the formation of **Jupiter** should **scatter planetesimals from its formation region** outward, **supplying** further **material to** the forming cores of **Neptune and Uranus**.



The **formation of Jupiter** also causes the sudden **appearance of mean motion resonances** in the asteroid belt and trigger a **primordial bombardment** through the planetary system (Turrini et al. 2011,2012).

As a consequence of the two effects (scattering and resonances), the **formation of a giant planet** causes a **reshuffling of planetesimals** in the protoplanetary disk.

Long-Range Post-Formation Accretion

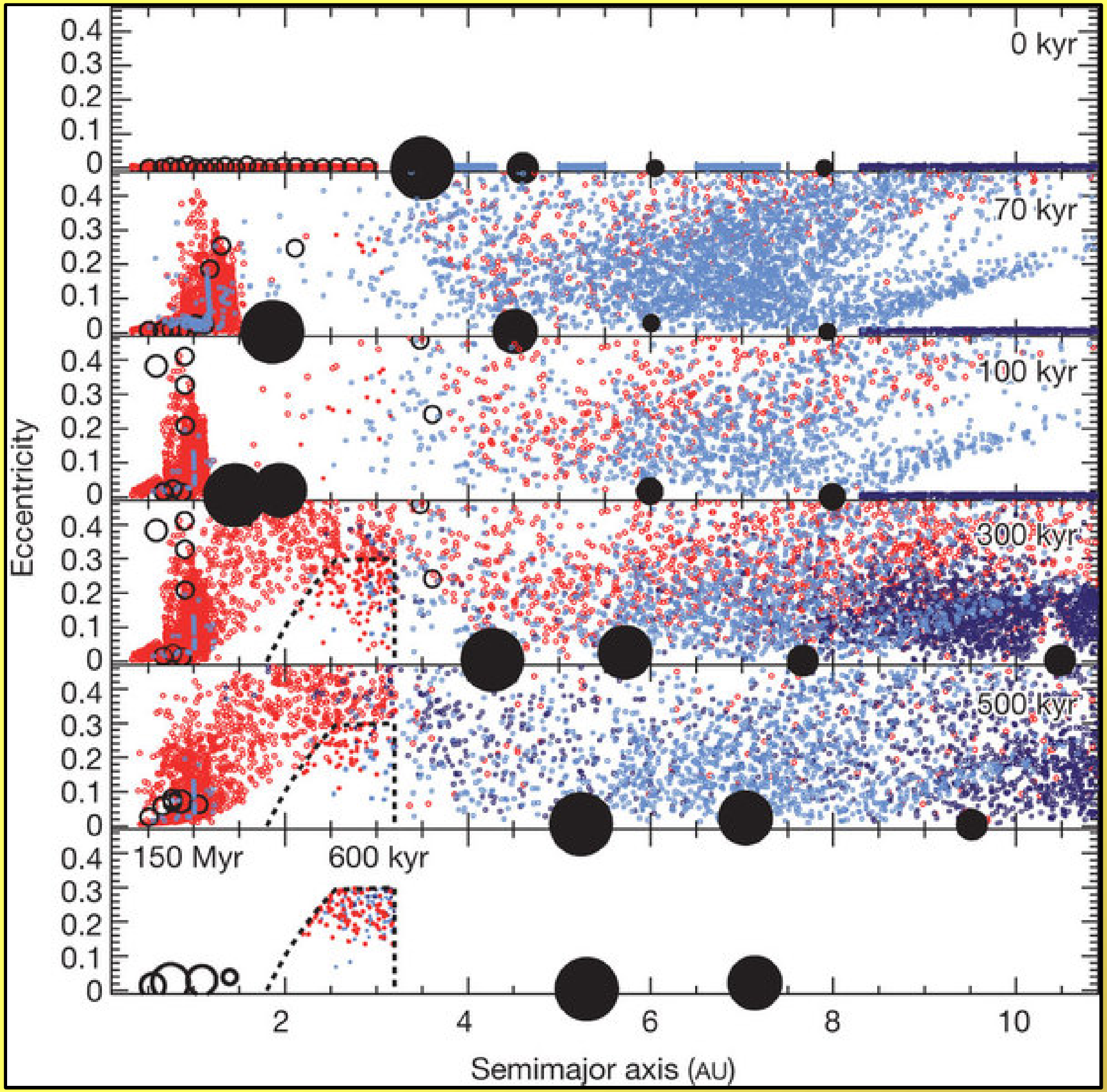


The mass accreted from **Region A** (red area) is analogous to **ordinary chondrites** (30% Fe, 70% Si);

The mass accreted from **Region B** (black area) is analogous to **carbonaceous chondrites** (1% Fe, 85% Si, 5% C, 9% H_2O);

The mass accreted from **Region C** (blue area) is analogous to **comets** (72.8% H_2O, 25.84% C, 0.62% N, 0.74% S);

Enrichment and Cataclysmic Scenarios



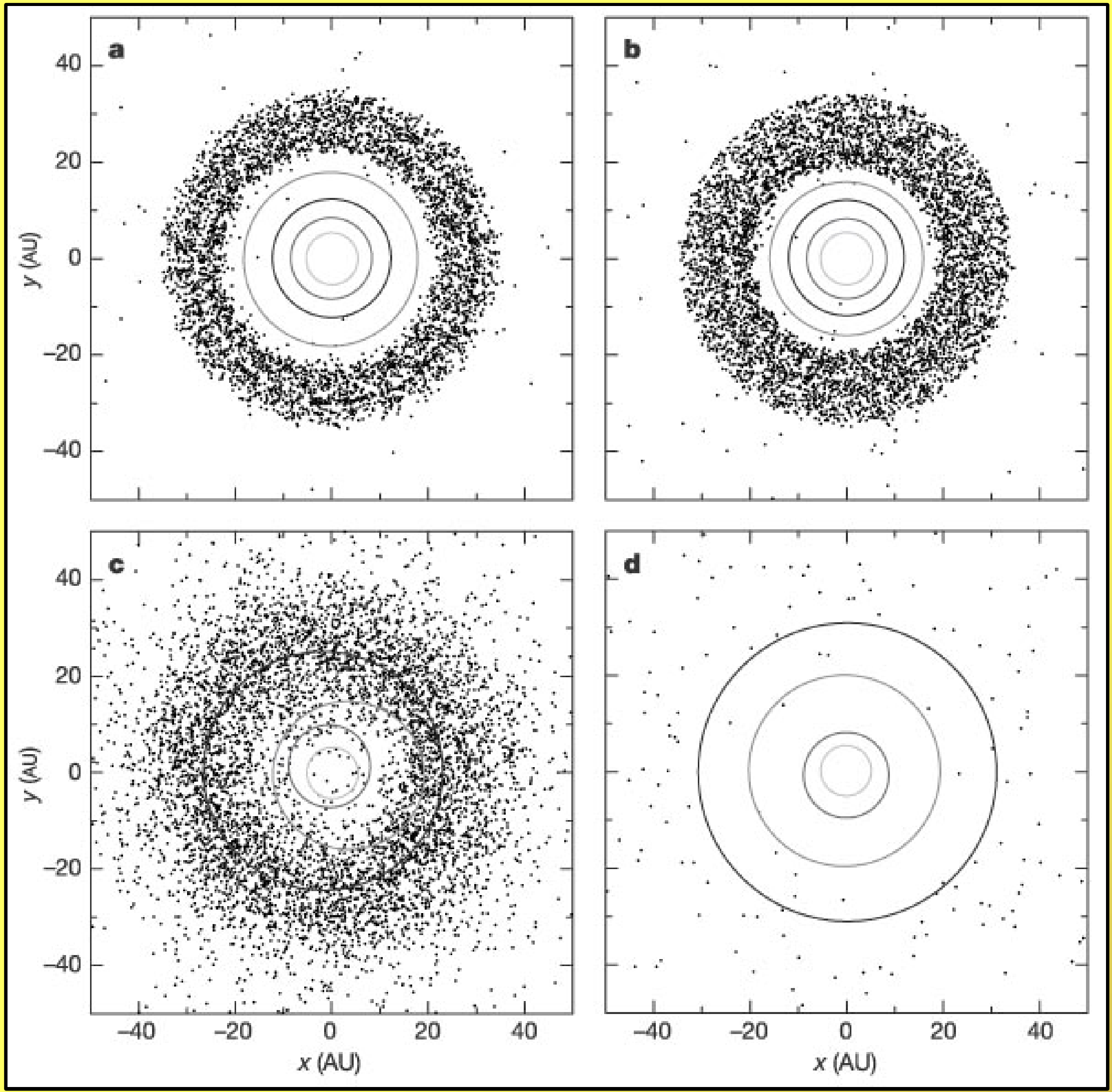
Recently, scenarios based on the **"Jumping Jupiters" mechanism** (Weidenschilling & Marzari 1996) have been proposed for the **evolution of the early Solar System** (Walsh et al. 2011, Nesvorny et al. 2011).

Scattering and resonances would **act even more dramatically** in such scenarios, resulting in a more marked enrichment of the giant planets.

Even if these scenarios have a **low probability to produce the Solar System** we know (D'Angelo & Marzari 2012), they can produce the **richness of orbital configuration of extrasolar giant planets**.

Evolution of the early Solar System (figure from Walsh et al. 2011)

Late Enrichments?



A **"Jumping Jupiters" scenario** that would produce a further compositional evolution of the giant planets is the **"Nice Model",** proposed to explain the **Late Heavy Bombardment** (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2005).

The **compositional changes** that can take place **at such a late time**, however, have been shown to be **extremely limited** (Guillot et al. 2009).

Evolution of the early Solar System (figure from Gomes et al. 2005)

That's All Folks… For Now!