Spectroscopy of protostellar systems: Herschel observations and the role of SPICA

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→ A biased and not-complete view of what SPICA could do for protostellar studies
Following proto-stellar evolution

- High extinction and warm gas \((Av > 40 \text{ mag}, T \sim 100-2000 \text{ K})\)
- Main route of gas cooling is line emission from mid- to far-IR \((H_2, CO, O, H_2O)\)

\(\Rightarrow\) Space far-IR facilities are the only way to study the active regions
The complex structure of the inner protostellar regions

Cavity walls
Hot core/disk
Infalling envelope
Jets/winds

Kristensen et al. 2011

Complex systems: different regions spatially not resolved
PACS & SPIRE spectra of YSOs

Different gas components in the not resolved region

OI, CO, H$_2$O, OH
Which component is traced by the FIR lines?

FIR molecular emission in the more active class 0/I sources dominated by outflows

- Offsets wrt continuum
- Line-widths > 30 km/s
HIFI: $\text{H}_2\text{O}$ line profiles

Variety of features probing the different components (infalling envelope, outflows, jets)
Attempt to model the different components

- Passively heated envelope
- FUV heated cavity
- Shocks

Relative contribution change with evolution

Visser et al. 2012
A spectroscopic survey with SPICA

With low spectral/spatial resolution only global questions can be addressed:

→ Which are the main gas cooling channels during the various *-form stages? Are ‘averaged’ physical conditions changing?

→ Are there molecular abundance variations with age/luminosity of protostars?

→ What is the feedback of protostellar jets/outflows on their surrounding?
Herschel spectral surveys

About 100 class 0/I sources observed by PACS (and HIFI) as part of WISH-WILL (P.I. E. van Dishoeck), DIGIT (P.I. N. Evans).

Spitzer c2d with Tbol < 350 K

Mottram et al. 2016
Survey of embedded protostars:

Photometric surveys with Herschel: census of pre- and proto-stellar sources:

- Könyves et al. 2015
- Giannini et al. 2002

With SPICA-SAFARI

- explore evolutionary and luminosity effects
- establish when an heating source is switched on
Direct measure of $N(H_2)$ in protostellar envelopes

→ Absolute molecular abundance determinations in protostellar envelopes rely on CO abundance or dust/gas ratio

→ SMI observations of $S(0)\ 28\text{um}$ & $S(1)\ 17\text{um}$ can directly probe the $H_2$ gas with $T>100\text{ K}$
→ SAFARI observations of HD 1-0 $112\text{um}$ ($T>60\text{ K}$)

Possible confusion between envelope and outflowing gas

→ Would take advantage by the high resolution of SMI-HRS
Measuring water abundance

Physical conditions derived from HERSCHEL multi-line observations:

- High-T (> 300 K), high-dens (> $10^5\text{cm}^{-3}$)
- similar to *no other species* observable from ground
- Abundance determinations between $10^{-7}$-$10^{-5}$
Spatial correlation with $H_2$ mid-IR emission

Velocity resolved $H_2$ 0-0 lines as a unique tool to investigate the gas components traced by water

$\rightarrow$ Spica SMI-HRS

Unique possibility to have a direct measure of $H_2O$ abundance in the different kinematical components
Origin of mass loss in protostars: tracing the atomic jets in class 0 sources

CO, SiO collimated jets
Similar to T Tauri jets

• Are the jets intrinsically molecular or only the cold envelope of embedded atomic jets?

• How warm are the molecular jets?
Atomic jets observed with Spitzer and Herschel

SPICA-SMI will do velocity resolved observations in:
- $\text{[FeII]}$ at 17.9um
- $H_2$ S(0) at 12.3um
- $H_2$ S(1) at 17.0um

+maps of many more lines

SAFARI will resolve the fastest $[\text{OI}]$ jets ($V > 100$ km/s)

PACS-[OI]63um

[SI]26um  [FeII]25um

HH211

Dionatos et al. 2011

Nisini et al. 2015

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Mass accretion in embedded protostars

→ How do we know the evolution of mass accretion with time?

→ Are class 0/I really accretion dominated sources?

- Class 0 sources: assume $L_{\text{bol}} = L_{\text{acc}}$

- Class I sources: $L_{\text{acc}} / L_{\text{bol}}$ variable 0.1-0.8 (Antoniucci et al. 2008)

In T Tauri stars, UV excess or luminosity of HI lines:

In class I extinction too poorly known
Measuring accretion luminosity with mid-IR HI lines

HI(7-6)12um vs $L_{\text{acc}}$ in T Tauri stars

Rigliaco et al. 2014

HI flux vs $A_v$
Importance of moderate resolution for blending.

Spitzer $R = 600$
Conclusions

Scientific area in which SPICA can give important contributions:

• Specroscopic census of the youngest objects identified by Hershel → SAFARI

• Measure of N(H₂) for abundance determinations → SAFARI (HD) + SMI-HRS

• Characterize accretion and jets in class0/classI sources → SMI-MRS/HRS