Herschel View on Atomic/Molecular Emission in Class II Sources: Outflows and Disks

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& the GASPS team
Accretion disks & stellar jets in the star formation process

GOAL of Herschel obs: to investigate the origin of atomic/molecular emission from Class II sources
GASPS: GAS in Protoplanetary System (PI: B. Dent)

Herschel/PACS survey of atomic/molecular gas and dust in ~ 200 disks
wide range of ages: 1-30 Myr
disk masses: $10^{-1} – 10^{-5}$ M$_{\text{sol}}$
Class II/III sources
spectral types (A to M)
Nearby star-forming regions (Taurus, ηCha, βPic, Herbig Ae/Be, ...): d ~100-200 pc

Dent et al. 2013, see talk by W.F. Thi

the GASPS survey includes OPTICAL-JET sources (late Class I/II sources in Taurus)

**MOLECULAR LINES:** $\text{H}_2\text{O}$, OH, high-J CO ($J \geq 18$)

**ATOMIC LINES:** [OI] 63, 145 um, [CII] 158 um

$\rightarrow$ **DISKS**
$\rightarrow$ **SHOCKS in the jet**
$\rightarrow$ **OUTFLOW cavities**
[O I] 63 um in Taurus/Auriga – disk or outflow emission?

See posters

P72 - G. Sandell et al.
P84 - S. Vicente & I. Kamp

Howard+ 2013

OPTICAL-JET SOURCES
enhanced [O I] 63 μm

DISKS

[O I] 63 μm – cont correlation

Howard+ 2013
optical-JET SOURCES ---> FIR ATOMIC, MOLECULAR emission

**ATOMIC LINES**, i.e. [O I] 63 μm, [C II] 158 μm → **Extended**, velocity shifted

**MOLECULAR LINES**, i.e. high-J CO, OH, H$_2$O → **Unresolved** with PACS

Thanks to Herschel sensitivity we can observe FIR emission associated to Class II!
FIR cooling & mass loss rate: an evolutionary picture

[O I] cooling

Molecular cooling (H$_2$O, CO)

Outflow efficiency $L_{\text{FIR}}/L_{\text{bol}}$

Podio+ 2012

Class 0
Giannini+ 2001 (ISO)

Class I
Nisini+ 2002 (ISO)
Podio+ 2012 (PACS)

Class II
Podio+ 2012 (PACS)

Karska+ 2013

Class 0/I
Karska+ 2013 (PACS)

Class II
Podio+ 2012 (PACS)
Molecular emission: outflows or disks?

OT1 Herschel/HIFI observations (25 hours, PI: L. Podio)
→ line kinematics
Low-exc $\text{H}_2\text{O} \, ^{1}\!_{0}^{-1}\!_{01}$ (557 GHz, $E_{\text{up}} \sim 61$ K) from Class 0/I sources dominated by ENVELOPE + OUTFLOW emission

Kristensen+ 2012
in Class II?
High excitation H$_2$O lines from INNER DISK

detected in 8 TTSs in Taurus ...

... and in 1 Herbig Ae/Be

Low excitation H$_2$O lines from OUTER DISK

H$_2$O 63.32um
(E$_{up} \sim$ 1007 K)

Riviere-Marichalar+ 2012

HD 163296
Meeus+ 2012, Fedele+ 2012

Hogerheijde+ Science 2011
Kamp+ 2013
Herschel/HIFI observations of DG Tau

DG Tau is low-mass Class II source associated with:

- an optical blue-shifted jet (e.g., Eisloffel+ 1998)
- dispersing envelope seen in CO lines (Kitamura+ 1996)
- compact disk-like emission in $^{13}$CO interf maps (Testi+ 2002)
Herschel/HIFI observations of DG Tau

evidence of low-exc WATER emission from OUTER DISK!

1. double-peaked profile: strong kinematic evidence of keplerian rotating disk!

2. \( R_{\text{out}}(\text{H}_2\text{O}) \sim 77-105 \text{ AU} \sim R_{\text{out}}(\text{dust}) \)

3. H2O line peaks in the velocity ranges where \(^{13}\text{CO} 2-1\) interf maps trace the disk rotation (V gradient perp to jet direction)

CARMA cont maps Isella+ 2010

Testi+ 2002
DG Tau DISK model: the region emitting low-exc H2O lines

**Protoplanetary Disk Models (ProDiMo)**

Woitke+ 2009, Kamp+ 2010, Thi+ 2011

- H2O 557, 1113 GHz (HIFI)
- H2O 179.5µm (PACS)
- emitted by same disk region

\[ R = 10 – 90 \text{ AU} \]
\[ T = 50 – 600 \text{ K} \]
\[ < n_H > = 1e8 – 1e10 \text{ cm}^{-3} \]

--> H2O emission close to LTE
--> optically thick lines

uses global iterations to consistently calculate physical, thermal, chemical structure of protoplanetary disks.

large chemical network: 120 species, ~1650 reactions

**Protoplanetary Disk Models (ProDiMo)**

uses global iterations to consistently calculate physical, thermal, chemical structure of protoplanetary disks.

large chemical network: 120 species, ~1650 reactions

observed line fluxes in agreement with predicted ones within a factor 2

Model uncertainty related to: collisional rates, chemistry on dust grains (e.g. desorption and adsorption rates) details of radiative transfer

**High dust opacity model**

\[ M_{dust} = 1e-4 \text{ M}_\odot \]
\[ a_{min} = 0.005\mu m, \ a_{max} = 750\mu m, \ q = 3 \]

Kamp+ 2013
Estimating the WATER RESERVOIR in the DISK of DG Tau

dust grain size distribution / disk dust mass
to reproduce cont emission at 1.3, 2.8 mm (Isella+ 2010):

“low dust opacity” model

\[ M_{\text{disk}} = 0.1 M_\oplus \]
\[ H_2O_{\text{gas}} \sim 1e-6 M_\oplus \sim 0.37 M_\oplus \]
\[ H_2O_{\text{ice}} \sim 3e-4 M_\oplus \sim 100 M_\oplus \]

“high dust opacity” model

\[ M_{\text{disk}} = 0.015 M_\oplus \]
\[ H_2O_{\text{gas}} \sim 1.7e-7 M_\oplus \sim 0.06 M_\oplus \]
\[ H_2O_{\text{ice}} \sim 2e-5 M_\oplus \sim 7 M_\oplus \]

Since \( H_2O \) lines are optically thick
disk and water masses are constrained with one order of magnitude uncertainty

\[ M_{\text{disk}} = 0.01 - 0.1 M_\oplus \]
\[ \geq \text{ Minimum Mass of the Solar Nebula (MMSN) before planets formation} \]

\[ M(H_2O) \sim 7 - 100 M_\oplus \sim 1e4 - 1e5 \text{ earth oceans} \]

supports the “DRY ACCRETION” scenario
water can be delivered on terrestrial planets
by means of icy bodies forming in the outer disk
Herschel/HIFI observations of T Tau

**TRIPLE SYSTEM**
T Tau N (Class II)
T Tau Sa, Sb (Class I or II ?)
  Dyck et al. 1982
  Kohler et al. 2008
  Luhman et al. 2010

**S-N, E-W OUTFLOWS**
  Bohm & Solf 1994
  Eisloffel & Mundt 1998
  Solf et al. 1999
  Herbst+ 2007

**T Tau N: almost face-on DISK**
  Guilloteau+ 2011, 2013
  Ratzka+ 2009

VLT-NACO - H$_2$ 2.12um
  Herbst+ 2007
**Herschel/HIFI obs of T Tau – envelope, outflows and disk em**

**CN lines: disk ?**

- **CN 5-4 9/2-7/2**: $566.7 \text{ GHz}$, $82 \text{ K}$, $37^\circ$
- **CN 5-4 11/2-9/2**: $566.9 \text{ GHz}$, $82 \text{ K}$, $37^\circ$
- **SO 12$_{13}$ - 11$_{12}$**: $558.1 \text{ GHz}$, $194 \text{ K}$, $38^\circ$

**H$_2$O, CO, [C II] lines: envelope + outflow**

- **$\nu$H$_2$O 1$_{01}$ - 1$_{00}$**: $566.9 \text{ GHz}$, $61 \text{ K}$, $38^\circ$
- **$\nu$H$_2$O 1$_{11}$ - 0$_{00}$**: $1113.3 \text{ GHz}$, $53 \text{ K}$, $19^\circ$
- **$\nu$H$_2$O 3$_{21}$ - 2$_{12}$**: $1153.1 \text{ GHz}$, $249 \text{ K}$, $18^\circ$

**CN → confusion-free probe of disk kinematics (Chapillon+ 12, Guillotetou+ 13)**

- CN 2-1: less confusion by residual cloud em than in $^{13}$CO -- high disk detection rate (>50%) in TTSs/HAeBe
- CN 5-4: Eup, ncr > than CN 2-1 -- hyperfine components separated by $0.2 – 0.5 \text{ km/s} <$ peak separation

Podio+ in prep

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L. Podio

The Universe Explored by Herschel – ESA-ESTEC – Oct 15-18 2013
**T Tau DISK model: the region emitting CN lines**

*Protoplanetary Disk Models (ProDiMo)*

Woitke+ 2009, Kamp+ 2010, Thi+ 2011

uses global iterations to consistently calculate physical, thermal, chemical structure of protoplanetary disks

large chemical network: 120 species, ~1650 reactions

Podio+ in prep

Woitke+ 2009, Kamp+ 2010, Thi+ 2011

observed line fluxes in agreement with predicted ones within a factor 1.4
Conclusions

Herschel allowed observing atomic/molecular emission by late Class I, Class II

**Herschel / PACS obs**

- **ATOMIC EMISSION**, i.e. [O I] 63 $\mu$m, [C II] 158 $\mu$m → associated with jets (**Extended**, velocity shifted)
- **MOLECULAR EMISSION**, i.e. high-J CO, OH, H$_2$O → origin is unclear (**Unresolved** with PACS)
  
  FIR cooling & mass loss rate decreases as the source evolve from Class 0 to Class II

**Herschel / HIFI obs**

- Kinematics is crucial to understand the line origin !
  
  H$_2$O lines in Class 0/I → dominated by envelope/outflow emission
  
  In Class II → may probe the disk
  
  CN lines → effective confusion-free disk tracer

**What's next ?**

Final test on line origin with spatially resolved maps of H$_2^{18}$O, CN lines with PdBI and ALMA

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