Water in Star-forming Regions with Herschel (WISH)

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Water In Star-forming regions with Herschel
The WISH team

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70+ scientists from 30 institutions (PI: EvD)
15 papers in Herschel A&A first results issues,
25 papers total

Summary in van Dishoeck et al. 2011, PASP
Follow journey of parcel from cores to disk

Herbst & vD 2009
WISH questions

- Where is water formed in space and by which processes?
  - Gas vs grains

- Which physical components does water trace?
  - Quiescent envelope, hot core, outflows, disks, …
  - Cooling budget

- What is the water ‘trail’ from clouds to planets?
  - Origin of water on Earth

To do so, we also need to understand the physics => independent tracer CO
Observe mix of low- and high-excitation lines to probe cold and hot environments; Include $^{12}$CO 10-9, $^{13}$CO 10-9, C$^{18}$O 9-8, PACS
Water reveals profile components
From low to high mass protostars

Note similar profiles: broad, medium and narrow

Kristensen et al. 2010
Johnstone et al. 2010
Chavarria et al. 2010
Which physical component dominates which lines?

Protostellar envelope with hot core:
Low-J CO
Also swept-up outflow

UV irradiated cavity walls, disk surface:
Mid-J CO
Hot water?

Outflow shocks:
High-J CO,
Hot water?
High velocity O I

Modeling by Visser, Bruderer, Kristensen
Velocity resolved CO lines

- Combination of instruments allows full ladder up to $J=10-9$ to be observed; $J=16-15$ in one source
High-J CO lines

- Note mix of narrow and broad lines
From broad to narrow profiles

NGC 1333

L1448

Yildiz et al. 2010

Kristensen et al. 2011
Points addressed here

- Importance of velocity resolution
- Importance of isotopologues
- Importance of spatial information

Focus here on low-mass sources
Examples: NGC 1333 IRAS 4A/B

- NGC 1333 IRAS 4A/B protostars ($d=235$ pc)
- APEX-CHAMP+ CO 6-5 map, 9” resolution
- Spectrally resolved dynamics of the region
- Spatially resolved outflow (entrained gas)

Yildiz et al., 2012
Extracting quantitative information

Temperatures inferred from CO 3-2/6-5 and 6-5/10-9 ratios in line profiles indicate 70-200 K for entrained outflow gas

Unresolved $^{12}$CO low-J lines primarily trace this outflow
$^{13}\text{CO}$: UV heating of cavity walls

$^{13}\text{CO}$ 6-5

- $^{13}\text{CO}$ 6-5 narrow emission at source can be produced in the envelope.

Used C$^{18}$O model to predict $^{13}\text{CO}$

Yildiz et al., 2012
UV heating of cavity walls

$^{13}$CO 6-5

(Observed Spectra
– Outflow
– Envelope Emission)
= UV heated gas

- $^{13}$CO 6-5 reveals the first direct observational evidence for the UV heated gas distribution
- For IRAS 4A, the mass of the UV-heated gas is at least comparable (even higher) to the mass of the outflow.

Note that Intensity Scale changes

Yildiz et al., submitted; see also van Kempen et al. 2009, Spaans et al. 1995
Message 1

- $^{12}\text{CO}$ and $^{13}\text{CO}$ up to $J \sim 10$ trace different physical components
  - $^{12}\text{CO}$: entrained outflow gas
  - $^{13}\text{CO}$: quiescent envelope + UV heated gas

$\rightarrow$ Velocity-unresolved $^{12}\text{CO}/^{13}\text{CO}$ flux ratios are meaningless for protostars
Comparing CO ladders

- Protostars have $^{12}$CO excitation
  - similar ⇒ a ULIRG, a PDR
  - different ⇒ Milky Way, a Quasar

- $^{13}$CO excitation similar to PDR

Normalized relative to $^{12}$CO 4-3 and $^{13}$CO 6-5

Van der Werf et al., 2010; Wright et al., 1991; Habart et al., 2010; Weiss et al., 2007; Yildiz et al., 2012
Message 2

- Only $^{12}\text{CO } J>10$ probes same physical components as PACS
  - UV heated gas
  - Directly shocked gas
Origin of hot CO

Only parameters: UV field $G_o$ and $\nu_{\text{shock}}$

van Kempen, Kristensen et al. 2010
Envelope and outflow of HH46
Spatially-resolved Herschel/PACS Spectroscopy

**Blueshifted Outflow**
**Inner envelope**
**Red-shifted Outflow**

van Kempen, Kristensen, Herczeg et al. 2010

R=1500-4000, 9.4” pixels

Note association of CO and H$_2$O with outflow
NGC1333 IRAS4A with PACS

APEX-CHAMP$^+$ CO 6-5

Herschel/PACS CO 14-13

Karska+, in prep.

Yildiz+2012
Do hot water and CO trace accretion shock onto disk?

Watson et al. 2007, Nature
NGC1333 IRAS4B: PACS spectral scan

- One of the richest PACS spectral scans

Herczeg et al. 2012
H$_2$O and CO in outflow, not disk

Use PACS raster mode for fully sampled map

Hot CO and H$_2$O clearly displaced from far-infrared continuum → not disk

Herczeg et al. 2012
Message 3

- CO PACS lines spatially extended and associated with outflow direction
- Hot H$_2$O follows high-$J$ CO, not low-$J$ CO

WISH = Water IS Hot
CO ladders for Class 0+1 YSOs

Karska+, in prep.

Class 0
- IRAS4A
  - \( T_{\text{rot}} = 297 \text{ K} \)
  - \( T_{\text{rot}} = 573 \text{ K} \)
- IRAS4B
  - \( T_{\text{rot}} = 344 \text{ K} \)
  - \( T_{\text{rot}} = 709 \text{ K} \)
- SMM3
  - \( T_{\text{rot}} = 314 \text{ K} \)
  - \( T_{\text{rot}} = 726 \text{ K} \)
- L483
  - \( T_{\text{rot}} = 394 \text{ K} \)
  - \( T_{\text{rot}} = 579 \text{ K} \)

Class I
- L1489
  - \( T_{\text{rot}} = 513 \text{ K} \)
  - \( T_{\text{rot}} = 543 \text{ K} \)
- CedIRS4
  - \( T_{\text{rot}} = 352 \text{ K} \)
  - \( T_{\text{rot}} = 267 \text{ K} \)
- L15398
  - \( T_{\text{rot}} = 395 \text{ K} \)
- RNO91
  - \( T_{\text{rot}} = 267 \text{ K} \)

High-T and high-n required to explain observations

✧ “Warm” (T~300 K) and “hot” (T~700 K) components
✧ “Hot” component disappears for some Class I sources (TBC)?
Far-IR cooling budget

NGC 1333 IRAS 4A (Class 0)

HH 46 (Class I)

✧ Cooling by [OI] marginal in Class 0, but rises with evolution
✧ H_2O dominates far-IR cooling of deeply embedded YSOs

Karska+, in prep.
Message 4

- CO ladder can change from position to position
- CO ladder perhaps changes with evolution Class 0 to I (TBC)?
- CO significant coolant for Class 0 sources, but less for Class I
From low to high mass:
$^{13}$CO 10-9 as tracer of warm gas mass:

SanJose-Garcia et al. in prep
Yildiz et al. in prep
Message 5

- Same conclusions hold from low to high-mass protostars (\(<1 \text{ to } >10^5 \, L_{\text{Sun}}\))
TW Hya ortho and para H$_2$O

Points to water ice reservoir of 6000 oceans

Also CO 10-9 HIFI data for same sources

Hogerheijde et al. 2011, Science
HD 100546 : CO ladder

Evidence that gas- and dust temperatures are decoupled in atmosphere

HST: Grady et al. 2001

Bruderer et al. 2012

Different $\text{H}_2$ formation rates

Lineflux (W m$^{-2}$)

$T_{\text{gas}} > T_{\text{dust}}$

$T_{\text{gas}} = T_{\text{dust}}$
Message 6

- High-$J$ CO from disks readily reproduced by models with $T_{\text{gas}} > T_{\text{dust}}$
- Emission comes from a range of radii

DIGIT, Bruderer et al. 2012
Conclusions

- CO is seen in cold, warm and hot components
- Importance of velocity resolution, isotopologues and spatial extent to assign physical components