Are we measuring the right water abundance in shocks?

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Water in protostellar systems

- Among the **main coolants** of shocks
- **Sensitive to local physical conditions:** large variations of its abundance between cold and warm regions

**In cold** interstellar medium:
$$X(H_2O)_{gas} < 10^{-8} \ (Bergin \ & \ Snell \ 2002, \ Klotz \ et \ al. \ 2008, \ Caselli \ et \ al. \ 2010)$$

**In warm** protostellar environments:
- Evaporation from dust grains ($T_{dust} > 90 \ K$)
- Chemical reactions in gas phase ($T_{gas} > 300 \ K$)
$$X(H_2O)_{gas} \sim X(CO) \sim 3 \times 10^{-4} \ (Kaufman \ & \ Neufeld \ 1996, \ Bergin \ et \ al. \ 1998)$$

→ **in protostellar outflows!**
Previous observations of H$_2$O

SWAS: H$_2$O $1_{1,0}-1_{0,1}$
$\Theta = 3.3'$ x 4.5'

Bergin et al. (2004)

$X_{H_2O} \sim 10^{-6} - 10^{-4}$
using CO: H$_2$O & CO trace the same gas
(e.g. Franklin et al. 2008, Giannini et al. 2001)

ODIN: H$_2$O $1_{1,0}-1_{0,1}$
$\Theta = 126''$

Olberg et al. (2006)

ISO-LWS: 55-180$\mu$m $\Theta = 80''$

(Nisini et al. 1999)

Herschel: $\Theta = 9.4''$ - 40"
Water In Star-forming regions with Herschel

PI: Ewine van Dishoeck
Total GT ~ 500 hr

G. Santangelo

- Prestellar
- Class 0
- Class 1
- Disks
- High-mass
- Mass
- Time

~80 sources

L. Kristensen
**H$_2$O IN OUTFLOWS WITH WISH**

- H$_2$O emission peaks trace the positions of strong shock regions
- Strong water emission detected from the central embedded protostar
- **Correlation between H$_2$O and mid-IR H$_2$ (T ~ 300-1000 K)** (Nisini et al. 2010, Santangelo et al. 2012, Vasta et al. 2012, Tafalla et al. 2013)

![Spitzer IRAC](image)

![PACS H$_2$O 179µm](image)

*Nisini et al. (2010)*
- Correlation H$_2$O and mid-IR H$_2$
- High-J CO follows H$_2$O, while low-J CO is shifted
  $\rightarrow$ Shocked versus ambient gas

Santangelo et al. (2012, 2013), Nisini, Santangelo et al. (2013)
H$_2$O versus CO

- Correlation H$_2$O and mid-IR H$_2$
- High-J CO follows H$_2$O, while low-J CO is shifted
  → Shocked versus ambient gas

Need to revise previous H$_2$O abundance estimates, using mid-IR H$_2$

Santangelo et al. (2012, 2013), Nisini, Santangelo et al. (2013)
• Mid-IR $\text{H}_2$ can help constraining the $\text{H}_2\text{O}$ excitation conditions: the same two-temperature model for $\text{H}_2$ and $\text{H}_2\text{O}$

• $X_{\text{H}_2\text{O}} \sim 10^{-6} - 10^{-5}$, using Spitzer mid-IR $\text{H}_2$ (Santangelo et al. 2012, 2013, Bjerkeli et al. 2012, Vasta et al. 2012, Nisini et al. 2013, Tafalla et al. 2013, Busquet et al. 2014)

→ **Lower than expected in warm shocked gas** (Kaufman & Neufeld 1996, Flower & Pineau Des Forêts 2010)
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Based on the spatial association between $\text{H}_2\text{O}$ and mid-IR $\text{H}_2$

→ To test this hypothesis we need spectrally resolved mid-IR $\text{H}_2$ data to compare the line profiles

Giannini et al. (2011)
**HH54: A CASE STUDY**

- Herbig-Haro (Chameleon II at 180 pc, $L_{bol}=8\, L_\odot$), uncertain driving source (Nisini et al. 1996, Caratti o Garatti et al. 2006, Alcalà et al. 2008, Bjerkeli et al. 2011)

- Mid-IR cooling dominated by rotational H$_2$ lines, probing a **warm** gas with $T=500$-1200 K (Cabrit et al. 1999, Neufeld et al. 1998, 2006)

- Clumpy appearance with arcsec-scale bright knots

*Free of contamination from other objects, spatially confined, and one of the brightest and largest known bow-shocks in the mid-IR H$_2$*
Two kinematic components: LV ($v_{\text{sys}} \approx 2.4$ km s$^{-1}$) & HV (-9 km s$^{-1}$)

HV CO (associated with high-J CO) traces the H$_2$O emitting gas

VLT-VISIR spectrally-resolved observations of H$_2$ S(4) at 8$\mu$m (R=32000→10 km s$^{-1}$): to test the association H$_2$O (HV CO) & mid-IR H$_2$

→ Mid-IR H$_2$ associated with the LV CO rather than with H$_2$O and HV CO

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$\rightarrow$ The assumption of H$_2$O and mid-IR H$_2$ coming from the same gas is wrong!

Bjerkeli et al. (2009, 2011)
Possible $H_2$ stratification

- VLT-ISAAC NIR vibrationally excited $H_2$ at 2.12μm (R=9000→33 km s$^{-1}$)
- Shocked gas with $T>2000$ K faster than $H_2O$ and mid-IR $H_2$ (-15 km s$^{-1}$): stratification in velocity and excitation of the $H_2$ gas (mid-IR to NIR), see e.g. CO
Heading towards a solution...

- Stratification of $\text{H}_2$ in velocity and excitation (mid-IR to NIR) to be verified
- $\text{H}_2\text{O}$ in between the two $\lambda$ regimes → Is the $\text{H}_2$ component associated with $\text{H}_2\text{O}$ between the two regimes?
• Stratification of H$_2$ in velocity and excitation (mid-IR to NIR) to be verified

• H$_2$O in between the two $\lambda$ regimes $\rightarrow$ Is the H$_2$ component associated with H$_2$O between the two regimes?

$\rightarrow$ VLT-CRIRES obs. (DDT) of H$_2$ S(9) at $\sim$4.7$\mu$m (6 km s$^{-1}$ res) to fill in the velocity gap between mid-IR 8$\mu$m and NIR 2.12$\mu$m regimes to spectrally identify the H$_2$ component associated with H$_2$O and correctly measure H$_2$O abundances $\rightarrow$ Crucial test for shock models and for the low H$_2$O abundances derived with Herschel $\rightarrow$ Data taken last week!

$\rightarrow$ ALMA proposal: to spatially resolve LV&HV in CO(2-1) and spatially connect HV CO (and H$_2$O) and H$_2$ $\rightarrow$ H$_2$O abundance in shocked gas