



Waterfalls and fountains:

infall and outflow in solar-mass protostars traced by rotational lines of water

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Motivation

Key Questions

- Water is a good tracer of both physics and chemistry
- What physical component(s) does water trace in protostellar systems and what can it tell us about them?
- How important is water for gas cooling?



Surveys

WISH: Water In Star-forming regions with Herschel

- 425 hrs of Herschel time (van Dishoeck et al., 2011, PASP)
- HIFI spectroscopy & PACS spectral maps of H₂O and related molecules



- ~ 80 sources:
- − From 1 L_☉ -10⁵L_☉
- Prestellar cores to disks
- LM outflow hotspots
- 27 LM sources

WILL: William Herschel Line Legacy

- OT2 follow-up to WISH-LM of a statistically selected sample
- ~50 sources selected from Herschel and Spitzer GB surveys using the criteria:



Infall

Infall on cloud to envelope scales

- 7 sources show inverse P-cygni (IPC) profiles
- 1-D modelling shows that infall takes place on cloud (10000 AU) to core (3000 AU) scales in 5 sources
- Due to cloud-scale motions in 2 sources
- The IPC in the 2_{02} - 1_{11} line for IRAS4A lets us probe



infall down to 1000 AU

• In IRAS4A

$$\dot{M}_{\rm inf} >> \dot{M}_{acc} + \dot{M}_{out}$$

Mottram et al., 2013

Outflows & Shock - PACS

Molecular excitation

NGC1333-IRAS4B Herczeg et al.,2012



- Universal Warm and hot components on H₂O and CO rotational diagrams (CO T_{rot}≈300 K and ≈1000 K)
- Most likely trace irradiated non-dissociative and dissociative shocks in the outflows

Karska et al.,2013 ; Green et al.,2013 ; Manoj et al.,2013 ; Kristensen et al., 2013

Gas Cooling Budget



- Total far-IR cooling dominated by CO and H₂O, fraction contributed by O increases for more evolved sources;
- L_{FIRL}/L_{bol} decreases with evolution

Outflows & Shock - HIFI

Example H₂O Line Profile

- H₂O lines exhibit complex line profiles
- Different from ground-based line profiles => probing new parts of the protostellar system

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Kristensen et al., 2010,
2012
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Consistent with Excitation



 All components seen in multiple transitions and consistent line ratios across large sample

Kristensen et al., 2010, 2012, 2013, Mottram et al., 2013

Consistent with Excitation



- All components seen in multiple transitions and consistent line ratios across large sample
- Can isolate the different components for separate study

Kristensen et al., 2010, 2012, 2013, Mottram et al., 2013

Origin of Components?



Offset Dynamical Component

- Now also identified in high-J (J≥10) CO and Hydrides but absent in low-J CO
- Origin: dense (> 10⁶ cm⁻³) and hot (> 500 K) K gas



Dissociative shocks on 100AU scales

- New component is identical to "hot" PACS CO and H₂O component
- Dissociative shock models reproduce observations (Neufeld & Dalgarno 1989)



- Models point to origin in dissociative shocks on 100 AU scales
- See Kristensen et al., 2013 for more details

New Outflow Component

• Not the same as 'classical' low-J CO component either spectrally or spatially (Santangelo et al., 2012, Kirstensen et al., 2012, Tafalla et al., 2013)



• No correlation with F_{co}

Mottram et al., in prep

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- No correlation with
 F_{co}
- Correlation with M_{env}

Mottram et al., in prep

Evolution

• Width of line components decreases with evolution



Evolution

- Width of line components decreases with evolution
- Evolution from infall, strong shocks and outflows in Class 0 to expansion, weak shocks in Class I



Conclusions

- Water traces several distinct kinematic components within protostellar systems
- Multiple temperature components in CO and H₂O rotational diagram dissociative and non-dissociative shocks in outflow
- Dissociative (offset) and non-dissociative (broad) components also seen in HIFI spectra as distinct kinematic components
- Water also traces infall on cloud to core (10000 -3000 AU) scales
- WILL survey shows that the trends seen in WISH are general

More details and papers can be found at http://www.strw.leidenuniv.nl/WISH/ index.php



Thank you for your attention.

Any questions?