Protostellar outflows: Lessons from Herschel and ALMA

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Arce et al. 2012, ALMA CO + NTT optical image of HH46/47
Low-mass YSO evolution

Class 0

Class I

Class II

Jet / wind driving outflow present at all evolutionary stages

Arce & Sargent (2006)
Outflows matter

- **Feedback agent**: turbulent injection, open cavities where UV escapes, heat surrounding material, …

- **Determines IMF**: removes angular momentum from collapsing protostar, removes mass, changes disk dynamics, …

- **Chemical catalyst**: through heating + UV changes chemical properties, ice composition, …
Lesson 1:
Water is the best shock/outflow tracer we currently know of: it traces a 300K component not seen from the ground.

Lesson 2:
Outflows are more energetic than pre-Herschel/ALMA observations revealed and shocks are predominant.

Lesson 3:
High angular resolution + sensitivity required for completing the dynamical picture of winds + outflows.
Lesson 1:

Water is the best shock/outflow tracer we currently know of: it traces a 300K component not seen from the ground.
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Barring any destruction processes, all O not in CO will be in H$_2$O, $x$(H$_2$O) $\sim$ 10$^{-4}$

$\text{H}_2$ + O $\rightarrow$ OH

OH + H$_2$O $\rightarrow$ H$_2$O

Sputtering
H$_2$O is not CO

- Low-J CO ($E_{\text{up}}/k_B < 50$ K) traces cold entrained outflow
- No spatial overlap between low-J CO and H$_2$O: not tracing same outflow component

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H$_2$O moves differently than CO

- Lower contrast between high- and low-v material
- CO varies with excitation: higher-J CO has more momentum and energy

Kristensen et al. in prep.
San Jose-Garcia et al. 2012, in prep.
H$_2$O is warm and dense

- H$_2$O follows CO 16-15: excitation in 300 K gas
- High dipole moment: excitation in dense gas
- Collisional excitation, even close to the central protostar

Water abundance

- CO 16-15 as reference frame: $x(\text{H}_2\text{O})$ constant with velocity

- At source position: $x(\text{H}_2\text{O}) \sim 10^{-5}$

- At outflow position: $x(\text{H}_2\text{O}) \sim 10^{-7} - 10^{-5}$

- Lower than expected: UV photodissociation?

Water chemistry: sputtering & gas-phase synthesis

- CH$_3$OH and H$_2$O: grain products released through sputtering
- H$_2$O: also efficient gas-phase route
- Comparison: 90-99% of molecules destroyed in sputtering process, H$_2$O reforms at high velocities

Suutarinen et al. 2014
Lesson 2:

Outflows are more energetic than pre-Herschel/ALMA observations revealed and shocks are predominant.
CO, H$_2$O, OH: dominant coolants and probes

Herczeg et al. (2012)
Shocks dominate FIR cooling lines

- FIR spectra dominated by H$_2$O, CO, OH and O
- Shock models reproduce excitation: UV needed to reproduce chemistry

Karska et al. 2014, Kristensen et al. in prep.
Shock energetics as important as outflow energetics

- [O I] 63 micron observations velocity-resolve jet emission

Bjerkeli et al. 2012, 2013, Nisini et al. 2015
Lesson 3:

High angular resolution + sensitivity required for completing the dynamical picture of winds + outflows
Winds rotate

- Winds + outflows remove angular momentum: constraining the rate constrains the launch mechanism
- Observations difficult: require high sensitivity + resolution
- ALMA delivers!

Klaassen et al. 2013, Codella et al. 2014
ALMA confirms: outflows are energetic

- High-sensitivity CO 1-0 observations reveal higher-\(v\) material than previously observed.
- Outflows contain more mass and energy than previously assumed.
- Follows Herschel conclusions but now with spatial resolution.

\[\text{Arce et al. 2013}\]
Smaller arrays still useful: SMA and PdBI pinpoint shock locations
Summary

• Herschel was, and ALMA is fantastic new toys for outflow studies: complementary capabilities

• Herschel revealed where the momentum and energy are, ALMA reveals the total mass and location

• Future: constrain the launch mechanism, pinpoint where and how outflow entrainment takes place, establish the elemental budgets, expand initial ALMA observations to full surveys