Herschel-SPIRE Spectroscopy of Embedded Protostars (COPS-SPIRE)

CO in Protostars

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Active star formation within embedded protostars

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- The envelope provides abundant dust and gas for the growth of protostar. The mass accretion/ejection occurred at the embedded phase determines the conditions for disk evolution and planet formation.

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- The envelope provides abundant dust and gas for the growth of protostar. The mass accretion/ejection occurred at the embedded phase determines the conditions for disk evolution and planet formation. (e.g. Jorgensen+2009, Kristensen+2012, Yen+2015)
- Active outflows and jets, resulting from the mass infall/accretion, also feedbacks to the envelope. (e.g. Offner+2014, Nisini+2015, Yıldız+2015)
Sampling a wide range of source properties

Yang+2017

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What physical processes drive the early stage of star formation?

**Shock scenario**  
(Mottram et al. 2014)

- Cavity shocks
- Cold entrained outflow
- Spot shocks

**Wind scenario**  
(Yvart et al. 2016)

- Disk wind
- Broad cavity shock/wind
- Spot shock (hot)
- Orange spot

Envelope (not shown) also contributes to the CO emission at the source velocity.

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A single CO emission line exhibits multiple velocity components

**CO \( J = 16 \rightarrow 15 \) velocity-resolved spectra**

Kristensen+2017

For CO \( J = 16 \rightarrow 15 \):
- 20% spot shock
- 80% cavity shock/wind

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Correlations of CO Emission Lines:
From $J = 4 \rightarrow 3$ to $J = 36 \rightarrow 35$

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Correlations of CO Emission Lines:
From \( J = 4 \rightarrow 3 \) to \( J = 36 \rightarrow 35 \)

Spearman’s \( \rho \): the goodness of the relation can be described by a monotonic function, including the upper limits.

\[
\rho = 0.794, \ 4.4\sigma \\
\rho = 0.509, \ 2.7\sigma
\]
Bipolar morphology of CO emission

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How to systematically study the morphology of CO emission?

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Spatial Extent of CO Emission

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Spatial Extent of CO Emission

BHR71

\( F_{outer}/F_{cen} \)

\( \theta_{polar} [\text{deg.}] \)

- CO4-3
- CO5-4
- CO6-5
- CO7-6
- CO8-7
- CO9-8
- CO10-9
- CO11-10
- CO12-11
- CO13-12
The variation of bipolar feature as a function of $J$-level

![Graph showing the variation of bipolar feature as a function of $J_{up}$.]
Summary

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• We develop a new method to visualize the morphology of the CO emission from Herschel data by comparing the flux ratio to the central spaxel and smoothing the profile as a function of polar angle.

• Bipolar features are found in 50% of the sources at low-\(J\) CO lines, which may decrease as the \(J\)-level increases.