The Herschel Orion Protostar Survey (HOPS): A Multi-Observatory Survey of Protostars in the Orion Molecular Clouds

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Blue: Spitzer 3.6 micron
Green: PACS 70 micron
Red: PACS 160 micron
HOPS: Herschel Orion Protostar Survey

- PACS imaging: 298 protostars at a common distance and in a variety of environments
  - Spitzer-identified protostars down to $\sim 0.2 L_{\odot}$
  - 70 and 160 µm
  - 114 fields of 5’ to 8’
  - Medium (20”/s) scan rate

- PACS range spectroscopy of 33 protostars (see P. Manoj Poster!!!)

And........
- Spitzer imaging + spectra
- Hubble and ground based near-IR imaging + spectra
- Ground-based sub-mm data
The conversion of cores to stars occurs in the protostellar phase. In this phase, the basic properties of stars are determined. We need a detailed understanding of protostellar evolution!

\[ b = L_\star + L_\text{flare} + \frac{GM_\star}{r} \]
Goals of HOPS

• Dependence of Protostellar Properties on “Environment”
  - Properties of surrounding core (this talk)
  - Presence of binary or cluster
  - Properties of parental filament (poster by T. Stanke)

• Auditing infall and outflow
  - Infall estimated from SED
  - Outflow from PACS spectroscopy and ground-based data (poster by P. Manoj)

• Providing definitive data set for testing models of protostellar evolution (this talk and Amy Stutz’s talk)
  - Understand connection between evolution and environment due to feedback (this talk).
The HOPS Model Grid (John Tobin)

- Generated with Whitney Monte-Carlo code
- 3600 models viewed from 10 angles - giving 36000 SEDs
- Vary envelope density, outflow cavity angle, centrifugal flattening, luminosity.
$T_{\text{bol}}$ (Bolometric Temperature: temperature of a blackbody with the same mean frequency of the protostar)

- $T_{\text{bol}}$ is intended to track envelope evolution
- Can be skewed upward by scattered light
- With model, count only the thermal emission

$\log \left[ \lambda F_{\lambda} \text{ (erg s}^{-1} \text{ cm}^{-2}) \right]$

$\lambda$ ($\mu$m)

$T_{\text{bol}} = 465$ K
$T_{\text{bol}} = 328$ K

$T_{\text{bol}} = 106$ K
$T_{\text{bol}} = 52$ K

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$T_{\text{bol}} = 52$ K

$T_{\text{bol}} = 94$ K
$T_{\text{bol}} = 68$ K

$T_{\text{bol}} = 66$ K
$T_{\text{bol}} = 57$ K

$T_{\text{bol}} = 54$ K
$T_{\text{bol}} = 53$ K
Tracing Protostellar Evolution with Bolometric Temperature

Bolometric Temperature vs Luminosity Plot for 298 Protostars
Tracing Protostellar Evolution with Bolometric Temperature

Is this the HR diagram for protostars?

Class 0 < 70 K
Early Class I = 70 - 215 K
Late Class I = 215 - 650 K
What is the effect of inclination on the bolometric temperature?

Protostars are not spherically symmetric objects!

HOPS 136: NICMOS at 1.6 and 2.05 micron
What is the effect of inclination on the bolometric temperature?

HOPS 136: NICMOS at 1.6 and 2.05 micron
What is the effect of inclination on the bolometric temperature?

- Inc. = 18°,  
  - Tbol = 606 K

- Inc. = 81°,  
  - Tbol = 67 K

- Inc. = 57°,  
  - Tbol = 371 K

Red: Thermal emission  
Blue: Thermal+Scattered

HOPS 136: NICMOS at 1.6 and 2.05 micron
What is the effect of inclination on the bolometric temperature?

- Inc. = 18°  
  • Tbol = 606 K

- Inc. = 81°  
  • Tbol = 67 K

- Inc. = 57°  
  • Tbol = 371 K

Inclination averaged bolometric temperature is <Tbol> = 393 K

Red: Thermal emission  
Blue: Thermal+Scattered

HOPS 136: NICMOS at 1.6 and 2.05 micron
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Tbol
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Fit model and use $T_{bol}$ averaged over 10 inclinations: $<T_{bol}>$

Many Class 0 objects may be highly inclined Class I sources
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Evolution

Class 0

Early Class I

Late Class I

$L_\text{sun}$ vs. $<T_{bol}>$ (angle averaged)
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Model grid calculated by John Tobin
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

- Lower inner envelope density
- Larger outflow cavity
- Model grid calculated by John Tobin

![Graph showing density vs. cavity angle](image-url)
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62°
Median Lsun = 2.5
<Mdot> = 1 \times 10^{-5} M_{\odot} yr^{-1}
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62°
Median L$_{\text{sun}}$ = 2.5
<Mdot> = $1 \times 10^{-5}$ M$_{\text{sun}}$ yr$^{-1}$

Number = 123
<inc> = 61°
Median L$_{\text{sun}}$ = 2.4
<Mdot> = $4 \times 10^{-5}$ M$_{\text{sun}}$ yr$^{-1}$
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

Number = 155
<inc> = 62°
Median Lsun = 2.5
<Mdot> = 1 x 10^{-5} M_{\odot} yr^{-1}

Number = 123
<inc> = 61°
Median Lsun = 2.4
<Mdot> = 4 x 10^{-5} M_{\odot} yr^{-1}

Number = 27
<Inc> = 30°
Median Lsun = 2.5
<Mdot> = 2 x 10^{-4} M_{\odot} yr^{-1}
Tracing Protostellar Evolution with Inclination Averaged Bolometric Temperature

- Large spread in luminosities at all $<T_{bol}>$
- Median luminosity is very constant
- $\dot{M}$ decreasing with increasing $<T_{bol}>$
- The higher inclination red objects are missing: see Amy Stutz talk.

Number = 155  
<inc> = 62$^\circ$  
Median Lsun = 2.5  
$\langle \dot{M} \rangle = 1 \times 10^{-5} \, M_{\odot} \, yr^{-1}$

Number = 123  
<inc> = 61$^\circ$  
Median Lsun = 2.4  
$\langle \dot{M} \rangle = 4 \times 10^{-5} \, M_{\odot} \, yr^{-1}$

Number = 27  
<inc> = 30$^\circ$  
Median Lsun = 2.5  
$\langle \dot{M} \rangle = 2 \times 10^{-4} \, M_{\odot} \, yr^{-1}$
Connecting Protostellar Evolution with “Environment”

Red dots: Spitzer identified protostars

Greyscale: LABOCA 850 micron

Used LABOCA and Herschel PACS 160 micron data to find temperature and column densities.

L1641 South: wide spacing, weak 850 micron emission

OMC 2/3: close spacing, strong 850 micron emission
Connecting Protostellar Evolution with “Environment”

Red dots: Spitzer identified protostars

Greyscale: LABOCA 850 micron

Used LABOCA and Herschel PACS 160 micron data to find temperature and column densities.

Spacing inversely proportional to gas column density - consistent with Jeans fragmentation: see Thomas Stanke Poster
Luminosity vs Column Density

L_{\text{sun}} = k \ N(H_2)^{1.5}

Approximately consistent with Mdot = Mass/t_{\text{ff}}
Luminosity vs Column Density

Evolution

This shows a clearing of the surrounding gas with increasing $\langle T_{bol} \rangle$, probably the result of feedback.
Summary

Presented a preliminary examination of indicators of evolution

• Tbol is strongly affected by inclination

• Inclination averaged Tbol, $<\text{Tbol}>$, a much better indicator of evolution
  • $<\text{Tbol}>$ decreases as envelope density decreases and cavity opening angle increases.
  • Caution: much more model dependent.

• Wide spread in luminosities at all $<\text{Tbol}>$

• Median luminosity constant with $<\text{Tbol}>$

• Higher inclination Class0 objects not detected with Spitzer (see Amy Stutz talk)

• We find that for the reddest objects, the Luminosity $= k \ N(\text{H}_2)^{1.5}$

• For a given luminosity - gas column density decreases with increasing $<\text{Tbol}>$

Posters by Thomas Stanke and P. Manoj