The Herschel Orion Protostar Survey: Photometry in Complex Fields

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OMC 3
Spitzer 3.6 µm
Herschel 70 µm
Herschel 160 µm
HOPS: Herschel Orion Protostar Survey

PACS imaging and spectroscopy of Spitzer-identified protostars in the Orion molecular clouds

Main components:
1. PACS imaging at 70 and 160 µm of 300+ protostars: 108 fields of 5’ to 8’ on a side
2. PACS spectroscopy of 33 targets

Plus…
HST imaging
Spitzer imaging, spectroscopy
APEX imaging
Other ground-based data

A complete survey of the largest star-forming region within 500 pc
HOPS covers a range of environments: from single protostars with little nebulosity to highly complex regions.

Mapping techniques:

- **Photproject** for photometry (HPF-30 at 70 µm; HPF-40 at 160 µm)
- **Scanamorphos** or **MADmap** to study extended emission

Photometry agrees to within a few percent across techniques.
HOPS Aperture Photometry

- Use Rob Gutermuth’s *Photvis* IDL app for source detection, aperture photometry (http://www.astro.umass.edu/~rguter/Rob_Gutermuth_Astronomy/IDL_Page.html)

*Photvis* extracts sources with width of order the PSF FWHM, an input parameter (5″ at 70 µm, 12″ at 160 µm)

User sets a S/N threshold (we use 7)
HOPS Aperture Photometry

- Use Rob Gutermuth’s *Photvis* IDL app for source detection, aperture photometry (http://www.astro.umass.edu/~rguter/Rob_Gutermuth_Astronomy/IDL_Page.html)

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FWHM, coverage are retained to be used as criteria in the final catalog

Reject edge sources (coverage \(\leq 100\)), extended sources (FWHM \(\leq 8"\))
Aperture Parameters

- Orion nebular background can be strong and non-uniform
- To reduce contamination, we use small apertures and close-in sky annuli

Non-negligible source flux in small sky annuli means signal is subtracted
HIPE does not account for annulus size in its aperture correction tool (*photApertureCorrectionPointSource*)
Need custom aperture corrections to recover subtracted signal

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<th>λ</th>
<th>Ap Radius</th>
<th>Inner Sky</th>
<th>Outer Sky</th>
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<td>70 μm</td>
<td>9.6”</td>
<td>9.6”</td>
<td>19.2”</td>
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<tr>
<td>160 μm</td>
<td>12.8”</td>
<td>12.8”</td>
<td>25.6”</td>
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Custom Aperture Corrections

- Encircled energy fractions for each band are available as tables online or in HIPE.
- HIPE's `photApertureCorrectionPointSource` interpolates these curves.
- To estimate effect of sky subtraction, do photometry on an azimuthally symmetric PSF derived from the EEF.
- For our apertures, fluxes were underestimated by 3.3% at 70 µm, 3.5% at 160 µm.

### Encircled Energy Fraction Table

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<td>9.6”</td>
<td>9.6”</td>
<td>19.2”</td>
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<td>160 µm</td>
<td>12.8”</td>
<td>12.8”</td>
<td>25.6”</td>
<td>0.6838</td>
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(HIPE corrections are recovered for large sky annuli)
Aperture photometry is problematic in crowded regions

- Extended emission
- Blending of point sources

Mainly a concern at 160 μm (envelopes may be resolved)
PSF Photometry: StarFinder


- Uses spatial filtering to remove backgrounds – and thus, some of PSFs – so must recalibrate with aperture photometry of isolated sources

- Pros:
  - Used in the Herschel community
  - Allows treatment of complex backgrounds via spatial filtering
  - Relatively user-friendly

- Cons:
  - Requires independent calibration
  - Lacks documentation of some “sausage-making” details
  - Some potentially valuable functionality difficult to implement (e.g., fixed source positions)
Mysterious that a power law is the best calibration; tests are ongoing.
Differences remain between aperture and PSF photometry for HOPS.

\[ F(\text{Jy}) = c \cdot \text{StarFinder}^8 \]
\[ F(\text{Jy}) = c_0 + c_1 \cdot \text{StarFinder}^2 \]
HOPS Analysis: Fitting SEDs with a Model Grid

- Use the Whitney et al. RT code
- 3040 model protostars
- 10 viewing angles
- 30,400 unique SEDs

- Vary parameters relevant for protostars
  - Envelope density
  - Luminosity
  - Cavity opening angle
  - Disk radius

- Fits are evaluated with a $\chi^2$-like statistic

- We track the bolometric properties of the best fits
  - Integrated luminosity
  - Bolometric temperature: effective temperature of a blackbody with the same mean frequency as the SED

Ali et al. 2010
Fitting SEDs with a Model Grid

Data:
- 2MASS
- IRAC
- IRS
- MIPS
- PACS
- APEX

Models:
- Total
- Thermal

Wavelength (µm)

SEDs with different temperatures:
- HOPS 203: $T_{\text{bol}} = 44$ K
- HOPS 1: $T_{\text{bol}} = 67$ K
- HOPS 170: $T_{\text{bol}} = 103$ K
- HOPS 166: $T_{\text{bol}} = 270$ K
- HOPS 254: $T_{\text{bol}} = 410$ K

Log [Flux (erg s$^{-1}$ cm$^{-2}$)]
How does Herschel improve our understanding of the timeline for star formation?

• Do our estimates of source properties change with the inclusion of far-IR data?

• Are we missing a population of cold sources?

Pre-Herschel:
BLT diagram for 5 nearby clouds (without $A_V$ correction) (Evans et al. 2009: Spitzer c2d)

The BLT diagram is essentially an HR diagram for protostars.
Tracing Protostellar Evolution with Bolometric Temperature

$T_{\text{bol}}$ (K)

$L_{\text{bol}}$ ($L_\odot$)

Late Class I

Early Class I

Class 0

294 Orion protostars
Effect of Inclination on Bolometric Temperature

Inc = 18°
$T_{bol} = 606$ K

Inc = 81°
$T_{bol} = 67$ K

Inc = 57°
$T_{bol} = 371$ K

Red: Thermal Emission
Blue: Thermal + Scattered

Inclination-averaged bolometric temperature is $\langle T_{bol} \rangle = 393$ K
The 24 µm / 70 µm flux ratio traces inclination

Inclination

Dense envelope

Edge-on

Face-on

Tenuous envelope

log dM_{env}/dt

-4.0
-4.3
-5.0
-5.3
-6.0
-6.3
-7.0

(15° cavity angle)

F_v (24 µm) / F_v (70 µm)

i=76°

i=70°

i=81°

i=81°
Tracing Protostellar Evolution with Inclination-Averaged Bolometric Temperature

Late Class I
Early Class I
Class 0
294 Orion protostars

\( \langle T_{\text{bol}} \rangle \) (K)

\( L_{\text{bol}} \) (L*)
Number = 168
\(<L> = 4.9 \text{ } L_\odot\)
\(<dM/dt> = 5.0 \times 10^{-7} \text{ } M_\odot \text{ yr}^{-1}\)
\(<\text{Inc}> = 63^\circ\)

Number = 109
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\(<dM/dt> = 5.0 \times 10^{-6} \text{ } M_\odot \text{ yr}^{-1}\)
\(<\text{Inc}> = 63^\circ\)

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\(<dM/dt> = 2.5 \times 10^{-5} \text{ } M_\odot \text{ yr}^{-1}\)
\(<\text{Inc}> = 41^\circ\)
New Orion Protostars: PBRS
PACS Bright Red Sources (Stutz et al. in press)

- PACS images: 55 new candidate protostars that are undetected or too faint to be classified as protostars in MIPS 24 $\mu$m
- 11 unambiguous Class 0
- 14 likely Class 0 or low-luminosity Class I
- 30 likely contaminants
- Class 0 PBRS partially restore the deficit left after the inclination correction
HOPS is characterizing the 300+ Spitzer-identified Orion protostars with PACS and extensive ancillary data

Photometric Techniques
- Nebular emission: small apertures, close-in sky annuli, custom aperture corrections
- PSF photometry with StarFinder: HOPS PSF fluxes differ from aperture fluxes (under investigation)

Effect of Herschel Imaging and Inclination Correction on Protostellar Properties
- Many apparent Class 0 protostars are more evolved but appear young due to edge-on orientations
- 70 μm / 24 μm flux ratio drives SED-based inclinations; generally confirmed with HST imaging of scattered-light nebulae
- After correcting for inclination, luminosity increases with evolutionary state
- Herschel revealed 11 new unambiguous Class 0 protostars and 14 more candidates
- Accounting for new Herschel sources, protostars spend about
  - 10% of their lifespan in a high-infall stage (Class 0)
  - 40% of their lifespan in a moderate-infall stage (early Class I)
  - 50% of their lifespan in a low-infall stage (late Class I)