Far-IR Photometric Monitoring of Protostars in Orion Molecular Clouds

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Variability is a defining characteristic of Young Stellar Objects (Joy 1945)

Optical / Near-IR: accretion shocks – hot spots (e.g. Carpenter et al 2001)

Mid-IR: Inner disk structure (warped disks, variable scale height)
  - YSOVAR (Morales-Calderón et al. 2009), LRLL 31 (Flaherty et al. 2011), etc.

Far-IR (>50μm): Only sparse and rare time series yet observed…
  - KAO: Harvey et al. (1998)
  - ISOPHOT: Juhász et al. (2007), Kóspál et al. (2007)

- 70 μm flux good proxy to protostellar total luminosity (Dunham et al. 2008)
Far-IR photometric monitoring

- Herschel PACS/Photometer 70 + 160 µm (10h obs. time)
- 18 epochs through 4 visibility windows (first 6 epochs are observed & analyzed)
  Sampling ~week ~months ~1.5 years
- Large maps (35’x35’) preferred to pointed observations
  Covering OMC-1 to 3 which contain 100+ Spitzer-identified Class I/0 protostars
- High redundancy of scan directions
  Secular spacecraft rotation + orthogonal consecutive scans
PACS 160 μm
PACS 70 μm
Spitzer 8/24 μm

6 epochs combined with Scanamorphos (Roussel et al., sub.)

Image prepared by R. Hurt
OMC 2-3

6 epochs combined with Scanamorphos (Roussel et al., sub.)

Image prepared by R. Hurt
Source Photometry

- Search for point sources in the 70 µm 6-epoch **combined map**
  - Automated source-finding algorithms gave unsatisfactory results → Visual inspection

- Photometry measured on individual **single-epoch maps**
  - Small apertures encircling the PSF core (4’/8’ radius @ 70/160 µm)
  - Aperture corrections applied (based on measured PACS PSF)

- Results:
  - 43 point-like sources at 70 µm with flux 0.4 – 500 Jy
  - 34 have counterparts at 160 µm
    - 13 are point like with fluxes 15 – 300 Jy
    - 21 are resolved/extended sources

- Most sources are Class I/0 protostars
  - (Morales-Calderón et al. 2009, following presentation by T. Megeath)
Building Reliable Light Curves

- Photometric errors on **single-epoch maps**
  - Standard deviation in background annulus inappropriate
  - Flux uncertainty estimated from varying aperture radii
    - ~5% uncertainty at 70 µm (up to 20% in crowded/structured regions), ~20+% uncertainty at 160 µm

- Relative uncertainties:
  - Same approach with varying aperture radii
  - Light curve deemed unreliable if any single-epoch flux varies by > 5% for various aperture radii

- 17 sources have reliable light curves
  - Variability detection: peak-to-peak variations > 10%
Rapid far-IR variability

- 20% variation @ 70 µm over 6 weeks
- Phased light curve @ 160 µm
- High S/N detection (relatively isolated source with smooth background)
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- Mid-IR variability, 30% (YSOVAR)
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- High S/N detection (relatively isolated source with smooth background)
- Mid-IR variability, 30% (YSOVAR)
- Accretion rate ~ $3 \times 10^{-4} M_\odot/yr$

Likely variable mass accretion...
Rapid far-IR variability

- 20+% variation @ 70 µm
- Same trend at 160 µm, but noisy photometry
Rapid far-IR variability

- 20+% variation @ 70 µm
- Same trend at 160 µm, but noisy photometry
- 50% variability at 4.5 µm
Rapid far-IR variability

- **20+% variation @ 70 \( \mu m \)**
- **Same trend at 160 \( \mu m \), but noisy photometry**
- **50% variability at 4.5 \( \mu m \)**

8 protostars out of 17 show 10+% variability at 70 \( \mu m \)

From atoms to pebbles: Herschel’s view of star and planet formation  
Grenoble – March 21, 2012 – Nicolas BILLOT
Inconclusive variability detections...

Non-contemporaneous IRAC 4.5 µm flat-ish light curve
Inconclusive variability detections...

Non-contemporaneous IRAC 4.5 µm flat-ish light curve

One-week cadence does not sample faster/slower periodic variations
Future Work…

- SED modeling of variable sources
- Extended emission, PDR (data are public, volunteers?)
- Improved photometry with PSF fitting
- 12 epochs remain to be observed/analyzed
- PACS spectrometer monitoring just started on selected sources
  - See poster by Manoj Puravankara

- More Herschel projects to monitor YSOs:
  GT2_zbalog_2, OT2_jforbric_3, OT2_nbillot_2, OT2_pabraham_4,
  OT2_rvisser_1, OT2_zbalog_3
Data reduction

- HIPE Standard pipeline up to calibrated data cubes (Level1 frames) including non-linearity corrections

- Single-epoch maps (single-direction scan map) are produced with the standard masked high-pass filtering scheme + projection

  - Large spatial scales are affected to some extent by the high-pass filter
  - Small spatial scales (point sources) are NOT affected

- First 6 epochs combined with the IDL-based mapmaker Scanamorphos (Roussel et al. 2012) to preserve extended emission…