Cores, fragmentation, and the earliest observable stages of protostellar disks

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Class 0 protostars...

- Thought to represent the first ~10^4 - 10^5 yrs after collapse.
- Emit more than 0.5% of their luminosity at submm wavelengths - or have accreted less than half their final mass (André et al. 1993, 2000).

- Initial core angular momentum centrifugal radius, R_c, material piles up in disk: R_c ~ t^3 in traditionally inside-out collapsing core with solid body rotation (Terebey, Shu & Cassen, 1984) - or R_c ~ t in magnetized cores (Basu 1997).

- Shu et al. 1987; from JWST science case.
The quest for Class 0 disks

- a non-exhaustive list


Looney et al. (2000, 2003): BIMA survey of Class 0 and I sources, multiplicity, and analytic fits. Low disk/envelope mass ratios → fast processing of material (>85% of continuum flux ~ envelope).


Brown et al. (2000): JCMT+CSO interferometric survey of Class 0 protostars on baselines at 70-190 kλ. Resolved (100-150 AU radius) disks.

Havey et al. (2003*): IRAM PdBI and HST studies of the structure of B335.

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**Fig. 3.**—The observed 2.73 mm visibilities. The dashed line shows the visibilities resulting from an envelope with 0.29 Jy total flux and with a volume emissivity $\propto r^{-2}$. The solid line shows the visibilities resulting from a similar envelope with a flux of 0.14 Jy plus a compact Gaussian source with a flux of 0.15 Jy (for a total flux of 0.29 Jy) and a half-power radius of 0.4. It is obvious that the two-component model fits the data much better than a simple power-law source.
Outline

1. Identification of pre- and protostellar cores from large scale Spitzer+SCUBA maps.
2. Mid-infrared emission from of low-mass protostars and the implications for their envelope structures.
3. Disks around Class 0 protostars from high angular resolution submillimeter (SMA) continuuum observations.
4. Toward less embedded Class I objects
3.86 degree$^2$ (overlap) mapped by c2d with Spitzer/IRAC (3.6, 4.5, 5.8, and 8.0 µm)

Green colors reflect emission from H$_2$ rotational transitions in the 4.5 µm band - probing shocked gas of 500-1000 K. Red is PAH emission in the 8 µm band.

Spitzer/IRAC from c2d (Jørgensen et al. 2006) and GTO (Gutermuth et al. 2007)
NGC1333

Spitzer/IRAC from c2d (Jørgensen et al. 2006) with SCUBA map (yellow contours; Kirk et al. 2006)
Comparison: SCUBA+Spitzer maps

MIPS-24 micron sources are concentrated toward center of SCUBA cores...

...with most of those within 10-15" of the peaks having red $[3.6] - [4.5] > 1.0$ colors.

Of 72 SCUBA cores, 40 have embedded protostars within 15” (3750 AU). Pre- and protostellar time scales similar.

Little dispersal of protostars ($v \sim 0.1 \text{ km/s} \leq c_s$). Bondi-Hoyle accretion not applicable

“Current” star formation efficiency of 10-15%. No significant differences between NGC1333 and other parts of Perseus.

Comparison between SCUBA and Spitzer data allow us to build unbiased samples of embedded protostars and most Class 0 sources (including those previously known) are detected at wavelengths as short as 3.6 μm.
We can now start characterizing even the very deeply embedded protostars at mid-IR wavelengths.
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Jes Jørgensen (AlfA, Bonn), Charlottesville, June 22, 2007
Framework

Single-dish submm/FIR dust continuum emission

High resolution (sub)mm data

Mid-infrared observations

Envelope large scale physical structure (temperature, density)

Confirm/disprove envelope model, $R_{\text{in}}$

Disk: existence, SED, structure (physical, chemical)

Chemical/dynamical structure

High resolution line observations

Radial variations in env. structure

Single-dish line observations
Envelope structure

Data:
- SED, images
- Distance

Constrain:
- $p$, $n_0$ (or $\tau_{100}$), $R_{\text{out}}$

Radiative transfer, calculate:
- Temperature profile
- Model images, SED

See Jørgensen et al. (2002), Schöier et al. (2002), Shirley et al. (2002)
Low-mass protostars

- Densities ranging from $10^4$ cm$^{-3}$ to $10^7$-$10^8$ cm$^{-3}$ (H$_2$)
- Temperatures ranging from $\sim$10 K to a few hundred K.

$\sim$ 20,000 AU (100"")

$\sim$ 200 AU (1")
Envelope structure

- Trying to fit Spitzer/IRS data for IRAS 16293-2422

IRAS16293-2422 mid-IR is not well-reproduced with standard envelope model extending to 25 AU scales... but we know it is a binary with a separation of about 800 AU.

Dashed line: Best fit model of Schöier et al. (2002). Inner radius assumed to be radius where $T_{\text{dust}} = 300$ K.
Blue line: model with $r_i = 600$ AU ($T_{\text{dust}} = 65$ K)

Spitzer: c2d/IRS

Envelopes structure

Assume:
- Central source of heating
- Inner radius
- Density profile “type” (e.g., \( n = n_0 (r/r_0)^{-\rho} \))
- Dust properties

Data:
- SED, images
- Distance

Constrain:
- \( \rho, n_0 \) (or \( \tau_{100} \)), \( R_{out} \)

Radiative transfer, calculate:
- Temperature profile
- Model images, SED

See Jørgensen et al. (2002), Schöier et al. (2002), Shirley et al. (2002)
Envelope structure

- Do the envelopes extend all the way to the smallest scales?

Inside 600 AU the envelope has to be “cleared” of material: otherwise envelope severely optically thick at mid-IR wavelengths; no emission escapes from the central source(s).

For comparison the binary sep. (radius) is 400 AU (2.5").

Dashed line: Best fit model of Schöier et al. (2002), inner radius assumed to be radius of MM2.

We need data from not just (sub)mm obs. but additional constraints from, e.g., mid-IR (Spitzer) observations are important...
Two other low-mass protostars...

Inner cavities of ~100 AU sizes present to let of “enough” mid-IR emission escape. This is not new: Known already to be a problem for less embedded Class I objects when explaining IRAS measurements (e.g., Adams et al. 1987, Myers et al. 1987)
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Protostellar Submillimeter Array Campaign “PROSAC”

- Line + continuum survey (230/345 GHz) of a sample of 8 deeply embedded (Class 0) protostars. Half from Perseus and half more isolated cores (including one from Taurus).
- 3 spectral setups per source: CO, CS, SO, HCO+, H$_2$CO, CH$_3$OH, SiO, ... transitions (and isotopes)
- “Large scale” envelope structure of each source from detailed line and continuum rad. transf. models (Jørgensen et al. 2002; 2004)
- Follow-up program(s) aiming to build comparable sample of Class I sources currently ongoing at the SMA.

NGC1333-IRAS2A: 850 µm dust continuum

…the SMA resolves the warm dust in the inner envelope and the (300 AU diameter) circumstellar disk.

Dust continuum fits for 8 Class 0 protostars

- Disk sizes of $< 50$ AU - $300$ AU (radius)
- Masses of $0.01 - 0.5 \, M_\odot$ (modulo uncertain dust properties etc.) - compared to envelope masses of $0.9 - 4 \, M_\odot$
  - Note that objects with lower $M_{\text{disk}}/M_{\text{envelope}}$ ratios are those with the least collimated outflows

Comparison between 230 and 345 GHz data suggest dust opacity law, $\kappa_\nu \sim \nu^\beta$ with $\beta \approx 1.0$. Grain growth such as in more evolved disks around Class II protostars? Or just reflecting that we don’t understand dust?
Adding it all together

Simple “0D” disk model (Butner et al. 1994). Inner radius appears most important for shape of short (IRAC) wavelength SED.

$\beta \sim 1$ and disk mass $\sim 0.1 \, M_\odot$ (size constr. by SMA obs.)
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Example: L1489-IRS

- Class I YSO ($3.7 \, L_\odot; \, T_{\text{bol}} = 240 \, K$) in Taurus.
- Large scale infalling and rotating envelope constrained by single-dish observations and 2D radiative transfer (Brinch et al. 2007).
- Mapped in HCO$^+$ $J = 3-2$ and continuum at subarcsecond resolution with the SMA.
- Central disk added to envelope model and modeled self-consistently (Brinch et al., submitted).

HST image of L1489 (Padgett et al. 1999) with SMA HCO+ 3-2 emission (contours; Brinch et al. submitted).
Example: L1489-IRS

- Continuum reveal central disk source - and test envelope structure on small scales.
- HCO$^+ 3-2$ reveal velocity field including infall + rotation in central Keplerian disk.
- Best fit L1489 IRS model:
  $M_{\text{env}} = 9\times10^{-2} \ M_\odot$
  $M_{\text{disk}} = 4\times10^{-3} \ M_\odot$
  $M_{\text{star}} = 1.4 \ M_\odot$
- Similar observations for an additional 8 Class I objects in progress...

Brinch et al., A&A, submitted
A legacy for ALMA...?

Systematic survey of large sample of embedded YSOs in differing regions, evolutionary stages, etc. could constrain theoretical models for protostellar evolution.

Toy-model\(^1\) for the evolution of 1 \(M_\odot\) core inspired by the work of Hueso & Guillot (2005) with simple parameterizations of envelope and disk accretion rates.

\(^1\) any resemblance to actual YSOs is purely coincidental.
Where do we (need to) go next?

**Interferometric Studies:**
- Dynamics of protostellar envelopes/outflows, envelope dissipation
- Chemistry (radial variations in abundances, shocks)
- More evolved YSOs (direct evidence for Keplerian rotation in disks)

**Large-scale mapping surveys:**
- Comparison across clouds/cloud samples; relation to environment
- Gould Belt surveys (Spitzer, JCMT, Herschel)

**Underlying physics, tools:**
- We need to understand dust (better) to relate the emission across wavelengths.
- Also issues for identification of lines, molecular data etc.
Conclusions

- Large scale submillimeter and mid-infrared surveys are building large sample of embedded protostars and characterizing their distribution and physical properties from hundred AU to parsec scales.

- Deeply embedded protostars posses circumstellar disks with significant masses (~0.1 M$_\odot$) and sizes (~100 AU). The physical structure of the inner envelope reflects the formation of these disks.

- A detailed framework is in place/being continuously developed to perform the full dust and line radiative transfer necessary to interpret coming observations of low-mass protostars, e.g., from ALMA. Still, there are things that we need to understand better - e.g., the properties of dust.