Disks in Class 0 protostars:
The Resolved Massive Disk in Serpens FIRS 1

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Project working on with...
Based on c2d, bolocam surveys, follow up on a large census of cores & protostars in per, ser, oph
The mass distribution of lifetime of presteller cores in Perseus, Serpens, and Ophiuchus

Fig. 13.—Combined prestellar core mass distribution (CMD), with power law and lognormal fits. The prestellar sample is composed of all starless cores from Perseus, Serpens, and Ophiuchus, and the 50% mass completeness limit (dotted line) is defined by the completeness limit for average-sized cores in Perseus. Recent measurements of the stellar IMF for $M \gtrsim 0.5 M_\odot (\alpha = -2.3$ to $-2.8)$ are similar to the best-fit CMD power law slope ($\alpha = -2.3 \pm 0.4$). IMF fits from Chabrier (2005) (lognormal) and Kroupa (2002) (three-component power law) are shown as thick gray lines for reference. The shaded histogram indicates how the mass distribution changes if a small fraction of cores (15%, based on the six “unbound” cores from Figure 12) with $M < 1 M_\odot$ are excluded from the prestellar sample.

assign a total uncertainty of 0.4 to our best fit slope, when also taking into account formal fitting errors. We fit a lognormal distribution to $M > 0.3 M_\odot$, finding a best-fit width $\sigma = 0.30 \pm 0.03$ and characteristic mass $M_0 = 1.0 \pm 0.1$. Although the lognormal function is quite a good fit ($\tilde{\chi}^2 = 0.5$), the reliability of the turnover in the prestellar CMD is highly questionable given that the completeness limit in Perseus coincides closely with the turnover mass. The prestellar CMD can also be fit by a broken power law with $\alpha = -4.3 \pm 1.1$ for $M > 2.5 M_\odot$ and $\alpha = -1.7 \pm 0.3$ for $M < 2.5 M_\odot$, although the uncertainties are large.

Given that source detection is based on peak intensity, we may be incomplete to sources with very large sizes ($M > 0.8 M_\odot$). Completeness varies with size similarly to $M \propto R^2$, thus the fraction of (possibly) missed sources should decrease with increasing mass.

The effect of missing such low surface brightness cores, if they exist and could be considered prestellar, would be to flatten the CMD slightly (i.e. the true slope would be steeper than the observed slope). Instrumental selection effects are discussed further in Paper I.

To be completely consistent, we should exclude the “unbound” cores from Figure 12 (those with $M_{\text{dust}}/M_{\text{vir}} < 0.5$) from our prestellar CMD. This represents 6 out of the 40 cores that have measured virial masses in Perseus, all 6 of which have $M_{\text{dust}} < 1 M_\odot$. We do not have virial masses for cores in Serpens or Ophiuchus, but we can randomly remove a similar fraction of sources with $M < 1 M_\odot$ from each cloud sample (2 sources from Serpens, 4 from Ophiuchus, and an additional 4 from Perseus). The shaded histogram in Figure 13 indicates how the mass distribution is altered when these 16 “unbound” cores are excluded from the sample. Our derived CMD slope is not affected, as nearly all of the starless cores below the “gravitationally bound” line in Figure 12 have masses below our completeness limit, and even at low masses the CMD is not significantly changed.

There may also be some concern over the use of a single dust temperature $T_D = 10 K$ for all cores. To test the validity of this assumption, we use the kinetic temperature $T_K$ to determine the effect of using different dust temperatures on the derived mass distribution.

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One of papers in mario’s list should have had a red et al. Was lucky to have the king of cores’ insight on our analysis of the starless cores... MF, lifetime
Class 0 disks

- **Goals:**
  - When does the disk form?
  - Typical mass?
  - What does the inner envelope look like?

- **Previous work**
  - Evidence for disks in a few Class 0 sources (Chandler et al. 95, Looney et al. 03, Jorgensen et al. 07)

- **Need:**
  - Representative sample of Class 0 protostars
  - Broadband SED, tracer of MIR flux
  - High resolution images at optically thin wavelengths

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That established... Like I said, this is follow up in a sense, looking deeper at subset populations from large sample. Increase toward younger times (Andrews & Williams 2007) vs. Start small (theory)? When form = do all class 0 have disks? Envelope structure important as well, need both together.

Some measurements, but vary quite a bit, mostly “famous” sources (Jes exception). Rep sample – from collapse to Mstar=Menv. Can constrain models with... [SHOWN BY JES]
Class 0 disks

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- **Need:**
  - Representative sample of Class 0 protostars
  - Broadband SED, tracer of MIR flux → c2d, IRS spectra
  - High resolution images at optically thin wavelengths → CARMA maps
Spitzer IRAC/MIPS + Bolocam 1.1 mm surveys ("Cores to Disks"; Evans et al. 2003)
- ~20 sq deg in Per, Ser, Oph
- $M_{\text{env}}$ limit ~ 0.1-0.2 $M_{\odot}$

~40 Class 0 sources
- $T_{\text{bol}} < 70$ K
- $M_{\text{env}}$ ~ 0.2 - 10 $M_{\odot}$
- $L_{\text{bol}}$ ~ 0.2 - 10 $L_{\odot}$

The sample is from census.... Complete to $M_{\text{env}}$ & Lint limits.
40 class 0, defined by Phil’s $T_{\text{bol}}$, having $T$<70K
Selected sample that do not have mid-IR spectra and/or high resolution millimeter maps.
The Resolved Massive Disk in FIRS 1

Fig. 4.—Three color Spitzer image (8 µm blue, 24 µm green, 70 µm red) of Serpens FIRS 1, with CARMA 230 GHz continuum contour overlaid. The direction of the radio jet (Rodríguez et al. 1989; Curiel et al. 1993) is shown again here; it lines up fairly well with extended 8 µm emission (blue), which is likely scattered light from the outflow cavity. The 8 µm source to the south is a more evolved YSO (Harvey et al. 2007).

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Modeling & testing completed for 1 source (brightest)
To serve as proof of feasibility of method.
Direction of cm jet from....
CARMA 230 GHz map

Fig. 3.— CARMA 230 GHz maps of Serpens FIRS 1 for short baseline data only (D,E configurations; panel A), all data (panel B), and long baseline data only (B,C configurations; panel C). Contours in panel B are $(2,4...10,20...70) \times \sigma$, for a synthesized beam of $0.94\,'' \times 0.89\,''$ (shown, lower right). Contours in panels A and C start at $4\sigma$ and $6\sigma$, respectively. A linear scale of 500 AU is indicated in panel (B); note the change in scale in each panel. The direction of the 3.6 cm jet (Rodríguez et al. 1989; Curiel et al. 1993) is also shown for reference.

Short baseline data only (E,D array)  |  All data (B,C,D,E array)  |  Long baseline data only (B,C array)

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Note pick up different structures with different configurations. Envelope, resolve out some env, disk. Binary??
CARMA 1mm visibilities

Fig. 4.— CARMA 230 GHz visibility amplitude versus $uv$-distance for Serpens FIRS 1. Observations in the B, C, D, and E CARMA antenna configuration provide $uv$-coverage from $4.5 \, \lambda$ to $500 \, \lambda$. The expected value in the case of zero signal, or amplitude bias, is shown with a dotted line and is typically small (less than $0.1 \, \text{Jy}$).

Fig. 2.— Spitzer IRS spectrum of Serpens FIRS 1, using the Low Res 7.4–14.5 $\mu$m (SL1), Hi Res 9.9–19.6 $\mu$m (SH), and Hi Res 18.7–37.2 $\mu$m (LH) modules. Binned data ($\Delta \lambda \sim 1 \, \mu$m) are over-plotted as diamonds; error bars represent the variation within each bin. Binned fluxes are used in the model fitting and given in Table 1.

Really get more information from visibilities than map. Lots of emission at intermediate, maybe point like at >200 klam.... Other new data is IRS spectrum. Binned points used in model fit.
Radiative Transfer Models
(RADMC; Dullemond & Dominik 2004)

- SED is sensitive to:
  - $R_{out}$, $R_{cent}$
  - Inclination, outflow opening angle

- 1mm visibilities are sensitive to:
  - $M_{disk}$, $R_{disk}$
  - $(R_{out}, R_{cent})$

- Set by 1mm/Spitzer photometry:
  - $M_{env}$, $L_{star}$

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Model – RADMC, env of infalling rotating spheroid, w/ outflow & disk
SED & 1mm almost orthogonal constraints
Serpens FIRS 1: best-fit model

- Rcent ~ 600 AU, outflow full opening angle ~ 20 deg
- Disk mass ~ 1.0 Msun, Disk radius ~ 300 AU
- Disk-to-Envelope mass ratio ~ 0.13

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Blue=just envelope
500/6000 fits a bit better, but hard to fit intermed uv dist
Of course, a range of params works
HIGH MASS. Higher than would expect for young source, unless high env infall rate and/or very rapid rotation in initial core.
PROSAC: A Submillimeter Array survey of low-mass protostars

II. The mass evolution of envelopes, disks, and stars from the Class 0 through I stages

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Estimate $M_{\text{disk}}$ from the 1mm flux at 50 klm. Subtract out fixed % from envelope.
If calculate in same way....
Average mass Jes $\sim$0.05 both Class 0/Class I
COMPLEMENTARY STUDIES
Start with Serpens sample, 7 sources, have most of CARMA data, preliminary models.
Serpens Class 0 sample

- \( \frac{M_{\text{disk}}}{M_{\text{env}}} \approx 10\% \)
- Median \( M_{\text{disk}} \approx 0.1 \) Msun

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Only one with no disk, even in “complete” sample
Menv limit 0.1
Summary

- Radiative transfer models with IRS spectra + millimeter interferometry constrain Class 0 disk & envelope structure.

- Massive resolved disk in Serpens FIRS 1 (M~1 \( M_{\text{Sun}} \), R~300 AU)
  - May require high rotation or envelope infall rates.

- **Preliminary** results for Serpens sample: disk-to-envelope mass ratios ~10%.

- Disks are relatively massive at very early times.

Use SED to get envelope params, w/ those, disk mass is robustly constrained. Need very good uv coverage.

Obviously need larger sample to draw any general conclusions.

Notable exceptions – FIRS 1, bolo 15 (large disk/env mass ratio). median mass ~0.1, mean ~0.25

Dust props, mostly long wavelength.
Power law envelope model

- Only 0.1 Msun disk required, but doesn’t reproduce MIR spectrum

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If really don’t like large disks early on, may be able to get around it....
Lesson from this depends on point of view.
Prev results (looney et al) – can fit vis w/o disk. Yes, but doesn’t fit sed. NEED TO FIT BOTH
If you don’t like the large disk there are some ways around it
MULTIPICITY OF THE PROTOSTAR SERPENS SMM 1 REVEALED BY MILLIMETER IMAGING

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ABSTRACT

The Serpens SMM 1 region was observed in the 6.9 mm continuum with an angular resolution of about $0.6''$. Two sources were found to have steep positive spectra suggesting emission from dust. The stronger one, SMM 1a, is the driving source of the bipolar jet known previously, and the mass of the dense molecular gas traced by the millimeter continuum is about $8\,M_\odot$. The newly found source, SMM 1b, positionally coincides with the brightest mid-IR source in this region, which implies that SMM 1b is yet another young stellar object among them is SMM 1 (Harvey et al. 1984; Enoch et al. 2007). SMM 1 is a Class 0 source embedded among several Herbig-Haro objects and molecular outflows (Davis et al. 1999). The synthesized beam is $FWHM = 0.6''$.

The position of the millimeter source given by Hogerheijde et al. (1999) is $24$ and P.A. $= 51^\circ$. Outflow knots are labeled following the convention used by Casali et al. 1993; Enoch et al. 2007). SMM 1 is probably a protobinary system with a projected separation of $18''$. The newly found source, SMM 1b, positionally coincides with the brightest mid-IR source in the SMM 1 region. In order to investigate the source structure and the continuum emission from dust, the Serpens dark cloud is a nearby star-forming region (see D'Arco et al. 2002). The Serpens SMM 1 region was observed in the 6.9 mm continuum with an angular resolution of about $0.6''$. Two sources were found to have steep positive spectra suggesting emission from dust. The stronger one, SMM 1a, is the driving source of the bipolar jet known previously, and the mass of the dense molecular gas traced by the millimeter continuum is about $8\,M_\odot$. The newly found source, SMM 1b, positionally coincides with the brightest mid-IR source in this region, which implies that SMM 1b is yet another young stellar object among them is SMM 1 (Harvey et al. 1984; Enoch et al. 2007). SMM 1 is a Class 0 source embedded among several Herbig-Haro objects and molecular outflows (Davis et al. 1999). The synthesized beam is $FWHM = 0.6''$.

Subject headings: ISM: individual (Serpens SMM 1) — ISM: structure — stars: formation

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Fig. 5.— Reduced $\chi^2$ contours resulting from fitting the observed SED and 230 GHz CARMA visibilities to the grid of envelope and disk models. Models have been run for the full parameter ranges shown; the model grid resolution corresponds to the axis labels (e.g. $R_{\text{cent}}$ values of 50, 100, 200, 300, ... 1000 AU), but the $\tilde{\chi}^2$ distribution has been smoothed for a better visual representation. Contours from fits to the both the SED (magenta) and visibilities (cyan, tick marks indicate downhill direction) are shown, although envelope parameters (panels A-C) are primarily constrained by the SED, while disk parameters (panel D) are constrained by the millimeter visibilities. In panels (A)-(C) the $\chi^2$ distribution is collapsed along the parameters not plotted. The lowest contour shown is $\tilde{\chi}^2 = 8$.

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Chisq – not perfectly constrained. Example = Rout

Disk well constrained by vis.
Implications for disk formation

• Disk growth via centrifugal balance (Terebey et al. 1984)

\[ R_d = 7 \left( \frac{c_s}{0.35 \text{km s}^{-1}} \right) \left( \frac{\Omega}{4 \times 10^{-14} \text{s}^{-1}} \right)^2 \left( \frac{t}{10^5 \text{yr}} \right)^3 \text{AU} \]

→ For t~10^5 yr, requires rapid initial rotation rate (4x10^{-13} s^{-1})

• Disk growth via accretion from the envelope (Shu 1977)

\[ \dot{M}_{\text{env}} \sim \frac{c_s^3}{G} \sim 10^{-5} \text{M}_\odot \text{yr}^{-1} \]

→ Can accumulate 1Msun in 10^5 years

→ Low viscosity disk or higher infall rate?
Radiative transfer modeling

- RADMC (Dullemond & Dominik 2004)
  - 2D Monte Carlo radiative transfer and ray tracing
- Envelope parameterized according to Ulrich (1967); see also Crapsi et al. (2008)

\[
\rho_{\text{env}} = \frac{\rho_{\text{env},1000}}{100} \frac{2.33m_H}{1000AU} \left( \frac{r}{1000AU} \right)^{-1.5} \left( \frac{1}{1 + \cos\theta/\mu_0} \right) \left( \frac{\cos\theta}{\mu_0} + 2\mu_0^2 \frac{R_{\text{cent}}}{r} \right)^{-1}
\]

, \( R_c \) is the centrifugal radius, \( \mu = \cos \theta \), and \( \mu_0 \) is the cosine polar angle of a streamline of infalling particles as \( r \rightarrow \infty \). The equation for the streamline is given by

\[
\mu_0^3 + \mu_0 (r/R_c - 1) - \mu (r/R_c) = 0 . \quad (2)
\]

\[
\rho_{\text{env}} = \rho_{\text{env}}(\mu_0 \leq \cos(An))
\]

\[
\Sigma_{\text{disk}} = \Sigma_0 (r/R_{\text{disk}})^{PL} \\
h = h_0 (r/R_{\text{disk}})^{PLH}
\]

Use spectral & spatial obs to constrain models & get at structure.
For infalling, rotating envelope, but replace dependence on \( dM/dt \) w/ \( \rho_{1000} \)
0 values set by total mass. Den pile-up at \( R_{\text{cent}} \)
Disk PL in surf den w/ radius, and scale height (flaring).
Can change envelope to pl, whatever
Model parameters

Some parameters held fixed, like..... Some testing to see if affect answers, some (lum) just have to characterize how affects...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed?</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{star}}$</td>
<td>Y</td>
<td>11 $L_\odot$</td>
<td>Internal luminosity</td>
</tr>
<tr>
<td>$M_{\text{star}}$</td>
<td>Y</td>
<td>0.5 $M_\odot$</td>
<td>Protostar mass</td>
</tr>
<tr>
<td>$T_{\text{star}}$</td>
<td>Y</td>
<td>4000 K</td>
<td>Protostar effective temperature</td>
</tr>
<tr>
<td>$R_{\text{star}}$</td>
<td>Y</td>
<td>5 $R_\odot$</td>
<td>Protostar radius</td>
</tr>
<tr>
<td>$M_{\text{env}}$</td>
<td>Y</td>
<td>8.0 $M_\odot$</td>
<td>Total mass of envelope</td>
</tr>
<tr>
<td>$R_{\text{out}}$</td>
<td>N</td>
<td>3000 – 12000 AU</td>
<td>Outer radius of envelope</td>
</tr>
<tr>
<td>$R_{\text{cent}}$</td>
<td>N</td>
<td>50 – 1000 AU</td>
<td>Centrifugal (inner) radius of envelope</td>
</tr>
<tr>
<td>Ang</td>
<td>N</td>
<td>5 – 80 deg</td>
<td>Outflow opening angle</td>
</tr>
<tr>
<td>Incl</td>
<td>N</td>
<td>5 – 90 deg</td>
<td>Inclination angle</td>
</tr>
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<td>$M_{\text{disk}}$</td>
<td>N</td>
<td>0.0 – 3.0 $M_\odot$</td>
<td>Disk mass</td>
</tr>
<tr>
<td>$R_{\text{disk}}$</td>
<td>N</td>
<td>50 – 1000 AU</td>
<td>Disk radius</td>
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<td>$H_0$</td>
<td>Y</td>
<td>0.2 $R_{\text{disk}}$</td>
<td>Disk vertical pressure scale height</td>
</tr>
<tr>
<td>$p1$</td>
<td>Y</td>
<td>–1.0</td>
<td>Disk surface density radial power law ($r &lt; R_{\text{disk}}$)</td>
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<tr>
<td>$p2$</td>
<td>Y</td>
<td>2/7</td>
<td>Power law for H(R) (disk flaring)</td>
</tr>
</tbody>
</table>

Note. — The internal luminosity is set by the bolometric luminosity of the source, determined from the broadband SED, and the envelope mass is set by the 1.1 mm Bolocam single dish flux (see Enoch et al. 2009). Ang is the full outflow opening angle. Incl is the line of sight inclination angle of the disk: 0 deg is face-on, 90 deg is edge-on. Stellar, envelope, and disk parameters are discussed in Section 3.
IRS Spectra: Serpens Class 0 protostars

Serpens sources
CARMA maps: Serpens Class 0 protostars

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HAVE DATA FOR 8 SERPENS SOURCES SO FAR. Note uv coverage
Spitzer images (7, 24, 70 micron) with CARMA 1.3mm contours. Visibilities = amplitude as a function of uv–distance or baseline. Tell you more than images. Another resolved, less resolved, unresolved with extended envelope, disk only?
Relationship between Tbol & “age”

Based on number counts

Enoch et al. 2009
First source. Both pretty low inclination. Larger outflow angle.
Try to do all Class 0 in the cloud. Few had spectra in archive already. Few class I for good measure. When got 3mm data w/ carma (lower res, for mult), found most of mass (at least compact) was assoc w/ one sometimes.... In case of Bolo 24, had picked the wrong one, only have vis. Didn’t do 1mm obs if not det at 3mm (maybe just no disk, but still have to quantify env)
Very similar program with SMA, but don’t have SED info. Also have lines to trace outflows, etc, and keplerian motion in Class I. Still brightest most famous sources....