Masses: Probing the Origins of Protostars

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Early low-mass star formation

Greene 01
Early low-mass star formation

Core-filament system
Taurus L1495 Hacar+ 13

Greene 01

Near-neighbor protostars
Perseus L1448 Tobin+16
Early low-mass star formation

Basic question: **how do protostars get their mass?**

- how do protostars stop accreting?  
- role of outflows
- on what scale do protostars “inherit” environment properties?  
- direction of angular momentum
- how do protostar groups relate to larger groups?  
- multiscale fragmentation

The need for **finer resolution** – cores (10,000 au) to envelopes (1000 au) to disks (100 au)

The need for **complete statistical samples** – many observables have broad distributions (IMF, CMF, $N$-pdf,...)
**MASSES overview**

**History**
- Large SMA program 600 h 2014-2017
  - PIs Mike Dunham, Ian Stephens
- NASA Origins grant 2015-2019
  - PIs Tyler Bourke, Phil Myers

**Specs**
- $f = 230, 345 \text{ GHz, } \sigma_{1.3 \text{ mm}} \approx 1 \text{ mJy bm}^{-1}$
- $\Delta \theta = 1\text{-}4'' \text{ to } 20''$, $\Delta v = 0.09\text{-}0.3 \text{ km s}^{-1}$
- main lines $^{12}\text{CO}, ^{13}\text{CO}, C^{18}\text{O}, N_2\text{D}^+$
- SO, DCO$^+$, SiO, DCN, $C_3\text{H}_2$, $H_2\text{CO}$…

**Survey**
- Line, continuum 74 Class 0/I protostars
- same targets as 0.8 mm VLA continuum (VANDAM, Tobin+16)

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Perseus molecular cloud complex

350 $\mu$m (gray), clumps (blue), starless cores (red), Class 0/I protostars (green) (Sadavoy+10, Zari+16, Mercimek+17)
MASSES papers 2015-2019

\(^8\)Frimann, S. et al. 2017, A&A
\(^8\)Pokhrel, R. et al. 2018 ApJ
\(^8\)Agurto-Gangas et al. 2019 A&A
\(^4\)Heimsoth, D. et al. 2019, in prep.

kinematic origins of multiplicity
neighbor outflows have random angles
random angles \(\rightarrow\) turb fragmentation
C\(^{18}\)O map sizes \(\rightarrow\) episodic accretion
outflows, filaments have random angles
hierarchical fragmentation Perseus
subcompact data release
grain growth in Per-emb-50
evolution disk and envelope masses
full data release
evolution CO outflow opening angles
envelope masses and vel gradients

10 refereed papers + 2 in prep.
\(u\) or \(g\) = undergrad or grad student 1\(^{st}\) author
MASSES papers 2015-2019

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MASSES outflows and envelopes

CO 2-1 outflows Stephens et al. 19

C$^{18}$O 2-1 envelopes Heimsoth et al. 19
MASSES line profiles and images in many lines

SVS13A and SVS13B images in >30 distinct lines – Stephens et al. 19

SWARM correlator opens many opportunities for astrochemistry

C$^{18}$O 2-1 central spectra  Stephens et al. 19
Accretion environment

Spectral evolution: Classes of SED evolve from red to blue as winds end infall and unveil the star-disk system (Adams+87)

Quantification: the “bolometric temperature” of an SED is the temperature of a blackbody having the same mean frequency \( \bar{\nu} \)

\[
T_{\text{bol}} \equiv \frac{\zeta(4) h \bar{\nu}}{4 \zeta(5) \kappa}
\]

(Myers & Ladd 93, Chen+ 95)

Application: outflow opening angle increases with \( T_{\text{bol}} \), first rapidly, then more slowly - Arce & Sargent 06 (AS06).

Caveat: \( T_{\text{bol}} \) and \( \Delta \theta \) appear to be “evolutionary” properties with time scale ~ 0.1 Myr, but their relation to \( t \) is still unclear.

<table>
<thead>
<tr>
<th>SED Class</th>
<th>( T_{\text{bol}}(K) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>10</td>
</tr>
<tr>
<td>Class II</td>
<td>70</td>
</tr>
<tr>
<td>Class III</td>
<td>650</td>
</tr>
<tr>
<td>Pre-main sequence phase</td>
<td>2880</td>
</tr>
</tbody>
</table>

\( \Delta \theta \) \( v. T_{\text{bol}} \) Arce & Sargent (06)
Accretion environment 2

**Spectral evolution:** Classes of SED evolve from red to blue as winds end infall and unveil the star-disk system (Adams+87)

**Quantification:** the “bolometric temperature” of an SED is the temperature of a blackbody having the same mean frequency $\tilde{\nu}$

$$T_{bol} \equiv \frac{\zeta(4) h \tilde{\nu}}{4 \zeta(5) \kappa}$$

(Myers & Ladd 93, Chen+ 95)

**Application:** outflow opening angle increases with $T_{bol}$, first rapidly, then more slowly - Arce & Sargent 06 (AS06).

**Caveat:** $T_{bol}$ and $\Delta \theta$ appear to be “evolutionary” properties with time scale $\sim 0.1$ Myr, but their relation to $t$ is still unclear.
Accretion environment 3

What stops accretion? Collapse, feedback from neighbor stars, outflows

This work: Extend AS06 with better statistics and more info: \( \Delta \theta, \Delta \theta_{eo}, \) and \( M_e \) vs. \( T_{bol} \)

Result: 3 indep synchronized events: at same evolution milestone \( T_{bol} = 50-100 \) K:

1. outflow opens wide
2. envelope major axis orients toward disk plane
3. envelope mass dissipates until too low to feed disk & protostar

\[
\Delta \theta = 0.6
\]

1. \( \Delta \theta(T_{bol}) \)
Dunham+ 19

2. \( \Delta \theta_{eo}(T_{bol}) \)
Heimsoth+ 19

3. \( M_e(T_{bol}) \)
Andersen+ 18

curves: simple exponential fits with \( R \approx 0.6 \)
Accretion environment 3

What stops accretion? Collapse, feedback from neighbor stars, outflows

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1. outflow opens wide
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3. envelope mass dissipates until too low to feed disk & protostar

outflow opens until envelope can’t feed disk & protostar

1. $\Delta \theta (T_{bol})$
   Dunham+ 19
2. $\Delta \theta_{eo} (T_{bol})$
   Heimsoth+ 19
3. $M_e (T_{bol})$
   Andersen+ 18

curves: simple exponential fits with $R \approx 0.6$
Outflow directions

Are they set by magnetic alignment of outflow and filament axes?

One might expect magnetic alignment, since $\hat{B} \perp$ fil axis *(Planck)* and $\hat{B} \parallel$ outflow axis *(ALMA)*

**MASSES** analysis:

- select host filament
- fit skeleton, tangent direction
- fit outflow axis direction
- cumulative distribution $\Delta \theta (fil - of)$

**Conclude:** outflow directions are *not* set on filament scales (0.1 – 1 pc) - Stephens+17
Outflow directions

In multiple systems, are they set by angular momentum alignment of neighboring outflow axes?
One might expect angular momentum alignment, if a rotating circumbinary envelope becomes Keplerian

MASSES analysis: 19 angle pairs in 12 multiple systems

Conclude: outflow directions are not set on envelope scales (~1000 au) - Lee+ 16
candidate smaller-scale process: turbulent fragmentation – Fisher 04, Offner+16
Multiscale hierarchy suggests turbulent cascade down to transonic scales (Larson 81).

Multiplicity at each scale expected to depend on gravity, $\sigma_T, \sigma_{turb}$ (Clarke+17).

This work: compare $N$ and $N_j = M/M_j = 6MG^{3/2} \rho^{1/2} \pi^{-5/2} \sigma^{-3}$ at each scale.
### Multiplicity in Perseus: thermal Jeans efficiency

<table>
<thead>
<tr>
<th>Parent</th>
<th>scale (pc)</th>
<th>$N_{child}$</th>
<th>$N_j = (M/M_j)_{parent}$</th>
<th>$\bar{\epsilon}<em>j = N</em>{child}/N_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>cloud</td>
<td>20</td>
<td>7 clumps/cloud</td>
<td>120</td>
<td>0.06</td>
</tr>
<tr>
<td>clump</td>
<td>1</td>
<td>16 cores/clump</td>
<td>74</td>
<td>0.20</td>
</tr>
<tr>
<td>core</td>
<td>0.05</td>
<td>1.1 envelopes/core</td>
<td>2.7</td>
<td>0.41</td>
</tr>
<tr>
<td>envelope</td>
<td>0.005</td>
<td>1.3 protostars/env</td>
<td>2.8</td>
<td>0.47</td>
</tr>
</tbody>
</table>

**Conclude:**

1. Inefficient thermal Jeans fragmentation, efficiency $\bar{\epsilon}_j$ approaching 0.5 toward smaller scales

2. “Turbulent” Jeans fragmentation with $\sigma_{turb}$ from line width predicts too few fragments

3. First study applied to four scales in the same complex, confirms Palau+15,17 in diverse regions

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### $N_{child}$ surface density v. $N_j$ surface density

- **Protostars in Envelope** $\epsilon^h = 0.5$
- **Envelopes in Core** $\epsilon^h = 0.4$
- **Cores in Clump** $\epsilon^h = 0.2$
- **Clumps in Cloud** $\epsilon^h = 0.06$

- Typical error

- [Pokhrel+18](#)
Summary

**MASSES**
large-scale SMA program, 600 h over 3 years
PIs: Dunham, Stephens, Bourke, Myers
goal: how protostars get their mass

**Survey**
74 Perseus protostars, 0.9 and 1.3 mm continuum, $^{12}$CO, C$^{18}$O, N$_2$D$^+$ and ~30 other lines resolve envelopes on scales >300 au.
largest complete line survey at this scale

**Accretion**
3 independent measurements strengthen case
outflows important for final protostar mass

**Outflow**
no direction correlation w filaments, neighbors
outflow direction set below 1000 au

**Multiplicity**
may reflect hierarchy of thermal and turbulent
fragmentation $\epsilon_{\text{ Jeans (thermal)}} \to 1/2$

**SMA Future**
wSMA SWARM protocluster groups physics & chemistry