The SOFIA Massive (SOMA) Star Formation Survey

Jonathan C. Tan

James M. De Buizer
Mengyao Liu
Yichen Zhang

Jan E. Staff
María T. Beltrán
Kei Tanaka
Barbara Whitney
Ralph Shuping

Nicola Da Rio
Viviana Rosero
Maria Drozdovskaya
The Importance of Massive Stars

Zinnecker & Yorke (2007)  
Tan et al. (2014)
The Physics of High-Mass Star Formation

A complicated, nonlinear process:

- Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.
- Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields.
- Chemical evolution of dust and gas.
- Fragmentation
- Stellar structure and evolution
- Feedback

- Wide range of scales (~12 dex in space, time) and multidimensional.
- Uncertain/unconstrained initial conditions/boundary conditions.

Notation for gas structures:
Core -> star or close binary
Clump -> star cluster
(Massive) Star Formation: Open Questions

- **Causation:** external triggering or spontaneous gravitational instability?
- **Initial conditions:** how close to equilibrium?
- **Accretion mechanism:** [turbulent/magnetic/thermal-pressure]-regulated fragmentation to form **cores** vs competitive accretion / mergers
- **Timescale:** fast or slow (# of dynamical times)?
- **End result**
  - Initial mass function (IMF)
  - Binary fraction and properties

How do these properties vary with environment? Subgrid model of SF? Threshold $n_H^*$? Efficiency $\epsilon_f$?
The Environments of Massive Star Formation

Mass surface density $\Sigma$ vs. mass $M$ diagram. The diagram shows the relationship between mass surface density and mass for star-forming regions. The equation $\Sigma = \frac{M}{\pi R^2}$ is used to calculate the mass surface density, and $\dot{P} \sim G \Sigma^2$ is the relationship between the mass surface density and the rate of change of pressure. The lifetime $t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$ is also shown.
Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \frac{\dot{P}}{k} = 4.3 \times 10^8 \Sigma^2 \text{ K cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

Local Galactic Disk

\[ A_V = 1.4 \]

\[ N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \]

\[ \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \]

\[ \Sigma \sim 10 \text{ M}_\odot \text{ pc}^{-2} \]
CO GMCs and Clumps
Solomon et al. (1987)
Roman-Duval et al. (2010)

$\Sigma \sim 10 M_{\odot} \text{ pc}^{-2}$

$A_V = 7.5$
$A_{A\mu m} = 0.30$
$N_H = 1.6 \times 10^{22} \text{ cm}^{-2}$
$\Sigma = 180 M_{\odot} \text{ pc}^{-2}$

$A_V = 1.4$
$N_H = 3.0 \times 10^{21} \text{ cm}^{-2}$
$\Sigma = 34 M_{\odot} \text{ pc}^{-2}$
Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \bar{P} \sim G \Sigma \]

\[ \bar{P}/k = 4.3 \times 10^8 \Sigma^2 \text{ K cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

**Dense Clumps**
Mueller et al. (2002)
Ma et al. (2013)
Ginsburg et al. (2012)
Longmore et al. (2012)

**Tan et al. (2014, PPVI)**

Local Galactic Disk

\[ \Sigma \sim 10 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 230 \]
\[ A_{8\mu m} = 8.1 \]
\[ N_H = 4.2 \times 10^{23} \text{ cm}^{-2} \]
\[ \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
\[ N_H = 1.6 \times 10^{22} \text{ cm}^{-2} \]
\[ \Sigma = 180 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 1.4 \]
\[ N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \]
\[ \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \]

Tuesday, April 4, 17
### Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \frac{\dot{P}}{k} = 4.3 \times 10^8 \Sigma^2 \text{K cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

**Star Clusters**

- **ONC** - Da Rio et al. (2014)
- **NGC3603** - Pang et al. (2013)
- **Quintuplet** - Hußmann et al. (2012)
- **Arches** - Habibi et al. (2013)
- **Westerlund 1** - Lim et al. (2013)
- **R136** - Andersen et al. (2009)
- **NGC346** - Sabbi et al. (2008)
- **NGC1569 SSCs** - Larsen et al. (2008)
- **M82 SSCs** - McCrady & Graham (2007)

**Local Galactic Disk**

- \( A_V = 1.4 \)
- \( A_{8\mu m} = 0.30 \)
- \( N_H = 3.0 \times 10^{21} \text{cm}^{-2} \)
- \( \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \)

**Star-Forming Regions**

- \( A_V = 7.5 \)
- \( A_{8\mu m} = 8.1 \)
- \( N_H = 4.2 \times 10^{23} \text{cm}^{-2} \)
- \( \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \)

**MSF Core/Clumps**

- \( A_V = 230 \)
- \( A_{8\mu m} = 8.1 \)
- \( N_H = 4.2 \times 10^{23} \text{cm}^{-2} \)
- \( \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \)
These are the (local) environments where massive stars form: can we scale-up low-mass SF theory?

Tan et al. (2014, PPVI)
Massive Star Formation Theories

Core Accretion:
wide range of $\text{dm}$/dt $\sim 10^{-5} - 10^{-2} \, \text{M}_\odot \, \text{yr}^{-1}$
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:
(McKee & Tan 2002, 2003)
Stars form from “cores” that fragment from the “clump”

$\Sigma \sim 1 \, \text{g cm}^{-2}$

If in equilibrium, then self–gravity is balanced by internal pressure: B–field, turbulence, radiation pressure (thermal P is small)

Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

$\dot{m}_* \sim M_{\text{core}} / t_{\text{ff}}$
Massive Star Formation Theories

Core Accretion:
wide range of $\frac{dm}{dt} \sim 10^{-5} - 10^{-2} M_\odot \text{ yr}^{-1}$
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:
(McKee & Tan 2002, 2003)
Stars form from “cores” that fragment from the “clump”

$$\Sigma \sim 1 \text{ g cm}^{-2}$$

If in equilibrium, then self-gravity is balanced by internal pressure: B-field, turbulence, radiation pressure (thermal $P$ is small)

Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

$$\dot{m}_* \sim \frac{M_{\text{core}}}{t_{\text{ff}}}$$

Competitive (Clump-fed) Accretion:
(Bonnell, Clarke, Bate, Pringle 2001; Bonnell, Vine, & Bate 2004; Schmeja & Klessen 2004; Wang, Li, Abel, Nakamura 2010; ...)
Massive stars gain most mass by Bondi-Hoyle accretion of ambient clump gas

Originally based on simulations including only thermal pressure.
Massive stars form on the timescale of the star cluster, with relatively low accretion rates.

Violent interactions?
Mergers?
(Bonnell, Bate & Zinnecker 1998; Bally & Zinnecker 2005 Bally et al. 2011)
Massive Star Formation Theories

**Core Accretion:**
wide range of \(\text{dm}/\text{dt} \sim 10^{-5} - 10^{-2} \, \text{M}_\odot \, \text{yr}^{-1}\)
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

**Competitive (Clump-fed) Accretion:**
(Bonnell, Clarke, Bate, Pringle 2001; Bonnell, Vine, & Bate 2004; Schmeja & Klessen 2004; Wang, Li, Abel, Nakamura 2010; ...)
Massive stars gain most mass by Bondi-Hoyle accretion of ambient clump gas

**Turbulent Core Model:**
(McKee & Tan 2002, 2003)
Stars form from “cores” that fragment from the “clump”

\[ P = \phi P G \Sigma^2 \]

If in equilibrium, then self-gravity is balanced by internal pressure:
B-field, turbulence, radiation pressure (thermal \(P\) is small)

Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores.
These cores collapse quickly to feed a central disk to form individual stars or binaries.

**SOFIA measurement of Clump Infall**
\(V_{\text{infall}} \sim 0.1 \, V_{\text{ff}}\)
(Wyrowski et al. 2016)

Limited fragmentation
(Csengeri et al. 2017)

Originally based on simulations including only thermal pressure. Massive stars form on the timescale of the star cluster, with relatively low accretion rates.
Schematic Differences Between Massive Star Formation Theories

- Massive prestellar core
- Massive-star-forming core [protostar + gravitationally-bound gas]
- Massive-protostar (MP)

Turbulent core model (MT02, 03)

- $t=0$
  - Protostar formation
- $m^* = 8M_\odot$
- Massive star $m^*_f > 8M_\odot$

Outflow-confined HII Region

- $\theta_{esc}
- \bar{P} \approx 0.88G\Sigma$

Time
Schematic Differences Between Massive Star Formation Theories

- **Turbulent core model** (MT02, 03)
  - massive prestellar core
  - Competitive Bondi-Hoyle accretion model (Bonnell ea. 2001; Bonnell & Bate 2006; Dobbs+, R. Smith+, P. Clark+)
  - protostar formation
  - massive protostar (MP)

- **massive-star-forming core** [protostar+gravitationally-bound gas]
  - time
  - massive prestellar core
  - massive-star-forming core
  - massive-protostar (MP)

- **massive star** $m_\star>8M_\odot$

- $m_\star=8M_\odot$

- Outflow-confined HII Region
  - $P \approx 0.88G_\odot$
  - $\theta_{esc}$

- Tuesday, April 4, 17
Turbulent core model (MT02, 03)

Schematic Differences Between Massive Star Formation Theories

massive prestellar core

Rare evolution from magnetically subcritical state?
Kunz & Mouschovias (2009)

Competitive Bondi-Hoyle accretion model
(Bonnell et al. 2001; Bonnell & Bate 2006; Dobbs+, R. Smith+, P. Clark+)

Prestellar core mass function?
(e.g., Motte et al. 1998; Testi & Sargent 1998; Alves et al. 2007)

massive-star-forming core [protostar + gravitationally-bound gas]

massive protostar (MP)

Radiation pressure likely to prevent accretion of dusty, unbound gas
(Edgar & Clarke 2004)

Is there any isolated massive star formation?
(Bressert et al. 2012; Oey et al. 2013)

Outflow-confined HII Region

\( m_* > 8M_\odot \)

\( m_* = 8M_\odot \)

protostar formation

t = 0

massive star

Tuesday, April 4, 17
Do massive starless cores exist? Are they close to virial equilibrium?

\[
\begin{align*}
R_{c,\text{vir}} & \rightarrow 0.0574 \left( \frac{M_c}{60 M_\odot} \right)^{1/2} \left( \frac{\Sigma_{\text{cl}}}{1 \text{ g cm}^{-2}} \right)^{-1/2} \text{ pc} \\
\sigma_{c,\text{vir}} & \rightarrow 1.09 \left( \frac{M_c}{60 M_\odot} \right)^{1/4} \left( \frac{\Sigma_{\text{cl}}}{1 \text{ g cm}^{-2}} \right)^{1/4} \text{ km s}^{-1}
\end{align*}
\]

McKee & Tan (2003)
Tan et al. (2014, PPVI)

Fiducial MT03 core:

$M_c = 60 M_\odot; \Sigma_{cl} = 1 \text{g cm}^{-2}$

Physical Properties of Star-Forming Regions

$\Sigma \equiv \frac{M}{\pi R^2}$

$\frac{\dot{P}}{k} = 4.3 \times 10^8 \Sigma^2 \text{K cm}^{-3}$

$t_{ff} = \left( \frac{3\pi}{32 G \rho} \right)^{1/2}$

A$_V = 230$

A$_{8 \mu m} = 8.1$

$N_H = 4.2 \times 10^{23} \text{cm}^{-2}$

$\Sigma = 4800 M_\odot \text{pc}^{-2}$

A$_V = 7.5$

A$_{8 \mu m} = 0.30$

$N_H = 1.6 \times 10^{22} \text{cm}^{-2}$

$\Sigma = 180 M_\odot \text{pc}^{-2}$

A$_V = 1.4$

$N_H = 3.0 \times 10^{21} \text{cm}^{-2}$

$\Sigma = 34 M_\odot \text{pc}^{-2}$

$\Sigma \sim 10 M_\odot \text{pc}^{-2}$

Local Galactic Disk

HCO$^+$ Clumps

13CO Clumps

18CO GMCs

H$_2$-10 GMCs

BGPS Clumps

Quintuplet

NGC346

NGC5253

SSC

NGC1569-A

NGC1569-B

GC Brick

Wd1

Arches

M82, SSCs

C286

R136

ONC

Griffin et al. (2007)
Mid-IR Extinction Mapping of Infrared Dark Clouds
(Butler & Tan 2009, 2012; see also Peretto & Fuller 2009; Ragan et al. 2009; Battersby et al. 2010)

G28.37+00.07

Spitzer IRAC 8µm (GLIMPSE)

(Churchwell et al. 2009)
Mid-IR Extinction Mapping of Infrared Dark Clouds
(Butler & Tan 2009, 2012; see also Peretto & Fuller 2009; Ragan et al. 2009; Battersby et al. 2010)

G28.37+00.07

Figure 1.— Mass surface density, $\Sigma_{SMF}$, maps of IRDCs A-F derived from Spitzer IRAC 8 $\mu$m images with pixel scale of 1.2$''$ and angular resolution of 2$''$. The color scale is indicated in g cm$^{-2}$. The dashed ellipse, defined by Simon et al. (2006) based on MSX images, defines the region where the background emission is estimated not directly from the small-scale median filter average of the image intensity, but rather by interpolation from nearby regions just outside the ellipse. The locations of the massive starless cores we have selected for analysis ($\S$3) are marked with crosses.

Bright MIR sources appear as artificial “holes” in the map, where we have set the values of $\Sigma=0$ g cm$^{-2}$.

~Arcsecond scale maps of regions up to $\Sigma \sim 0.5$ g cm$^{-2}$; independent of dust temp.

Distance from molecular line velocities $\rightarrow M(\Sigma)$

Median filter for background around IRDC; interpolate for region behind the IRDC

Correct for foreground
Physical Properties of Star-Forming Regions

\[ \Sigma = \frac{M}{\pi R^2} \]

\[ \bar{P} \sim G \Sigma^2 \]

\[ \tau = \left( \frac{3\pi}{32G \rho} \right)^{1/2} \]

Fiducial MT03 core:

\[ M_c = 60 M_\odot; \Sigma_{cl} = 1 \text{ g cm}^{-2} \]

\[ A_V = 230 \]
\[ A_{8\mu m} = 8.1 \]
\[ N_H = 4.2 \times 10^{23} \text{ cm}^{-2} \]
\[ \Sigma = 4800 M_\odot \text{ pc}^{-2} \]

\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
\[ N_H = 1.6 \times 10^{22} \text{ cm}^{-2} \]
\[ \Sigma = 180 M_\odot \text{ pc}^{-2} \]

\[ A_V = 1.4 \]
\[ N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \]
\[ \Sigma = 34 M_\odot \text{ pc}^{-2} \]

\[ \Sigma \sim 10 M_\odot \text{ pc}^{-2} \]
IRDC Studies
Butler & Tan (2009; 2012) - MIREX maps

Fiducial MT03 core:
$M_c = 60 M_\odot$; $\Sigma_{cl} = 1 \text{ g cm}^{-2}$

IRDC Core/Clumps
MSF Core/Clumps
CO Clouds
HCO$^+$ Clouds
\[ A_V = 230 \]
\[ A_{8\mu m} = 8.1 \]
\[ N_H = 4.2 \times 10^{23} \text{ cm}^{-2} \]
\[ \Sigma = 4800 M_\odot \text{ pc}^{-2} \]

\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
\[ N_H = 1.6 \times 10^{22} \text{ cm}^{-2} \]
\[ \Sigma = 180 M_\odot \text{ pc}^{-2} \]

\[ A_V = 1.4 \]
\[ N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \]
\[ \Sigma = 34 M_\odot \text{ pc}^{-2} \]

$\Sigma - M$ Diagram
Local Galactic Disk
\[ \Sigma \equiv \frac{M}{\pi R^2} \]
\[ \dot{P} \sim G \Sigma^2 \]
\[ \frac{\dot{P}}{k} = 4.3 \times 10^8 \Sigma^2 K \text{ cm}^{-3} \]
\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]
SOFIA Capabilities

$\Sigma - M$ Diagram
Physical Properties of Star-Forming Regions

$\Sigma \equiv \frac{M}{\pi R^2}$
$\dot{P}/k = 4.3 \times 10^8 \Sigma^2 K cm^{-3}$
$t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2}$

$A_V = 230$
$A_{8\mu m} = 8.1$
$N_H = 4.2 \times 10^{23} cm^{-2}$
$\Sigma = 4800 M_\odot pc^{-2}$

$A_V = 7.5$
$A_{8\mu m} = 0.30$
$N_H = 1.6 \times 10^{22} cm^{-2}$
$\Sigma = 180 M_\odot pc^{-2}$

$A_V = 1.4$
$N_H = 3.0 \times 10^{21} cm^{-2}$
$\Sigma = 34 M_\odot pc^{-2}$

Tan et al. (2014, PPVI)

$A_{37\mu m} \sim 3$ mag

$3'' @ 3 kpc$

$\Sigma (g cm^{-2})$
$M (M_\odot)$

Local Galactic Disk

$\Sigma \sim 10 M_\odot pc^{-2}$
Comparison to Turbulent Core Model

Core masses inside $3\sigma$ $N_2D^+$ contour:

$$\Sigma_{cl} = 0.36 \text{ g cm}^{-2}$$

$$M_{c, MIREX} = 55.2 \pm 25 M_\odot$$

$$M_{c, mm} = 62.5^{129}_{26.9} M_\odot$$

Equation:

$$\phi_B \equiv \frac{\langle c^2 \rangle}{\langle \sigma^2 \rangle} = 1 + \frac{3}{2} \frac{E_B}{E_K} + \frac{E_\delta B}{2E_K} = 1.3 + \frac{3}{2m_A^2}$$

$$\sigma_{c, \text{vir}} \rightarrow 1.09 \left( \frac{M_c}{60M_\odot} \right)^{1/4} \left( \frac{\Sigma_{cl}}{1 \text{ g cm}^{-2}} \right)^{1/4} \text{ km s}^{-1}$$

Tan, Kong et al. (2013)
Predictions from Virial Equilibrium

- 1D velocity dispersion if virialized:
  \[
  m_A = \sqrt{3\sigma_c/v_A} = 1
  \]

\[
\sigma_{c,vir} \to 1.09 \left( \frac{M_c}{60M_\odot} \right)^{1/4} \left( \frac{\Sigma_{cl}}{1 \text{ g cm}^{-2}} \right)^{1/4} \text{ km s}^{-1}
\]

<table>
<thead>
<tr>
<th>Core</th>
<th>C1-N</th>
<th>C1-S</th>
<th>F1</th>
<th>F2</th>
<th>G2-N</th>
<th>G2-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Sigma_{cl} \text{ (g cm}^{-2})</td>
<td>0.48</td>
<td>0.40</td>
<td>0.22</td>
<td>0.32</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>(M_c \text{ (M}_\odot)</td>
<td>16</td>
<td>63</td>
<td>6.5</td>
<td>4.7</td>
<td>2.4</td>
<td>0.83</td>
</tr>
<tr>
<td>(\sigma_{vir} \text{ (km/s)}</td>
<td>0.66\pm0.22</td>
<td>0.88\pm0.30</td>
<td>0.43\pm0.15</td>
<td>0.44\pm0.15</td>
<td>0.33\pm0.11</td>
<td>0.25\pm0.09</td>
</tr>
<tr>
<td>(\sigma_{obs} \text{ (km/s)}</td>
<td>0.41\pm0.03</td>
<td>0.41\pm0.02</td>
<td>0.25\pm0.02</td>
<td>0.42\pm0.04</td>
<td>0.34\pm0.02</td>
<td>0.30\pm0.02</td>
</tr>
</tbody>
</table>

\(\langle \sigma_{obs}/\sigma_{vir} \rangle = 0.81 \pm 0.13\)

\[
m_{A,vir} = 0.28 \rightarrow B_{vir}=0.9\text{mG}
\]

\[
B_{\text{med}} \approx 0.12n_H^{0.65} \mu\text{G (for } n_H > 300 \text{ cm}^{-3}\text{)} \text{ (Crutcher et al. 2010)}
\]

\[
n_{H,c}=6.4\times10^5\text{cm}^{-3} \rightarrow B_{\text{med}} = 0.7\text{mG}
\]

**Tentative Conclusion:** Cores appear to be near virial equilibrium, after accounting for clump envelope. Possibly slightly sub-virial; or have stronger B-fields (see also - Kauffmann, Pillai & Goldsmith 2013).
Massive Pre-Stellar Core
C1-S High Resolution (0.2'', 0.005pc @ 5kpc)

<table>
<thead>
<tr>
<th>Core property (% error)</th>
<th>C1-S inner</th>
<th>C1-S outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_c$ ('')</td>
<td>1.10</td>
<td>1.85</td>
</tr>
<tr>
<td>$d$ (kpc) (20%)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$R_c$ (0.01 pc) (20%)</td>
<td>2.67</td>
<td>4.48</td>
</tr>
<tr>
<td>$M_{c,mm}$ ($M_\odot$)</td>
<td>16.24$^{+2.8}_{-4.25}$</td>
<td>47.9$^{+11.0}_{-18.6}$</td>
</tr>
<tr>
<td>$n_{H,c,mm}$ (10^6 cm^-3)</td>
<td>5.90$^{+1.54}_{-1.94}$</td>
<td>3.67$^{+8.26}_{-1.74}$</td>
</tr>
</tbody>
</table>

CO depletion factor: $f_D$>600

DCO+ Envelope

Kong, Tan et al. (2017b, submitted)
### Constraints for Initial Conditions of Numerical Simulations

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Mass $M$</th>
<th>Radius $R$</th>
<th>Density $n_H$</th>
<th>Magnetic Field $B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peters et al. (2011)</td>
<td>$100 M_\odot$</td>
<td>$0.5 \text{pc}$</td>
<td>$5400 \text{cm}^{-3}$</td>
<td>$10 \mu \text{G}$</td>
</tr>
<tr>
<td>Seifried et al. (2012)</td>
<td>$100 M_\odot$</td>
<td>$0.25 \text{pc}$</td>
<td>$4.4 \times 10^4 \text{cm}^{-3}$</td>
<td>$1 \text{mG}$</td>
</tr>
<tr>
<td>Myers et al. (2013)</td>
<td>$300 M_\odot$</td>
<td>$0.1 \text{pc}$</td>
<td>$2.4 \times 10^6 \text{cm}^{-3}$</td>
<td>$\gtrsim 1 \text{mG}$</td>
</tr>
</tbody>
</table>

![Simulation Results](image_url)

Figure 2. Column density in logarithmic scaling for the top-on view of disc 1 (top left) and disc 2 (top right) of run 2.6-4-A and run 2.6-4 without turbulence (bottom). The figures show close-up views of each disc. In combination with the sphere mass and box size, the CoM of each disc is shown. In the left panel of Fig. 3, the results of each disc are plotted for the time variation of $M_\text{tor}$, the disk radius $r_d$, and the mass-to-flux ratio $\mu$. The right panel of Fig. 3 shows the inclination of the mean rotation axis of the disk in the four discs.

Figure 3. Mass-to-flux ratio $\mu$ (left) and inclination of the mean rotation axis of each disc (right). The mean rotation axis varies significantly within the range where simulations without turbulent motions have been found. The inclination of the mean rotation axis is found to be scattered around 0 in each disc, and is almost always smaller than $90^\circ$. This is in strong contrast to the disc in run 2.6-4, which has the same initial setup as the runs presented here except the initial turbulence field (Seifried et al. 2011). We find that $\mu$ is mainly extracted by toroidal Alfvénic waves, which supports the picture of a reduced magnetic braking efficiency. The magnetic braking efficiency while simultaneously keeping the inwards angular momentum transport can remain high due to the presence of coherent rotation structure. Locally, the inwards angular momentum transport can be reduced in the environment of the disc despite a low mass-to-flux ratio (compare left panel of Fig. 3). Despite the lack of coherent flow, it is very likely that the magnetic field and the angular momentum vector of the disc (right) are Keplerian discs in our runs. We emphasise that for the other runs we find qualitatively similar results, i.e. discs with sizes of up to 800 AU in size.
Observations:

Evidence for strong magnetic fields in some massive star-forming cores

Girart+ (2009)
see also Q. Zhang+ (2015)

Evidence for nonthermal support
Do massive protostars have morphologies similar to low-mass protostars? What sets the star formation efficiency from the core? CMF $\rightarrow$ IMF?
Protostellar Evolution
Zhang, Tan, Hosokawa (2014)

see also Palla & Stahler 1993; Hosokawa et al. (2010)
Protostellar Evolution
Zhang, Tan, Hosokawa (2014)

see also Palla & Stahler 1993; Hosokawa et al. (2010)
Diagnostics of the Turbulent Core Model


Prediction: increasing symmetry from MIR-FIR
Figure 21. Resolved images for the selected evolutionary stages ($m_\ast = 1, 2, 4, 8, 12, 16, \text{ and } 24 \, M_\odot$, from top to bottom) of the fiducial models in various bands (columns) at the inclination of 60° between the line of sight and the axis. Each image is normalized to its maximum surface brightness, which is labeled in the bottom left corner. The total fluxes are labeled in the top right corners. A distance of 1 kpc is assumed. Each image has a field of view of 40′′ × 40′′. The dotted lines mark the projected opening angle of the outflow cavity on the sky plane.

(A color version of this figure is available in the online journal.)

are g i o nl a r g ee n o u g ht oc o v e rt h e w h o l e m o d e ls o u r c e , i n c l u d i n g the clump on the sky plane. In such a case, the observed SEDs are significantly higher at the wavelengths longer than $\sim 100 \, \mu m$. The short wavelength emission is lower than the model without the clump but higher than that observed with a smaller aperture at wavelengths $< 10 \, \mu m$. This is because the short wavelength emission can be seen toward the opening area of the outflow cavity, and this part of the emission is excluded with a smaller aperture. In real observations, depending on the resolutions in different bands, the observed SEDs may be similar to the model SED with smaller aperture in short wavelengths but also similar to the model SED with full aperture in long wavelengths, i.e., the short wavelength fluxes are strongly suppressed but the fluxes at $\gtrsim 100 \, \mu m$ become higher with the clump.

NIR to FIR morphologies

Rotation and outflow axis inclined at 60° to line of sight.
Massive Protostar G35.2N: d=2.2kpc; L\sim 10^5L_\odot

De Buizer (2006)

Zhang, Tan, De Buizer et al. (2013)
Spectral energy distribution

Flux profiles along outflow cavity axis

\[ \Sigma_{\text{clump}} = 1 \text{ g cm}^{-2} \]
\[ M_{\text{core}} = 240 \text{ M}_{\odot} \]
\[ m^* = 34 \text{ M}_{\odot} \]

MIR SED requires high \( \Sigma \) core/clump

\[ L_{\text{bol}} \sim (0.66 - 2.2) \times 10^5 L_{\odot} \]
\[ M_{\text{core}} \sim 240 M_{\odot} \]
\[ \Sigma_{\text{cl}} \sim 0.4 - 1 \text{ g/cm}^2 \]
\[ \theta_w \sim 35 - 51^\circ \]
\[ \theta_{\text{view}} \sim 43 - 58^\circ \]
\[ m^* \sim 20 - 34 M_{\odot} \]
Simple, symmetric model provides good fit to SED & image intensity profiles: detailed constraints on how a massive star is forming.

\[ \Sigma_{\text{clump}} = 1 \text{ g cm}^{-2} \]
\[ M_{\text{core}} = 240 \text{ M}_\odot \]
\[ \mu \text{ bol} \sim (0.66 - 2.2) \times 10^5 \text{L}_\odot \]
\[ M_{\text{core}} \sim 240 \text{M}_\odot \]
\[ \Sigma_{\text{cl}} \sim 0.4 - 1 \text{ g/cm}^2 \]
\[ \theta_w \sim 35 - 51^\circ \]
\[ \theta_{\text{view}} \sim 43 - 58^\circ \]
\[ m^* \sim 20 - 34 \text{ M}_\odot \]
Evolutionary model

Initial & Environmental Conditions

Evolutionary Tracks

Protostellar properties

Density Profiles

Velocity Field

Photoionization Simulation

Ionization Structures

Continuum Radiative Transfer

Temperature Profiles

SEDs

IR Images

Density/Thermal Histories along Streamlines

Chemical Modeling

Chemical Evolution

Self-consistent evolutionary tracks for protostars, protostellar cores, disks, and outflow cavities

Explore the effects of the initial & environmental conditions and evolution on various processes

Other Applications...

Radio Continuum, H recombination lines (spectra/images)

(Tanaka, Tan, Zhang 2016)

(e.g. Zhang & Tan 2015
Drozdovskaya+ in prep.)
Fig. 1.—The Environments of Massive Star Formation. Mass surface density, $\Sigma = \frac{\mathcal{M}}{2\pi R^2}$, is plotted versus mass, $M$. Dotted lines of constant radius, $R$, number density, $n_H$ (or free-fall time, $t_{\text{ff}} = (\frac{3}{2} \frac{G \Sigma}{32} )^{1/2}$), and escape speed, $v_{\text{esc}} = (\frac{10}{\text{vir}})^{1/2}$, are shown. Stars form from molecular gas, which in the Galaxy is mostly organized into GMCs. Typical $^{12}\text{CO}$-defined GMCs have $\Sigma \approx 100 M_\odot \text{pc}^{-2}$ (Solomon et al., 1987) (see Tan et al., 2013a for detailed discussion of the methods for estimating $\Sigma$ for the objects plotted here), although denser examples have been found in Henize 2-10 (Santangelo et al., 2009). The $^{13}\text{CO}$-defined clouds of Roman-Duval et al. (2010) are indicated, along with $\text{HCO}^+$ clumps of Barnes et al., (2011), including G286.21+0.17 (Barnes et al., 2010). Along with G286, the BGPS clumps (Ginsburg et al., 2012) and the Galactic Center "Brick" (Longmore et al., 2012) are some of the most massive, high-$\Sigma$ gas clumps known in the Milky Way. Ten example Infrared Dark Clouds (IRDCs) (Kainulainen and Tan, 2013) and their internal core/clumps (Butler and Tan, 2012) are shown, including the massive, monolithic, highly-deuterated core C1-S (Tan et al., 2013b). CygX-N63, a core with similar mass and size as C1-S, appears to be forming a single massive protostar (Bontemps et al., 2010; Duarte-Cabral et al., 2013). The IRDC core/clumps overlap with Massive Star-Forming (MSF) core/clumps (Mueller et al., 2002). Clumps may give rise to young star clusters, like the ONC (e.g., Da Rio et al., 2012) and NGC 3603 (Pang et al., 2013) (radial structure is shown from core to half-mass, $R_1/2$, to outer radius), or even more massive examples, e.g., Westerlund 1 (Lim et al., 2013), Arches (Habibi et al., 2013), Quintuplet (Hußmann et al., 2012) (shown at $R_1/2$), that are in the regime of "super star clusters" (SSCs), i.e., with $M \gg 10^4 M_\odot$. Example SSCs in the Large Magellanic Cloud (LMC) (R136, Andersen et al., 2009) and Small Magellanic Cloud (SMC) (NGC 346, Sabbi et al., 2008) display a wide range of $\Sigma$, but no evidence of IMF variation ($\S$ 5.2). Even more massive clusters can be found in some dwarf irregular galaxies, such as NGC 1569 (Larsen et al., 2008) and NGC 5253 (Turner and Beck, 2004), and starburst galaxy M82 (McCrady and Graham, 2007).
Fig. 1.— The Environments of Massive Star Formation. Mass surface density, $\Sigma = M/\pi R^2$, is plotted versus mass, $M$. Dotted lines of constant radius, $R$, number density, $n_H$ (or free-fall time, $t_{\text{ff}} = (3\pi/32G)^{1/2}$), and escape speed, $v_{\text{esc}} = (10/t_{\text{vir}})^{1/2}$, are shown. Stars form from molecular gas, which in the Galaxy is mostly organized into GMCs. Typical $^{12}$CO-defined GMCs have $\Sigma \approx 100 M_\odot pc^{-2}$ (Solomon et al., 1987) (see Tan et al., 2013a for detailed discussion of the methods for estimating $\Sigma$ for the objects plotted here), although denser examples have been found in Henize 2-10 (Santangelo et al., 2009). The $^{13}$CO-defined clouds of Roman-Duval et al. (2010) are indicated, along with HCO$^+$ clumps of Barnes et al. (2011), including G286.21+0.17 (Barnes et al., 2010). Along with G286, the BGPS clumps (Ginsburg et al., 2012) and the Galactic Center "Brick" (Longmore et al., 2012) are some of the most massive, high-$\Sigma$ gas clumps known in the Milky Way. Ten example Infrared Dark Clouds (IRDCs) (Kainulainen and Tan, 2013) and their internal core/clumps (Butler and Tan, 2012) are shown, including the massive, monolithic, highly-deuterated core C1-S (Tan et al., 2013b). CygX-N63, a core with similar mass and size as C1-S, appears to be forming a single massive protostar (Bontemps et al., 2010; Duarte-Cabral et al., 2013). The IRDC core/clumps overlap with Massive Star-Forming (MSF) core/clumps (Mueller et al., 2002). Clumps may give rise to young star clusters, like the ONC (e.g., Da Rio et al., 2012) and NGC 3603 (Pang et al., 2013) (radial structure is shown from core to half-mass, $R_1/2$, to outer radius), or even more massive examples, e.g., Westerlund 1 (Lim et al., 2013), Arches (Habibi et al., 2013), Quintuplet (Hußmann et al., 2012) (shown at $R_1/2$), that are in the regime of "super star clusters" (SSCs), i.e., with $M \gg 10^4 M_\odot$. Example SSCs in the Large Magellanic Cloud (LMC) (R136, Andersen et al., 2009) and Small Magellanic Cloud (SMC) (NGC 346, Sabbi et al., 2008) display a wide range of $\Sigma$, but no evidence of IMF variation ($\S 5.2$). Even more massive clusters can be found in some dwarf irregular galaxies, such as NGC 1569 (Larsen et al., 2008) and NGC 5253 (Turner and Beck, 2004), and starburst galaxy M82 (McCrady and Graham, 2007).
\[ M_c = 60 \, M_\odot, \Sigma_{cl} = 1 \, \text{g/cm}^2, \beta_c = 0.02 \]

\[ M_c = 60 \, M_\odot, \Sigma_{cl} = 0.3 \, \text{g/cm}^2, \beta_c = 0.02 \]
Initial & Environmental Conditions

Evolutionary Tracks

Density/velocity Profiles

Continuum Radiative Transfer
(Code: Whitney+ 03, 12; also see Robitaille+ 11)

Temperature Profiles

SEDs

IR Images

\[ M_c = 60 \, M_\odot, \, \Sigma_{cl} = 1 \, \text{g/cm}^2, \, \beta_c = 0.02 \]

\[ M_c = 60 \, M_\odot, \, \Sigma_{cl} = 0.3 \, \text{g/cm}^2, \, \beta_c = 0.02 \]
**Initial & Environmental Conditions**

**Evolutionary Tracks**

**Density/velocity Profiles**

**Continuum Radiative Transfer**

(Code: Whitney+ 03, 12; also see Robitaille+ 11)

**Temperature Profiles**

**SEDs**

**IR Images**

---

\[ M_c = 60 \, M_\odot, \, \Sigma_{cl} = 1 \, \text{g/cm}^2, \, \beta_c = 0.02 \]

\[ M_c = 60 \, M_\odot, \, \Sigma_{cl} = 0.3 \, \text{g/cm}^2, \, \beta_c = 0.02 \]

---

\[ n_{HI} \sim 10^{-22} \, \text{cm}^{-3} \]

\[ T \sim 10^4 \, \text{K} \]

---

\[ m^* = 4 M_\odot \]

---

Images:

8 μm  20 μm  37 μm

---

Tuesday, April 4, 17
Initial & Environmental Conditions

Evolutionary Tracks

Density/velocity Profiles

Continuum Radiative Transfer

Temperature Profiles

SEDs

IR Images

$M_c = 60 \, M_\odot$, $\Sigma_{cl}=1 \, g/cm^2$, $\beta_c=0.02$

Images

8 µm  20 µm  37 µm  8 µm  20 µm  37 µm

$M_c = 60 \, M_\odot$, $\Sigma_{cl}=0.3 \, g/cm^2$, $\beta_c=0.02$
Initial & Environmental Conditions

Evolutionary Tracks

Density/velocity Profiles

Continuum Radiative Transfer
(Code: Whitney+ 03, 12; also see Robitaille+ 11)

Temperature Profiles

SEDs

IR Images

$m^*_c = 12 M_\odot$
**Initial & Environmental Conditions**

**Evolutionary Tracks**

**Density/velocity Profiles**

**Continuum Radiative Transfer**

(Code: Whitney+ 03, 12; also see Robitaille+ 11)

**Temperature Profiles**

**SEDs**

**IR Images**

\[ M_c = 60 \, M_\odot, \Sigma_{cl} = 1 \, \text{g/cm}^2, \beta_c = 0.02 \]

\[ M_c = 60 \, M_\odot, \Sigma_{cl} = 0.3 \, \text{g/cm}^2, \beta_c = 0.02 \]

\[ m^* = 16M_\odot \]
Model grid

3+3 parameters:

$\Sigma_{cl}$, $M_c$, $m_{star}$, $d$, inc., $A_V$

- Determine the evolutionary tracks
- Determine how it is viewed
- Determine the current stage

$\Sigma_{cl}$: 0.1 ~ 3 g/cm$^2$ (4)
$M_c$: 10 ~ 500 (15)
$m_{star}$: 0.5 ~ 160 (14)
SEDs: (8640) + (d, A_V)

Fig. 3.— Evolution of bolometric luminosity with envelope mass in the evolutionary tracks of various $M_c$ and $\Sigma_{cl}$. Different initial conditions are shown with different colors and line styles. The circles mark the evolutionary stages we perform radiation transfer simulations and comprise the model grid. The color of the circles indicate the evolutionary stages expressed as $m_{\star}/m_{\star f}$, the fraction of the current mass of the protostars and their final masses.
The SOFIA Massive (SOMA) Star Formation Survey
Jonathan C. Tan, James M. De Buizer, Mengyao Liu, Yichen Zhang, Jan E. Staff, Maria T. Beltrán, Ralph Shuping, Barbara Whitney

THE SOFIA MASSIVE (SOMA) STAR FORMATION SURVEY: I. OVERVIEW AND FIRST RESULTS
James M. De Buizer1, Mengyao Liu2, Jonathan C. Tan3, Yichen Zhang4,5, Maria T. Beltrán6, Ralph Shuping1, Jan E. Staff3,7, Kei E. I. Tanaka3, Barbara Whitney8
1SOFIA-USRA, NASA Ames Research Center, MS 232-12, Moffett Field, CA 94035, USA
2Department of Astronomy, University of Florida, Gainesville, FL 32611, USA
3Department of Physics, University of Florida, Gainesville, FL 32611, USA
4Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
5The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan
6INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
7College of Science and Math, University of Virgin Islands, St. Thomas, United States Virgin Islands 00802
8Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter St, Madison, WI 53706, USA

ABSTRACT
We present an overview and first results of the SOFIA Massive (SOMA) Star Formation Survey, which is using the FORCAST instrument to image massive protostars from ~10–40 μm. These wavelengths trace thermal emission from warm dust, which in Core Accretion models mainly emerges from the inner regions of protostellar outflow cavities. Dust in dense core envelopes also imprint characteristic extinction patterns at these wavelengths causing intensity peaks to shift along the outflow axis and profiles to become more symmetric at longer wavelengths. We present observational results for the first eight protostars in the survey, i.e., multiwavelength images, including some ancillary ground-based MIR observations and archival Spitzer and Herschel. These images generally show extended MIR/FIR emission along directions consistent with those of known outflows and with shorter wavelength peak flux positions displaced from the protostar along the blue-shifted, near-facing sides, thus confirming qualitative predictions of Core Accretion models. We then compile spectral energy distributions and use these to derive protostellar properties by fitting theoretical radiative transfer models. Zhang & Tan models, based on the Turbulent Core Model of McKenzie & Tan, imply the sources have protostellar masses \( m_\ast \sim 10–50 M_\odot \) accreting at \( \sim 10^{-4}–10^{-3} M_\odot \) yr\(^{-1}\) inside cores of initial masses \( M_0 \sim 30–500 M_\odot \) embedded in clumps with mass surface densities \( \Sigma \sim 0.3–1.3 \) g cm\(^{-2}\). Fitting Robitaille et al. models typically leads to slightly higher protostellar masses, but with disk accretion rates \( \sim 10^4 \) smaller. We discuss reasons for these differences and overall implications of these first survey results for massive star formation theories.

Keywords: ISM: jets and outflows — dust — star formation — stars: winds, outflows — stars: early-type — infrared radiation — ISM: individual (AFGL 4029, AFGL 437, IRAS 07299-1651, G35.20-0.74, G45.45+0.05, IRAS 20126+4104, Cepheus A, NGC 7538 IRS9)

1. INTRODUCTION
The enormous radiative and mechanical luminosities of massive stars impact a vast range of scales and processes, from reionization of the universe, to galaxy evolution, to regulation of the interstellar medium, to formation of planets (Bonnell et al., 2001; Wang et al., 2010), to Stellar Collisions (Bonnell et al. 1998; Bally & Zinnecker 2005). Massive stars are in approximate pressure and virial equilibrium with their surroundings, and are observed to form in dense gas clumps with mass surface densities \( \Sigma \sim 1–3 \) g cm\(^{-2}\) after MT03\], to Competitive Accretion models at the crowded centers of forming star clusters (Bonnell et al., 2001). Massive stars impact a vast range of scales and processes, from reionization of the universe, to galaxy evolution, to regulation of the interstellar medium, to formation of planets (Bonnell et al., 2001; Wang et al., 2010), to Stellar Collisions (Bonnell et al. 1998; Bally & Zinnecker 2005). Massive stars are in approximate pressure and virial equilibrium with their surroundings, and are observed to form in dense gas clumps with mass surface densities \( \Sigma \sim 1–3 \) g cm\(^{-2}\) after MT03\]...
The Astrophysical Journal

The SOMA Survey

SOFIA-FORCAST observations of a sample of ~50 massive & intermediate-mass protostars (Cycles 0, 1, 2, 3, 4).
The density drops rapidly with $T$ expect minimal dust formation to occur in the rapidly expanding gas at 2000 K. More details about these gas opacities are given in which is implemented in the new version of the code.

Paper I

We use the latest version of the Monte Carlo radiation transfer code and the new form of the mean opacity. These limit the star formation efficiency from a core to ~0.5 (Matzner & McKee 1999; Zhang et al., 2002). These limit the star formation efficiency from a core to ~0.5 (Matzner & McKee 1999; Zhang et al., 2002). These limit the star formation efficiency from a core to ~0.5 (Matzner & McKee 1999; Zhang et al., 2002). These limit the star formation efficiency from a core to ~0.5 (Matzner & McKee 1999; Zhang et al., 2002).

2.4. Simulations

Type I: MIR sources in IRDCs - relatively isolated sources in Infrared Dark Clouds, some without detected radio emission.

Type II: Hyper-compact - often jet-like, radio sources, where the MIR emission extends beyond the observed radio emission (e.g., G35.2).

Type III: Ultra-compact - radio sources where the radio emission is more extended than the MIR emission.

Type IV: Clustered sources - a MIR source exhibiting radio emission is surrounded by several other MIR sources within ~60”.

Also extended to Intermediate-Mass protostars.
First 8 Sources

Table 1. SOFIA FORCAST Observations: Obs. Dates & Exposure Times (s)

<table>
<thead>
<tr>
<th>Source</th>
<th>R.A.(J2000)</th>
<th>Dec.(J2000)</th>
<th>d (kpc)</th>
<th>Obs. Date</th>
<th>7.7 µm</th>
<th>11.1 µm</th>
<th>19.7 µm</th>
<th>25.3 µm</th>
<th>31.5 µm</th>
<th>37.1 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFGL 4029</td>
<td>03h01m31s28</td>
<td>+60°29′12″87</td>
<td>2.0</td>
<td>2014-03-29</td>
<td>112</td>
<td>...</td>
<td>158</td>
<td>...</td>
<td>282</td>
<td>678</td>
</tr>
<tr>
<td>AFGL 437</td>
<td>03h07m24s55</td>
<td>+58°30′52″76</td>
<td>2.0</td>
<td>2014-06-11</td>
<td>217</td>
<td>...</td>
<td>2075</td>
<td>...</td>
<td>2000</td>
<td>884</td>
</tr>
<tr>
<td>IRAS 07299-1651</td>
<td>07h32m09s74</td>
<td>−16°58′11″28</td>
<td>1.68</td>
<td>2015-02-06</td>
<td>280</td>
<td>...</td>
<td>697</td>
<td>...</td>
<td>449</td>
<td>1197</td>
</tr>
<tr>
<td>G35.20-0.74</td>
<td>18h58m13s02</td>
<td>+01°40′36″2</td>
<td>2.2</td>
<td>2011-05-25</td>
<td>...</td>
<td>909</td>
<td>959</td>
<td>...</td>
<td>4068</td>
<td>4801</td>
</tr>
<tr>
<td>G45.47+0.05</td>
<td>19h14m25s67</td>
<td>+11°09′25″45</td>
<td>8.4</td>
<td>2013-06-26</td>
<td>...</td>
<td>309</td>
<td>...</td>
<td>588</td>
<td>316</td>
<td>585</td>
</tr>
<tr>
<td>IRAS 20126+4104</td>
<td>20h14m26s05</td>
<td>+41°13′32″48</td>
<td>1.64</td>
<td>2013-09-13</td>
<td>...</td>
<td>484</td>
<td>...</td>
<td>1276</td>
<td>487</td>
<td>1317</td>
</tr>
<tr>
<td>Cepheus A</td>
<td>22h56m17s98</td>
<td>+62°01′49″39</td>
<td>0.7</td>
<td>2014-03-25</td>
<td>242</td>
<td>...</td>
<td>214</td>
<td>...</td>
<td>214</td>
<td>1321</td>
</tr>
<tr>
<td>NGC 7538 IRS9</td>
<td>23h14m01s77</td>
<td>+61°27′19″8</td>
<td>2.65</td>
<td>2014-06-06</td>
<td>215</td>
<td>...</td>
<td>653</td>
<td>...</td>
<td>491</td>
<td>923</td>
</tr>
</tbody>
</table>

De Buizer, Liu, Tan, Zhang et al. (2017)
Figure 1. Multiwavelength images of AFGL 4029, with facility and wavelength given in upper right of each panel. Contour level information is given in lower right: lowest contour level in number of \( \text{Jy per square arcsec} \); then step size between each contour in \( \log_{10} \) \( \text{Jy per square arcsec} \); then peak flux in \( \text{Jy} \). The color map indicates relative flux intensity compared to that of the peak flux in each image panel, but only showing signal above \( 3 \times 10^{-3} \). Grey circles in lower left show the resolution of each image. Sources IRS1 (target of interest of this paper) and IRS2 are labeled in panel (a). The black cross in all panels denotes the position of radio source G138.295+1.555(S) from Zapata et al. (2001) at R.A.(J2000) = 03\(^{h}\)01\(^{m}\)31\(^{s}\).28, Decl.(J2000) = +60\(^{d}\)29\(^{m}\)12\(^{s}\).0087. The line in panel (a) shows the outflow axis angle, with the solid span tracing the blue-shifted direction and dotted span the red-shifted direction. In this case, the outflow axis angle is from the \( \text{H}_2 \) and optical jet emission of Deharveng et al. (1997), and the blue-shifted outflow direction is given by the CO observations of Ginsburg et al. (2011). In panel (a), the point sources to the north of the G138.295+1.555(S) position are ghosts in the \textit{Spitzer} image and should not be interpreted as real structure.
Figure 2. Multiwavelength images of AFGL 437, following format of Fig. 1. The location of the radio continuum source WK34 (Weintraub & Kastner 1996) is shown as a cross in all panels at R.A.(J2000) = 03h07m24.55, Decl.(J2000) = +58°30′05′′.

The outflow axis angle is from the NIR bipolar emission angle from Meakin et al. (2005), and the blue-shifted outflow direction is given by the CO observations of Gómez et al. (1992).

accuracies of our astrometry (0.5005). As one looks to shorter wavelengths in the Spitzer IRAC data, the peak moves closer and closer to the 2µm peak location, suggesting that extinction might be playing a role. At the resolution of SOFIA, the object looks rather point-like, with a possible extension of emission to the north west seen at 31 and 37µm (Figure 3d&e).

Given the extended nature of the NIR and MIR emission of this target at high angular resolution, it was deemed a good candidate for being morphologically influenced by an outflow. The hypothesis is that the radio continuum source also drives an outflow, and the extended NIR and MIR emission are coming from the blue-shifted outflow cavity. To date, however, there are no maps of outflows indicators of this source from which we may derive an outflow axis. Evidence of an outflow from this region does exist, including spectra that show that the 12CO gas is considered to be in a "high-velocity" state (Shepherd & Churchwell 1996). Liu et al. (2010) mapped the integrated 13CO emission at ≈10 resolution, and found it to be extended parallel and perpendicular to the NIR/MIR extension on the scale of ≈40 in each direction. No velocity maps are presented in that work, and they claim that the emission is tracing a molecular core (not outflow), from which they estimate a gas mass of 1.2×10^3 M☉.

De Buizer (2003) claimed that in some cases the groupings of 6.7 GHz methanol maser spots may lie in an elongated distribution that is parallel to the outflow axis for some MYSOs. Fujisawa et al. (2014) showed that the 6.7 GHz methanol maser spots are distributed over two groupings separated by about 60 mas with total distributed area of about 20 mas×70 mas (or 40 AU×120 AU, given the distance of 1.68 kpc estimated from the trigonometric parallax measurements of the 12 GHz methanol masers present in this source by Reid et al. 2001).
Figure 3. Multiwavelength images of IRAS 07299-1651, following format of Fig. 1. The grey areas in panel (a) are where the sources have saturated in the IRAC image. Also in panel (a) there are extensions to the southwest of the three brightest sources, which are ghosts that should not be interpreted as real structure. The location of the radio continuum source of Walsh et al. (1998) is shown as a cross in all panels at R.A.(J2000) = 07h32m09.74, Decl.(J2000) = 16°58′01″.0028. There are no outflow maps from which to discern an outflow angle or direction for this source.

4.1.4. G35.20-0.74 (a.k.a. IRAS 18566+0136)

The G35.20-0.74 star forming region, at a distance of 2.2 kpc (Zhang et al. 2009; Wu et al. 2014), was first identified as a star-forming molecular cloud through ammonia observations by Brown et al. (1982). Dent et al. (1985a) were the first to resolve the emission in this region into a molecular ridge running northwest to southeast seen in CS(2-1), with a nearly perpendicular outflow seen in CO (1-0). Dent et al. (1985b) found the NIR emission to be coming from an elongated north-south distribution. Heaton & Little (1988) observed this region in cm radio continuum and were able to resolve three compact sources arranged north-south, and concluded that the central source was likely an UC H II region while the north and south sources had spectral indices consistent with free-free emission from a collimated, ionized, bipolar jet. The orientation of this jet (p.a. \( \sim 2\)) appears to be different from that of the CO outflow (p.a. \( \sim 58° \)), which has been interpreted either as evidence for precession of the ionized jet (Heaton & Little 1988; Little et al. 1998; Sánchez-Monge et al. 2014; Beltrán et al. 2016), or multiple outflows from multiple sources (Gibb et al. 2003; Birks et al. 2006).

G35.20-0.74 was the first source observed among those in the SOMA survey sample, and the SOFIA FORCAST imaging data were presented by Zhang et al. (2013b). These data helped define the infrared SED of the source, which implied an isotropic luminosity of \( 3.3 \times 10^4 L_\odot \). However, modeling the emission (with early versions of the ZT radiative transfer models that had fixed outflow cavity opening angles, ZTM13), including 10 to 40 µm intensity profiles, as being due to a single protostar driving an outflow along the N-S axis, Zhang et al. (2013b) derived a true bolometric luminosity in the range \( \sim (0.7-2.2) \times 10^5 L_\odot \), i.e., after correcting for...
Figure 5. Multiwavelength images of G35.20-0.74, following format of Fig. 1. The location of radio continuum source 7 from Gibb et al. (2003) is shown as a cross in all panels at R.A.(J2000) = 18 h 58 m 13 s, Decl.(J2000) = +01 40 03 00 2. In panel (a) the axis of the radio jet is shown (Gibb et al. 2003); blue-shifted direction is derived from CO observations of Birks et al. (2006). There is some debate as to the nature of the outflow and driving source in this region. Spitzer IRAC images show a source that is a bright "green fuzzy," and consequently was categorized as being a "likely MYSO outflow candidate" in the work of Cyganowski et al. (2008). However, Lee et al. (2013) find no H$_2$ emission component to the green fuzzy, and classify the NIR emission as a reflection nebula (possibly from an outflow cavity).

The observations of De Buizer et al. (2005) first showed that the MIR emission in this region is set 2.5 00 northwest of the radio continuum peak. Spitzer IRAC and 2MASS data confirm this set of the peak of the NIR/MIR emission, and show a similar extended morphology, with the axis of elongation oriented at a position angle of about -30 and pointing radially away from the radio continuum peak. The SOFIA data (Figure 6) show this same morphology at wavelengths greater than 19 µm (the 11 µm SOFIA observation is a shallow integration that only barely detects the peak emission from the source). We also present higher angular resolution Gemini T-ReCS imaging at 11.7 and 18.3 µm in Figure 7, which also shows this set and elongation. We note that the elongated morphology persists out to even longer wavelengths, as seen in both the
Figure 6. Multiwavelength images of G45.47+0.05, following format of Fig. 1. The location of the 6 cm radio continuum peak of the UC H II region of White et al. (2005) is shown as a large cross in all panels at R.A.(J2000) = 19h14m25.s67, Decl.(J2000) = +11°09′02.00″. The location of the 2MASS source J19142564+1109283 is shown by the small cross. The location of the peak of the blue-shifted SiO(2-1) emission of Wilner et al. (1996) is shown as an X. The outflow axis angle and the blue-shifted outflow direction are given by the HCO\(^+\) observations of Wilner et al. (1996).

Figure 7. Sub-arcsecond resolution MIR images of G45.47+0.05 from Gemini T-ReCS. Symbols and annotation are the same as in Figure 6.
Figure 8. Multiwavelength images of IRAS 20126+4104, following format of Fig. 6. The nominal location of protostar, derived from the model fit to the proper motions of the water masers from Moscadelli et al. (2011), is shown as a large cross in all panels at R.A.(J2000) = 20:14:26.05, Decl.(J2000) = +41:13:03.00. The outflow axis angle and the blue-shifted outflow direction are given by the HCO$^+$ observations of Cesaroni et al. (1999). This central region contains a compact, extremely high-velocity CO outflow (Narayanan & Walker 1996) with an axis at a position angle of $\sim50^\circ$ that is believed to trace a younger component than the rest of the outflow (Cunningham et al. 2009). This central outflow component appears to have an axis close to the plane of the sky but with blue-shifted emission to the NE (Gómez et al. 1999; Zapata et al. 2013). At NIR wavelengths the region displays an extremely bright reflection nebula (Cunningham et al. 2009), almost wholly contained within this blue-shifted outflow cavity.

At the center of this outflow is a cluster of radio sources, and there is confusion as to which source(s) might be driving the outflow(s) (Zapata et al. 2013). One of the main candidates for driving the outflow, and the brightest radio continuum source in the region, is HW 2 (Hughes & Wouterloot 1984). It has a luminosity of about $10^4 L_\odot$ (Garay et al. 1996), suggesting it is a B0.5 star approaching 20 $M_\odot$, given a distance to the source of 700 pc based on parallax measurements of 12 GHz methanol masers in the region (Moscadelli et al. 2009) and of radio source HW 9 (Dzib et al. 2011). HW 2 has not been detected at NIR wavelengths (Casselman & McLean 1996; Cunningham et al. 2009; Jones et al. 2014), nor in the MIR (De Buizer et al. 2005; de Wit et al. 2009; also Cunningham et al. 2009, however the absolute astrometry of their MIR images, and hence placement of radio sources with respect to the MIR sources, appear to be offset by over 6000).

The estimated extinction to the region around HW 2 is $A_V \sim 300–1000$ magnitudes (Goetz et al. 1998; Cunningham et al. 2009), and therefore it is not surprising it is not directly detected in the NIR, MIR, or in our SOFIA data (Figure 9f). However, it does appear that the contour peak shifts towards this location in the 70 $\mu$m Herschel data (Figure 9f). At 7 $\mu$m the emission seen by SOFIA corresponds well to the NIR reflection nebula and blue-shifted outflow cavity. As one goes to longer SOFIA wavelengths, we...
The cross in each panel shows the location of radio continuum source HW 2 at R.A.(J2000) = 22h56m17s.98, Decl.(J2000) = +62°01′04″.0039. The outflow axis angle and the blue-shifted outflow direction are given by the HCO+ observations of Gómez et al. (1999). We begin to see increasingly brighter emission to the SW, which corresponds to the direction of the red-shifted outflow. We suggest that we are beginning to penetrate the higher extinction towards this region and the emission we are seeing at wavelengths >30 µm is coming from the red-shifted outflow cavity.

4.1.8. NGC 7538 IRS 9

NGC 7538 is an optically visible H II region (Fich & Blitz 1984) located at a distance of 2.65 kpc, as determined from trigonometric parallax measurements (Moscadelli et al. 2009). Infrared observations of this region by Wynn-Williams et al. (1974) and Werner et al. (1979) led to the identification of multiple discrete sources in the vicinity of the optical nebula, which were named IRS 1 through 11. The source IRS 9 lies ⇠20 to the SE of the prominent and well-studied IRS 1 region. It powers its own reflection nebula, and has a total luminosity of about 3.5 × 10^4 L☉ (Sandell et al. 2005, corrected to the distance from Moscadelli et al. 2009), which is the equivalent of a B0.5 ZAMS star.

Though IRS 9 has the luminosity of a typical MYSO, it has very weak radio continuum emission. Sandell et al. (2005) found that the object has a flat radio spectrum consistent with free-free emission from a collimated, ionized jet. They also disentangled the rather complex structures seen in various outflow tracers into distinct outflows from three different sources, suggesting a cluster associated with IRS 9. The outflow associated most closely with the position of IRS 9 itself was measured to have a very high-velocity (Mitchell & Hasegawa 1991), leading to the suggestion that we might be observing the system nearly face-on (Barentine & Lacy 2012). The high spatial resolution (⇠6 arcsec) HCO+ maps of Sandell et al. (2005) show that IRS 9 indeed drives a bipolar, extremely high-velocity outflow approximately oriented E-W (p.a. ⇠85°) that is inclined by only ⇠20° to the line of sight. Given this orientation, the outflow lobes seen in HCO+ do not extend very far from IRS 9 in projection (⇠14 arcsec), but the blue-shifted outflow lobe is clearly to the west of IRS 9, and the red-shifted outflow lobe to the east (Figure 10a). We note here that the best fitting ZT and Robitaille et al. radiative transfer models (2011) favor a face-on geometry for this outflow (Sandell et al. 2015).
Figure 10. Multiwavelength images of NGC 7538 IRS9, following format of Fig. 6. The grey areas in panel (a) are where the source has saturated in the IRAC image. The extension to the northwest in panel (a) is a ghost, and not a real structure. The location of the 3.6 cm radio continuum peak from Sandell et al. (2005) is shown as a large cross in all panels at R.A.(J2000) = 2 3h 14m 01.77, Decl.(J2000) = +61° 27’ 01.00. The outflow axis angle and the blue-shifted outflow direction are given by the HCO+ observations of Sandell et al. (2005).

Our SOFIA data for this source look rather point-like at 7 µm, however beginning at 19 µm the source begins to show signs of being elongated in an E-W orientation, similar to the outflow axis (Figure 10). The Herschel 70 µm data also show a more prominent east-west elongation with a larger extension to the west in the direction of the blue-shifted outflow cavity.

4.2. General Results from the SOFIA Imaging

In addition to the monochromatic images presented above, we also construct three-color images of all the sources, presented together in Figure 11. The three-color images reveal color gradients across the sources: i.e., the more extincted, far-facing outflow cavities appear redder, with this morphology particular clear in the cases of G35.20-0.74 and Cep A. Note, however, that these RGB images have different beam sizes for the different colors (especially blue), with the effect being to tend to give small sources an extended red halo.

G35.20-0.74 was the first source observed for this survey, and it has been the subject of its own paper (Zhang et al. 2013b) describing how the outflow from this massive protostar is likely to directly influence the morphology we see at infrared wavelengths. The hypothesis is that massive stars form in dense cores, with extinctions of A_V & 100s of magnitudes along the line of sight to the central protostar. Outflows are driven by accretion and can effectively clear out material surrounding the core along the outflow axis direction, significantly decreasing extinction in those directions. Thus, radiation readily leaves via these cavities, and if the orientation to our line of sight is favorable, we can detect more intense and shorter wavelength infrared emission from these sources. Blue-shifted outflow cavities appear brighter. However...
De Buizer et al.

Figure 11. Gallery of RGB images of the eight protostellar sources, as labelled. The legend shows the wavelengths used and the beam sizes at these wavelengths. SOFIA-FORCAST 37 μm is always shown in red, and Spitzer-IRAC 8 μm is always shown in blue (note this occasionally saturates in the brightest parts of some sources: see previous individual source images). Green usually shows SOFIA-FORCAST 19 μm, except for G45.47+0.05 and IRAS 20126, where it displays FORCAST 25 μm. As one observes at longer wavelengths, it becomes possible to see emission from the red-shifted outflow cavities.

The previous subsection discussed the observational evidence that indicates that each of the regions in our sample contains a high- or intermediate-mass protostar driving an outflow. How widespread is the evidence in our sample that the MIR morphologies are influenced by the presence of these outflow cavities?

Of the eight sources in our sample, only AFGL 437 does not show clear signs of extended MIR/FIR emission. Of the remaining seven sources, we can conclude that six are extended in their MIR/FIR emission at a position angle comparable to the orientation of their outflow axes. The only exception is IRAS 07299-1651, and this is only excluded because no outflow maps exist for this source. However, since it displays similar behavior in morphology as a function of wavelength as the rest of the sources, we predict that an outflow is present at a position angle of \( \approx 300 \)°, with a blue-shifted lobe to the SE. For two of the sources in the sample it appears that their MIR/FIR emission is extended only to one side of the central stellar source: AFGL 4029 and G45.47+0.05. In both cases, this emission is on the blue-shifted side. Three sources appear to be extended to one side at shorter wavelengths and more symmetrically extended at longer wavelengths: G35.20-0.74, IRAS 20126+4104, and Cepheus A. In all three cases, the emission at shorter wavelengths comes predominantly from the blue-shifted side of the outflow. The remaining source is NGC 7538 IRS 9, which, perhaps because of an almost pole-on outflow orientation, we only see modest amounts of extended MIR/FIR emission. However, the little MIR/FIR extension that is seen is at the angle of the projected outflow axis. Somewhat surprisingly, however, is that the elongated morphologies seen at 7–40 μm are also present in most cases in the Herschel 70 μm images, showing that outflows can impact protostellar appearance even at such long FIR wavelengths.

Thus the first eight sources of the SOMA Star Formation survey give strong support to the hypothesis that MIR to FIR morphologies of high- and intermediate-mass protostars are shaped by their outflow cavities. Bipolar, oppositely-directed outflows are a generic prediction of Core Accretion models. The presence of dense core envelope gas near the protostar will tend to extinct shorter wavelength light to a greater degree so that the emission peaks at these wavelengths appear displaced away from the protostar towards the blue-shifted, near-facing side of the outflow. This qualitative prediction again appears to be confirmed by our survey results.

MIR to FIR morphologies thus give important information about how massive protostars are forming, especially the orientation and structure of their outflow cavities and the presence of dense core envelopes. In the following section we use the SOFIA and other data to make more quantitative assessments of the properties of these protostars.
**SEDs**

effect of aperture definition:

- **fixed**
- **variable**

effect of clump envelope subtraction:

- **total** (core+clump)
- **core** (total-clump)
The SOMA Survey: Overview and First Results

The data at clump envelope

Parameters of the Five Best Fitted Models of Zhang & Tan models

| Source    | \( \chi^2 \) | \( M_c \) (\( M_\odot \)) | \( \Sigma_{cl} \) (g cm\(^{-2} \)) | \( R_c \) (pc) (") | \( m_* \) (\( M_\odot \)) | \( \theta_{\text{view}} \) (\( \circ \)) | \( A_V \) (mag) | \( M_{\text{env}} \) (\( M_\odot \)) | \( \theta_{w, \text{esc}} \) (\( \circ \)) | \( \dot{M}_{\text{disk}} \) (\( M_\odot /\text{yr} \)) | \( L_{\text{bol}} \) (\( L_\odot \)) |
|-----------|---------------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| AFGL4029  | 1.00          | 100             | 3.2             | 0.04 (4)       | 48              | 89              | 64.6            | 2.6             | 71              | 7.1(-4)         | 4.6(5)          |
| \( d = 2.2 \text{ kpc} \) | 1.15          | 30              | 1.0             | 0.04 (4)       | 12              | 62              | 0.0             | 5.7             | 53              | 1.9(-4)         | 4.1(4)          |
| \( R_{ap} = 11.2'' \)  | 1.28          | 30              | 3.2             | 0.02 (2)       | 16              | 65              | 94.9            | 1.0             | 56              | 5.1(-4)         | 1.0(5)          |
|           | 1.34          | 200             | 0.1             | 0.33 (31)      | 48              | 89              | 64.6            | 29              | 74              | 5.7(-5)         | 3.3(5)          |
|           | 1.44          | 100             | 0.1             | 0.23 (22)      | 16              | 89              | 17.2            | 53              | 45              | 6.2(-5)         | 3.0(4)          |
| AFGL437   | 0.91          | 160             | 0.1             | 0.29 (30)      | 16              | 58              | 0.0             | 116             | 32              | 8.1(-5)         | 3.3(4)          |
| \( d = 2.0 \text{ kpc} \) | 1.48          | 160             | 0.1             | 0.29 (30)      | 24              | 86              | 15.2            | 87              | 45              | 8.5(-5)         | 7.8(4)          |
| \( R_{ap} = 32.0'' \)  | 1.55          | 50              | 3.2             | 0.03 (3)       | 8               | 29              | 0.0             | 35              | 25              | 6.0(-4)         | 1.7(4)          |
|           | 2.02          | 160             | 0.1             | 0.29 (30)      | 32              | 89              | 23.2            | 55              | 59              | 7.6(-5)         | 1.5(5)          |
|           | 2.22          | 200             | 0.1             | 0.33 (34)      | 12              | 34              | 0.0             | 174             | 20              | 8.0(-5)         | 2.0(4)          |
**Zhang & Tan models**

| Source         | $\chi^2$ | $M_c$ ($M_\odot$) | $\Sigma_{cl}$ (g cm$^{-2}$) | $R_c$ (pc) (″) | $m_*$ ($M_\odot$) | $\theta_{view}$ (°) | $A_V$ (mag) | $M_{env}$ ($M_\odot$) | $\theta_{w,esc}$ (°) | $\dot{M}_{disk}$ ($M_\odot$/yr) | $L_{bol}$ ($L_\odot$) |
|----------------|----------|--------------------|-----------------------------|---------------|-----------------|---------------------|------------|---------------------|---------------------|---------------------------|-----------------|---|
| IRAS07299      | 0.22     | 200                | 0.1                         | 0.33 (48)     | 8               | 89                  | 20.2       | 181                 | 14                  | 6.8(-5)                   | 9.5(3)         |
| $d = 1.4$ kpc  | 0.23     | 320                | 0.1                         | 0.42 (61)     | 8               | 83                  | 3.0        | 307                 | 11                  | 7.7(-5)                   | 8.8(3)         |
| $R_{ap} = 7.7$ ″| 0.32     | 240                | 0.1                         | 0.36 (53)     | 8               | 86                  | 22.2       | 226                 | 13                  | 7.1(-5)                   | 1.1(4)         |
|                | 0.59     | 60                 | 0.3                         | 0.10 (15)     | 12              | 77                  | 9.1        | 32                  | 40                  | 1.2(-4)                   | 2.7(4)         |
|                | 0.67     | 160                | 0.1                         | 0.29 (43)     | 8               | 89                  | 33.3       | 143                 | 17                  | 6.3(-5)                   | 1.1(4)         |
| G35.20-0.74    | 2.63     | 480                | 0.1                         | 0.51 (48)     | 16              | 48                  | 40.4       | 440                 | 15                  | 1.2(-4)                   | 3.8(4)         |
| $d = 2.2$ kpc  | 2.64     | 100                | 3.2                         | 0.04 (4)      | 12              | 29                  | 70.7       | 77                  | 20                  | 9.4(-4)                   | 5.2(4)         |
| $R_{ap} = 32.0$ ″| 2.76    | 320                | 0.1                         | 0.42 (39)     | 24              | 68                  | 81.8       | 256                 | 27                  | 1.2(-4)                   | 8.4(4)         |
|                | 2.76     | 80                 | 3.2                         | 0.04 (3)      | 12              | 39                  | 15.2       | 58                  | 22                  | 8.4(-4)                   | 5.0(4)         |
|                | 2.77     | 200                | 0.3                         | 0.19 (17)     | 12              | 22                  | 43.4       | 173                 | 17                  | 1.9(-4)                   | 4.0(4)         |
### Zhang & Tan models

<table>
<thead>
<tr>
<th>Source</th>
<th>$\chi^2$</th>
<th>$M_\odot$</th>
<th>$\Sigma_{cl}$</th>
<th>$R_c$</th>
<th>$m_\ast$</th>
<th>$\theta_{\text{view}}$</th>
<th>$A_V$</th>
<th>$M_{\text{env}}$</th>
<th>$\theta_{w,\text{esc}}$</th>
<th>$\dot{M}_{\text{disk}}$</th>
<th>$L_{\text{bol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G45.47+0.05</td>
<td>1.21</td>
<td>200</td>
<td>3.2</td>
<td>0.06</td>
<td>32</td>
<td>86</td>
<td>63.6</td>
<td>140</td>
<td>25</td>
<td>1.7(-3)</td>
<td>4.6(5)</td>
</tr>
<tr>
<td>$d = 8.4$ kpc</td>
<td>1.34</td>
<td>320</td>
<td>1.0</td>
<td>0.13</td>
<td>48</td>
<td>89</td>
<td>46.5</td>
<td>200</td>
<td>35</td>
<td>9.3(-4)</td>
<td>5.1(5)</td>
</tr>
<tr>
<td>$R_{ap} = 14.4''$</td>
<td>1.57</td>
<td>320</td>
<td>1.0</td>
<td>0.13</td>
<td>32</td>
<td>68</td>
<td>15.2</td>
<td>252</td>
<td>24</td>
<td>8.2(-4)</td>
<td>2.7(5)</td>
</tr>
<tr>
<td></td>
<td>1.62</td>
<td>240</td>
<td>1.0</td>
<td>0.11</td>
<td>32</td>
<td>86</td>
<td>1.0</td>
<td>170</td>
<td>30</td>
<td>7.2(-4)</td>
<td>2.6(5)</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>240</td>
<td>1.0</td>
<td>0.11</td>
<td>24</td>
<td>55</td>
<td>0.0</td>
<td>192</td>
<td>23</td>
<td>6.6(-4)</td>
<td>1.7(5)</td>
</tr>
<tr>
<td>IRAS20126</td>
<td>1.82</td>
<td>80</td>
<td>0.3</td>
<td>0.12</td>
<td>16</td>
<td>74</td>
<td>37.4</td>
<td>42</td>
<td>42</td>
<td>1.5(-4)</td>
<td>4.2(4)</td>
</tr>
<tr>
<td>$d = 1.64$ kpc</td>
<td>2.07</td>
<td>120</td>
<td>0.3</td>
<td>0.14</td>
<td>24</td>
<td>74</td>
<td>69.7</td>
<td>57</td>
<td>47</td>
<td>1.8(-4)</td>
<td>9.3(4)</td>
</tr>
<tr>
<td>$R_{ap} = 12.8''$</td>
<td>2.32</td>
<td>80</td>
<td>0.3</td>
<td>0.12</td>
<td>12</td>
<td>44</td>
<td>73.7</td>
<td>53</td>
<td>31</td>
<td>1.4(-4)</td>
<td>3.4(4)</td>
</tr>
<tr>
<td></td>
<td>2.33</td>
<td>200</td>
<td>0.1</td>
<td>0.33</td>
<td>12</td>
<td>86</td>
<td>65.7</td>
<td>174</td>
<td>20</td>
<td>8.0(-5)</td>
<td>2.0(4)</td>
</tr>
<tr>
<td></td>
<td>2.39</td>
<td>100</td>
<td>0.3</td>
<td>0.13</td>
<td>16</td>
<td>51</td>
<td>66.7</td>
<td>61</td>
<td>36</td>
<td>1.6(-4)</td>
<td>4.5(4)</td>
</tr>
</tbody>
</table>
The SOMA Survey: Overview and First Results

### Table 3

<table>
<thead>
<tr>
<th>Source</th>
<th>$\chi^2$</th>
<th>$M_c$ ($M_\odot$)</th>
<th>$\Sigma_{cl}$ (g cm$^{-2}$)</th>
<th>$R_c$ (pc) ($''$)</th>
<th>$m_*$ ($M_\odot$)</th>
<th>$\theta_{\text{view}}$ ($^\circ$)</th>
<th>$A_V$ (mag)</th>
<th>$M_{\text{env}}$ ($M_\odot$)</th>
<th>$\theta_{w, \text{esc}}$ ($^\circ$)</th>
<th>$\dot{M}<em>{\text{disk}}$ ($M</em>\odot$/yr)</th>
<th>$L_{\text{bol}}$ ($L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CepA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d = 0.725$ kpc</td>
<td>2.17</td>
<td>160</td>
<td>0.3</td>
<td>0.17 (47)</td>
<td>12</td>
<td>29</td>
<td>94.9</td>
<td>135</td>
<td>20</td>
<td>1.8(-4)</td>
<td>3.8(4)</td>
</tr>
<tr>
<td>$R_{ap} = 48.0''$</td>
<td>2.21</td>
<td>160</td>
<td>0.3</td>
<td>0.17 (47)</td>
<td>16</td>
<td>39</td>
<td>98.0</td>
<td>125</td>
<td>26</td>
<td>2.0(-4)</td>
<td>5.0(4)</td>
</tr>
<tr>
<td></td>
<td>2.65</td>
<td>400</td>
<td>0.1</td>
<td>0.47 (132)</td>
<td>16</td>
<td>86</td>
<td>100.0</td>
<td>364</td>
<td>17</td>
<td>1.1(-4)</td>
<td>3.8(4)</td>
</tr>
<tr>
<td></td>
<td>2.71</td>
<td>480</td>
<td>0.1</td>
<td>0.51 (145)</td>
<td>12</td>
<td>83</td>
<td>80.8</td>
<td>460</td>
<td>12</td>
<td>1.1(-4)</td>
<td>2.4(4)</td>
</tr>
<tr>
<td></td>
<td>2.81</td>
<td>160</td>
<td>0.3</td>
<td>0.17 (47)</td>
<td>24</td>
<td>74</td>
<td>100.0</td>
<td>98</td>
<td>37</td>
<td>2.2(-4)</td>
<td>9.9(4)</td>
</tr>
<tr>
<td>NGC7538 IRS9</td>
<td>0.15</td>
<td>400</td>
<td>0.1</td>
<td>0.47 (36)</td>
<td>16</td>
<td>22</td>
<td>23.2</td>
<td>364</td>
<td>17</td>
<td>1.1(-4)</td>
<td>3.8(4)</td>
</tr>
<tr>
<td>$d = 2.65$ kpc</td>
<td>0.19</td>
<td>320</td>
<td>0.1</td>
<td>0.42 (32)</td>
<td>16</td>
<td>39</td>
<td>2.0</td>
<td>281</td>
<td>19</td>
<td>1.1(-4)</td>
<td>3.7(4)</td>
</tr>
<tr>
<td>$R_{ap} = 25.6''$</td>
<td>0.35</td>
<td>240</td>
<td>0.1</td>
<td>0.36 (28)</td>
<td>24</td>
<td>39</td>
<td>52.5</td>
<td>171</td>
<td>33</td>
<td>1.1(-4)</td>
<td>8.2(4)</td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>480</td>
<td>0.1</td>
<td>0.51 (40)</td>
<td>16</td>
<td>22</td>
<td>17.2</td>
<td>440</td>
<td>15</td>
<td>1.2(-4)</td>
<td>3.8(4)</td>
</tr>
<tr>
<td></td>
<td>0.54</td>
<td>60</td>
<td>3.2</td>
<td>0.03 (2)</td>
<td>12</td>
<td>34</td>
<td>22.2</td>
<td>38</td>
<td>27</td>
<td>7.6(-4)</td>
<td>5.0(4)</td>
</tr>
</tbody>
</table>
The fitting method sets the data point to be at the middle of the errorbar range. The resulting model parameter results are shown as solid gray lines. Flux values are those from Table 3.

For each source, the best fit model is shown with a solid black line and the next four best models are shown with dotted black lines.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\chi^2$</th>
<th>$M_c$ (M$_\odot$)</th>
<th>$\Sigma_{cl}$ (g cm$^{-2}$)</th>
<th>$R_c$ (pc)</th>
<th>$m_*$ (M$_\odot$)</th>
<th>$\theta_{view}$ ($^\circ$)</th>
<th>$A_V$ (mag)</th>
<th>$M_{env}$ (M$_\odot$)</th>
<th>$\theta_{w,esc}$ ($^\circ$)</th>
<th>$M_{disk}$ (M$_\odot$/yr)</th>
<th>$L_{bol}$ (L$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAS07299</td>
<td>0.22</td>
<td>200</td>
<td>0.1</td>
<td>0.33 (48)</td>
<td>8</td>
<td>89</td>
<td>20.2</td>
<td>1.10</td>
<td>18</td>
<td>76</td>
<td>13.2</td>
</tr>
<tr>
<td>$d = 1.4$ kpc</td>
<td>0.23</td>
<td>320</td>
<td>0.1</td>
<td>0.42 (61)</td>
<td>8</td>
<td>83</td>
<td>3.0</td>
<td>1.13</td>
<td>17</td>
<td>76</td>
<td>10.0</td>
</tr>
<tr>
<td>$R_{ap} = 7.7''$</td>
<td>0.32</td>
<td>240</td>
<td>0.1</td>
<td>0.36 (53)</td>
<td>8</td>
<td>86</td>
<td>22.2</td>
<td>1.15</td>
<td>17</td>
<td>81</td>
<td>10.0</td>
</tr>
<tr>
<td>$d = 2.2$ kpc</td>
<td>0.59</td>
<td>60</td>
<td>0.3</td>
<td>0.10 (15)</td>
<td>12</td>
<td>77</td>
<td>9.1</td>
<td>1.16</td>
<td>18</td>
<td>81</td>
<td>12.5</td>
</tr>
<tr>
<td>$R_{ap} = 32.0''$</td>
<td>0.67</td>
<td>160</td>
<td>0.1</td>
<td>0.29 (43)</td>
<td>8</td>
<td>89</td>
<td>33.3</td>
<td>1.17</td>
<td>17</td>
<td>87</td>
<td>10.0</td>
</tr>
<tr>
<td>G35.20-0.74</td>
<td>2.63</td>
<td>480</td>
<td>0.1</td>
<td>0.51 (48)</td>
<td>16</td>
<td>48</td>
<td>40.4</td>
<td>2.26</td>
<td>20</td>
<td>87</td>
<td>20.7</td>
</tr>
<tr>
<td>$d = 2.2$ kpc</td>
<td>2.64</td>
<td>100</td>
<td>3.2</td>
<td>0.04 (4)</td>
<td>12</td>
<td>29</td>
<td>70.7</td>
<td>2.40</td>
<td>20</td>
<td>81</td>
<td>24.1</td>
</tr>
<tr>
<td>$R_{ap} = 32.0''$</td>
<td>2.76</td>
<td>320</td>
<td>0.1</td>
<td>0.42 (39)</td>
<td>24</td>
<td>68</td>
<td>81.8</td>
<td>2.49</td>
<td>20</td>
<td>76</td>
<td>33.0</td>
</tr>
<tr>
<td>$d = 2.2$ kpc</td>
<td>2.76</td>
<td>80</td>
<td>3.2</td>
<td>0.04 (3)</td>
<td>12</td>
<td>39</td>
<td>15.2</td>
<td>2.54</td>
<td>19</td>
<td>70</td>
<td>16.4</td>
</tr>
<tr>
<td>$R_{ap} = 32.0''$</td>
<td>2.77</td>
<td>200</td>
<td>0.3</td>
<td>0.19 (17)</td>
<td>12</td>
<td>22</td>
<td>43.4</td>
<td>2.70</td>
<td>18</td>
<td>76</td>
<td>16.8</td>
</tr>
</tbody>
</table>

The Zhang & Tan models are compared to the Robitaille et al. models. The Zhang & Tan models show a significant improvement in the fits, as indicated by the lower $\chi^2$ values. The Table 3 provides a detailed comparison of the model parameters for each source.
Figure 15. Bolometric flux weighted SEDs of the eight SOMA protostars analyzed in this paper. The ordering of the legend is from high to low ZT best fit model luminosity (top to bottom).

These distributions with the rank ordering of the predicted true luminosity of the protostars from the best fit ZT models (the legend in Fig. 15 lists the sources in order of decreasing ZT model luminosity). There is some, but not perfect, correspondence with the flux ordering seen in the figure. Differences are most likely due to varying levels of foreground extinction, local extinction in the core envelope (e.g., AFGL 4029's formal best fit ZT model has a low envelope mass and wide outflow cavity, so a large fraction of its luminosity would not be reradiated in the MIR to FIR) and anisotropic beaming (i.e., the "flashlight effect," Yorke & Bodenheimer 1999). Such non-intrinsic effects illustrate the need for larger samples of protostars, i.e., eventually statistically significant samples will be required as a function of environment, mass and evolutionary stage. This is the eventual goal of the SOMA Survey.

5. CONCLUSIONS

We have presented an overview and first results of the SOMA Star Formation Survey. The survey's scientific rationale is to test predictions of Core Accretion models of massive star formation, specifically the MIR to FIR thermal dust emission, including the influence of outflow cavities. We have presented results for the first eight sources observed in the survey. These tend to show extended MIR and FIR emission that aligns with known outflows, and being brighter on the near-facing, blue-shifted side, which are predictions of Core Accretion models that involve high mass surface density cores. In principle, unrelated foreground extinction could mimic these results, but the consistency of the observed multi-wavelength morphologies in the sample provides strong support for the Core Accretion scenario.

Global SEDs have been constructed and effects of choices of aperture definition and background subtraction investigated. Our fiducial method is an SED derived from a fixed aperture and including an estimate of background subtraction, i.e., the emission from the surrounding clump environment. These SEDs have been used to constrain properties of the protostars by comparison with theoretical radiative...
SOMA Next Steps

SOMA II. Massive Protostars Across Environments
(Liu et al.)

SOMA III. Model Fitting with SEDs & Image Intensity Profiles
(Zhang et al.)

SOMA IV. HST NIR Follow-up
(Da Rio et al.)

SOMA V. ALMA Outflow Follow-up
(Zhang et al.)

SOMA VI. ALMA Core Follow-up
(Liu et al.)
Outflow-Confined HII Regions

Tan & McKee (2003), Tanaka, Tan & Zhang (2016)

\[ \theta_{\text{view}} = 60^\circ \]

Properties of theoretical outflow-confined HII regions.

\[ P \simeq 0.88 GZ^2 \]

- Radio luminosity versus bolometric luminosity. Triangles show observed radio jets (blue: low-luminosity, and red: high-luminosity).
- Log size [pc] vs. FWHM [km/s].
- Log \( F_\nu / L_{\text{bol}} \) [mJy kpc\(^2\)] vs. FWHM [km/s].
- Log \( F_{\nu} d^2 \) [mJy kpc\(^2\)] vs. \( \log L_{\text{bol}} [L_\odot] \).
Feedback During Massive Star Formation

Is there a maximum stellar mass set by formation processes?

Salpeter (1955)
\[ \frac{dN}{dm} = A m^{-2.35} \]

Feedback processes:
1. Protostellar outflows
2. Ionization
3. Stellar winds
4. Radiation pressure
5. Supernovae

30 Doradus - LMC

\[ m_{\text{max}} \approx 150 M_\odot \]
(e.g., Figer 2005).

But Crowther et al. (2010) claim most massive star to form was initially \(~300M_\odot\), consistent with statistical sampling of Salpeter IMF with no maximum cutoff mass.

Accretion processes: Core/disk fragmentation (Kratter & Matzner 06; Peters et al. 10)

Stellar processes: Nuclear burning instabilities/enhanced mass loss

Currently unclear what sets the shape of the massive star IMF
Feedback

Tanaka, Tan, Zhang (2017)

momentum by MHD disk wind + radiation pressure

mass loss by MHD disk wind + photoevaporation + stellar wind

protostellar evolution

disk accretion

infall from core collapse

\[ \text{log } m_\ast [M_\odot] \]

\[ \theta_{\text{sc}} [^\circ] \]

\[ \log [M_\odot \text{ km s}^{-1}] \]

\[ \dot{M}_{\text{PE}} \]

\[ \dot{m}_{\text{sw}} \]

\[ p_{\text{dw}} \]

\[ p_{\text{tp}} \]

\[ m_\ast [M_\odot] \]

\[ 0.1 \text{ g/cm}^2 \]

\[ 0.316 \text{ g/cm}^2 \]

\[ 0.1 \text{ g/cm}^2 \]
Massive Star Formation Theories:
Core Accretion; Competitive Accretion; Protostellar Collisions

Theory: “Turbulent Core Model”:
normalize core surface pressure to surrounding clump pressure, i.e. self-gravitating weight. Core supported by non-thermal pressure (B-fields/turbulence). Radiative transfer model grid (Zhang & Tan, in prep.)

1: Massive starless/early-stage cores exist in IRDCs (Tan+ 2013; Kong+ 2017b)

2: SOMA Survey of Massive Protostars: (De Buizer+ 2017) High- & intermediate-mass protostars often have a similar morphology to low-mass protostars, e.g., collimated outflows. Bipolar outflow cavities shape MIR to FIR morphology and SEDs. SED fitting alone has significant degeneracies. We expect these to be broken by intensity profile fitting & multiwavelength follow-up.