Protoclusters in the Milky Way: 
Physical properties of massive starless 
& star-forming clumps from the BGPS

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Image Credit: Adam Ginsburg
Many fundamental questions remain open in high-mass star and cluster formation.

Initial protocluster physical conditions

Inflow in the mass growth of protoclusters

Fragmentation before star formation occurs

<table>
<thead>
<tr>
<th>Starless</th>
<th>Protostellar</th>
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</thead>
<tbody>
<tr>
<td>Mass $\sim 10^2-10^4 , M_{\odot}$</td>
<td></td>
</tr>
<tr>
<td>Radius $\sim 1 , \text{pc}$</td>
<td></td>
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<tr>
<td>Col. Dens. $\sim 10^2-10^3 , M_{\odot} , \text{pc}^{-2}$</td>
<td></td>
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<tr>
<td>Vol. Dens. $\sim 10^3 , \text{cm}^{-3}$</td>
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Image Credit: Battersby et al. (2010)
**Future is now:** Galactic plane surveys now exist to study pre-protoclusters / starless clumps

Image Credit: ESA, NASA, JPL-Caltech, S. Carey, A. Ginsburg, Dempsey et al. (2013)
Future is now: Galactic plane surveys now exist to study pre-protoclusters / starless clumps

In 55 degree survey region

4683 clumps in survey overlap
2925 unique velocities
1462 GBT NH$_3$ gas kinetic temps.
1650 well-constrained distances

Image Credit: ESA, NASA, JPL-Caltech, S. Carey, A. Ginsburg, Dempsey et al. (2013)
BGPS 1mm: cold dust, all stages, large swath of GP

Match to diverse set of protostellar indicators, from radio to IR.

Propagate uncertainties for property estimation with Monte Carlo random sampling techniques

Calculate distributions of properties on subsamples

**Indicators:** Blind surveys of star formation activity from the radio to mid-IR, half of clumps are starless

2238 (48%) Starless Candidate  
2446 (52%) Protostellar

1043 (22%) 70 um Unique  
*Hi-GAL 70 um visual inspection*

1022 (22%) Mid-IR  
*Red MSX, EGO, Robitaille+08*

556 (12%) Water Maser  
*GBT, Arcetri, HOPS*

296 (6%) Methanol Maser  
*MMB, Arecibo, Pestalozzi+05*

170 (4%) UCHII  
*CORNISH*

Only 70 um, deeply embedded candidates

Includes over 2000 targeted GBT observ.

Uniquely OB stars, not all clumps may produce these indicators

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~2200 starless clump candidates identified

**NH$_3$ Gas Temperatures**: Increasing temperatures with star formation activity, median for SCC = 13.9 K.

**Diagram Description**

- **Starless Cand.**
- **Protostellar**
- **70 µm Unique**
- **Mid IR**
- **H$_2$O**
- **CH$_3$OH**
- **UCHII**

**Property estimation:** MC samples are drawn for each clump based on PDFs for distance, flux, and temperature.

**Example:** 1 Clump with 10,000 Monte Carlo mass samples

Clump total mass ($M_{\text{sun}}$) from MC samples that draw from flux, temperature, and heliocentric distance.
**Mass Segregation:** Increase in median mass from 230 to 600 from Starless to Protostellar. Evidence for growth?

**Cannot be due to:**
- Incompleteness in distance or SF indicators
- Mass incompleteness for starless candidates
- $\text{NH}_3$ underestimate of kinetic temperature
- Isothermal temperature assumption

Growth only scenario
200 – 400 $M_{\text{sun}}$ / Myr

Lifetime only scenario
Starless lifetime $\sim M^{-0.4}$

**Time Scales:** SCC phase short, less than 0.5 Myr

**Class II Methanol Maser:** Absolute timescale between 0.06 to 0.09 Myr (van der Walt 2005; Battersby et al., in prep.)

High-mass starless phase < 0.5 Myr

Assumes no clump growth

Extrapolated to \( \sim 200 \, M_{\odot} \), starless phase would be 2-3 the free-fall time

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Virial parameter: More than 75% of clumps in “gravitationally bound”, no strong dependence on mass.

Median $\alpha = 0.75$

75% with $\alpha < 2$

Same for starless and protostellar

To virialize would need 50–100 uG (see Pillai+ 2015)

Summary & Conclusions

- **~2200** blindly identified starless clump candidates (SCCs): largest and most robust sample to date
- SCCs are **colder, lower mass, less turbulent, less concentrated, smaller, less dense, and lower column density** than protostellar clumps
- Increase in median mass is suggestive of multiple explanations: cloud infall, lifetime effects, and dust opacity
- Majority (75%) of clumps are gravitationally bound
- Timescale for high-mass SCCs < 0.5 Myr, but low-mass SCCs phase longer than free-fall time.
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<thead>
<tr>
<th></th>
<th>HG 0</th>
<th>HG 3</th>
<th>HG 1&amp;4</th>
<th>HG 2</th>
<th>R08 YSO</th>
<th>RMS</th>
<th>EGO</th>
<th>H2O</th>
<th>CH3OH</th>
<th>UCHII</th>
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</table>
Completeness: 70 um completeness depends on high or low background, but small luminosity limit

High Background
2000 – 3000 MJy / sr

Low Background
500 – 1000 MJy / sr
Distance PDFs: A novel Bayesian approach to resolving heliocentric distances

Image Credit: Ellsworth-Bowers+ (2013)
**Distance PDFs:** A novel Bayesian approach to resolving heliocentric distances

\[
\text{DPDF}(d_{\odot}) = \mathcal{L}(v_{\text{LSR}}, l, b; d_{\odot}) \prod_{i} P_{i}(l, b; d_{\odot})
\]

(a) Well Constrained

(b) Unresolved
**Distance PDFs:** Group distances are similar. Does not suggest strong distance bias.
**Contamination:** Far-IR 70 um much more effective indicator of deeply embedded YSOs without contamination from evolved stars.

Severe contamination in 24 um data from evolved stars.
More than 80% of clumps are LOS associated to 24 um.
70 um is a superior indicator of deeply embedded YSOs.
Flux Density: Lower flux clumps more frequently starless, but Full and Distance samples similar.

Distance PDFs: Fraction is constant. Does not suggest significant incompleteness in indicators.
Size Linewidth: No observed size-linewidth trend for SCCs, but protostellar consistent with Larson.

Spearman rank correlation coefficients of 0.24 and 0.50. Ammonia observations corrected for optical depth show better agreement than HCO+ (Schlingman et al. 2011, Shirley et al. 2013).
**Virial parameter**: More than 75% of clumps in “gravitationally bound”, no strong dependence on mass.

Population of SCCs shows similar distribution of virial parameters, without a large difference in fraction of “unbound” clumps. While sub-virial, 50 uG required to support typical clump to collapse (cf. Kauffmann et al. 2013; Pillai et al. 2015)
Astrophysical Cuts: Remove low-mass, low-density, and/or unbound objects. Mass difference robust.

Cloud-to-clump infall of 200 to 400 solar masses per Myr (over 0.8 Myr)

~ 1000 Msun / Myr (high-mass):
  - Battersby et al. (in prep.)
  - Peretto et al. (2013)
  - Schneider et al. (2010)

~ 100 Msun / Myr (low-mass):
  - Kirk et al. (2013)
  - Fernandez-Lopez et al. (2014)
  - Palmeirim et al. (2013)

No large, systematic samples exist, but inflow rates required are reasonable given existing observations.
**Time Scales:** Several of methods generally point to short SCC phase-lifetimes, less than 0.5 Myr

**IMF:** Kroupa IMF (Kroupa 2001)

**SFR:** $1.9 \pm 0.4 \, M_{\odot} \, yr^{-1}$ (Chomiuk & Povich 2011)

Galactic population of clumps is in steady state

\[
\epsilon_{SF} M_{\text{clump}} = \frac{\int_{0.08}^{150} N(M) M dM}{\int_{M_{\text{max}}}^{150} N(M) dM} \]

\[
M_{\text{max}} \approx 20 \, M_{\odot} \left( \frac{\epsilon_{SF} \, M_{\text{clump}}}{0.3 \, 1064 \, M_{\odot}} \right)^{1/1.3}
\]

\[
\tau_{\text{clump}} = \frac{N(M > M_{\text{max}})}{\text{SFR}} \frac{\langle M \rangle}{P(M > M_{\text{max}})}
\]

98 SCCs
Distance Sample
224 SCCs
Full Sample
1445 SCCs
Galactic Total

**SCC Lifetime**
0.2 – 0.3 Myr