SOFIA FORCAST Photometry of 12 Extended Green Objects in the Milky Way

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What are EGOs?

Cyganowski et al. (2008) identified in the GLIMPSE survey a class of objects defined by emission extended at 4.5 um but not in other IRAC bands

Size scales of order ~0.1 pc

4.5 um emission is due to shocked $\text{H}_2$ in IRAC Band 2 (e.g. Marston et al. 2004)

Preferentially coincident with IRDCs
What are EGOs?

Follow-up observations of curated subsamples identified evidence of:

- outflows (Class I CH$_3$OH and H$_2$O masers; Cyganowski et al. 2009, 2013; Towner et al. 2017)

- massive protostars (Class II CH$_3$OH masers; Cyganowski et al. 2009)

- cold, dense gas (NH$_3$ (1,1) – (3,3); Cyganowski et al. 2013)

Little evidence of significant ionizing radiation (weak 1.3 cm continuum emission; Towner et al. 2017)

→ EGOs are MYSOs in an active accretion state prior to the emergence of significant ionizing radiation
EGO-12 Sample

• 12 nearest, youngest-appearing EGOs from the previous sample: near-IR (3.6 um) to radio (5 cm) observations using archival infrared data, SOFIA, ALMA, and JVLA

• Open questions:
  • Bolometric luminosity
  • Properties of individual cluster members (mass, accretion disk/rate, etc.)
  • Luminosity-to-mass ratio (L/M) of the clump
  • Clustering and multiplicity
  • Birth order
  • Emergence and effect of ionizing radiation
  • Mechanical energy from outflows
EGO-12 Sample: Infrared Observations

• **SOFIA FORCAST observations**: 19.7 um and 37.1 um, ~10 minutes TOS

• Archival observations:
  • *Spitzer* IRAC (GLIMPSE): 3.6, 4.5, 5.8, 8.0 um
  • *Spitzer* MIPS (MIPSGAL): 24 um
  • *Herschel* PACS (Hi-GAL): 70 um and 160 um
  • APEX LABOCA (ATLASGAL): 870 um

• Additional single-dish observations of NH$_3$ from Cyganowski et al. (2013)

• Project goals:
  • Multiplicity and properties of massive sources
  • Bolometric luminosity
  • Overall clump properties ($T, M$)
  • $L/M$ as a tracer of evolutionary state of the clump
EGO-12 Sample: Infrared Observations

Left: RGB: 160, 70, and 24 μm; orange contours: 870 μm; white box: SOFIA FOV; blue box: FOV of right-hand panel

Right: RGB: 8, 4.5, 3.6 μm; red and blue contours: 37.1 and 19.7 μm, respectively; pink diamond: 6.7 GHz Φ H$_3$O maser
EGO-12 Sample: Multiplicity

Average 37.1 um detections of EGO-associated sources: 2 per FOV

If all 37.1 um detections are truly associated, sample multiplicity of massive sources is 1.9

If only half are, sample multiplicity of massive sources is 1.4

- similar to massive-source multiplicity in a subset of the SOMA sample (Rosero et al. 2019) at this resolution
EGO-12 Sample: Luminosities

• To get $L_{bol}$, we ran graybody fits (via lmfit), plus Robitaille et al. (2006), Robitaille (2017), Zhang & Tan (2018) radiative-transfer models

• $L_{gray}$ is returned directly by lmfit; Stefan-Boltzmann $L_{SB}$ calculated from R and T results for the radiative-transfer models

• $L_{gray} < L_{SB}$ in almost all cases, as expected
Notable variation between and among radiative-transfer model results in both SED shape and returned physical parameters.
Stellar radii for a particular source typically span 1-2 orders of magnitude across all three model results (results for G14.33-0.64, right)

Stellar temperatures typically span 1 order of magnitude

Stefan-Boltzmann luminosity typically agrees within a factor of 2.5 across all three results

<table>
<thead>
<tr>
<th>Source</th>
<th>R_\text{\textast} (R_\odot)</th>
<th>T_\text{\textast} (K)</th>
<th>L_\text{\textast} (10^3 L_\odot)</th>
<th>\chi^2</th>
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<tbody>
<tr>
<td>Robitaille (2017)\textsuperscript{a,b}</td>
<td>31.4</td>
<td>7976</td>
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<td>G14.33-0.64</td>
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<td>Zhang &amp; Tan (2018)\textsuperscript{a}</td>
<td>11.2</td>
<td>16,298</td>
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<td>110.7</td>
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</table>
EGO-12 Sample: Temperature and Mass

• Dust (graybody) and gas (NH$_3$) temperatures are similar for all sources; clump masses are therefore also similar

• Most sources fall between 22 – 29 K and 100 – 800 Msun; median $T = 26$ K, similar to ATLASGAL Top100 sample (Giannetti et al. 2014)

• Usually, $T_{\text{NH}_3} < T_{\text{dust}}$ slightly, in agreement with the trends noted for the ATLASGAL Top100 sample in Giannetti et al. (2017), König et al. (2017)
EGO-12 Sample: L/M Ratio

- No trend in L/M with mass
- L/M are typically between 5-60 Lsun/Msun, with median = 24.7+/-8.4, regardless of method used to determine L
- L/M span ~2.5x for a given source, depending on which L is used
EGO-12 Sample: L/M in Context

- L/M values are comparable to the Carpenter et al. (1990), Elia et al. (2017), Urquart et al. (2018) samples (10x higher than for low- and intermediate-mass-only regions, Enoch et al. 2009)

- L/M ratio is similar, but L and M ~10x lower, than Motte Large Program sample

- Compared to Tigé et al. (2017; Herschel-HOBYS program), EGOs span the “IR-quiet” and “IR-bright” flux and L/M values
EGO-12 Sample: Transitional Population?

• Compared to ATLASGAL Top100 sample, EGOs span the “IR-weak” and “IR-bright” temperature and flux values (2.6 Jy at 4 kpc), but with some significant scatter in temperature space

• In combination with EGO location in L/M space as compared to other samples, this suggests that it is possible EGOs represent a transitional population of MYSOs

• Caveats:
  • Small sample sizes
  • Sample selection methods for both EGO-12 and Top100 samples
Future Work

Construct radio SEDs to disentangle emission mechanisms (dust, free-free, synchrotron):

• ALMA 1.3 mm and 3.2 mm continuum (~0.8” resolution, ~0.1 mJy/beam)
• JVLA 1.3 cm and 5 cm continuum; H$_2$O, CH$_3$OH, and NH$_3$ (3,3) maser observations (~0.3” resolution, ~10 uJy/beam continuum sensitivity)
Summary

• Massive-source multiplicity at an angular resolution of ~3.0” is 1-2 per EGO, in line with results published by other teams (e.g. Rosero et al. 2009, SOMA survey)

• Physical properties returned by various radiative-transfer modeling packages can vary significantly, but luminosities are quite consistent regardless of model package

• Temperatures are consistent with those published for similar samples (e.g. Top100 sample, Giannetti et al. 2014, 2017; König 2017)

• L/M values show no trend with mass, and are similar to those published by other teams, even when other samples contain more massive and more luminous sources (e.g. Motte Large Program survey; Herschel-HOBYS; Tigé et al. 2017)

• EGO-12 sources lie between “IR-quiet” and “IR-bright” populations identified by other teams in both L/M and temperature space; possible indication that EGOs are a transitional population, but with some caveats
Details of Robitaille et al. (2017) Model Results

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<tr>
<th>G10.29—0.13</th>
<th>G10.34—0.14&lt;sup&gt;c&lt;/sup&gt;</th>
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<td><strong>Model</strong></td>
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<td>Model</td>
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<tr>
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