NGC 6334: A Bridge to Extragalactic Star Formation

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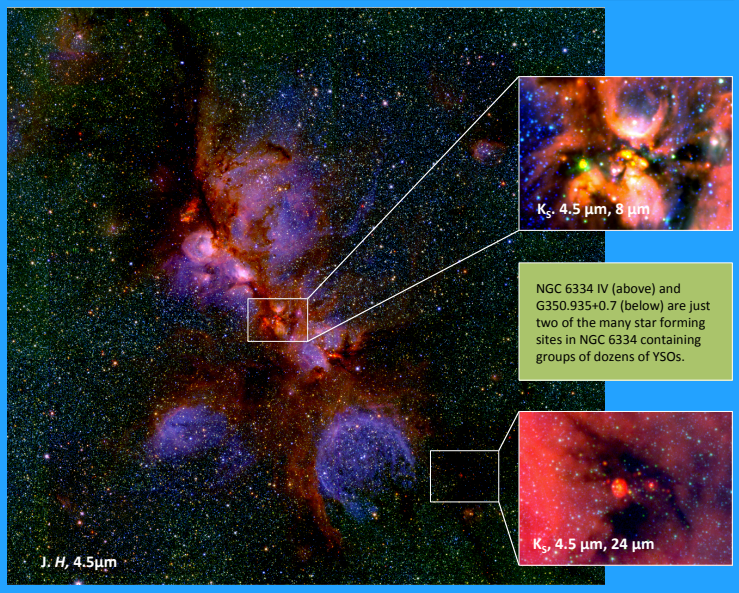
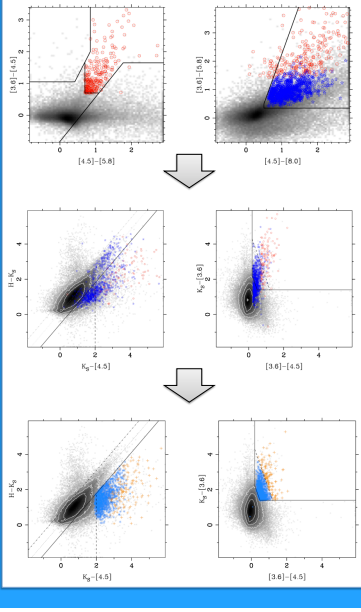
We have observed NGC 6334 using InfraRed Array Camera (IRAC) on the *Spitzer Space Telescope* and the National Optical Astronomy Observatory Extremely Wide-Field InfraRed IMager (NEWFIRM) at *J*, *H*, and K_s bands. We used PSF-fitting photometry to obtain a catalog containing more than 700,000 point sources over a 1.2 x 0.9 square degree area centered on the main star-forming ridge in NGC 6334. For 991 sources in areas with low levels of diffuse 24 µm emission we also used the *Spitzer* MIPSGAL survey program observations to obtain 24 µm fluxes. We examined this catalog to search for Young Stellar Objects (YSOs) within NGC 6334. We found 375 Class I YSOs (protostars) and 1908 Class II YSOs (stars with disks). From the number of observed YSOs we determine NGC 6334's star formation rate is 4900^{+3800}_{-2500} $M_\odot$ Myr^{-1} , with a star formation efficiency $0.06^{+0.04}_{-0.03}$. In the dense clumps and ridges, $\Sigma_{SFR} > 10$ $M_\odot$ Myr^{-1} pc^{-2} and SFE > 0.15, conditions found in Galactic "mini-starburst" regions.



YSO Identification with IRAC and near-Infrared



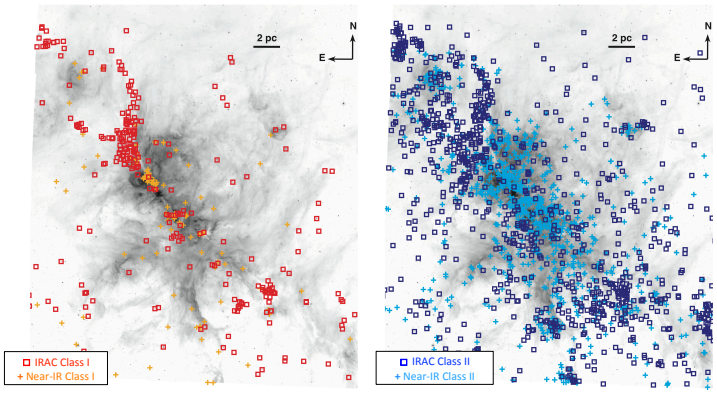
We used the Gutermuth et al. (2009) selection criteria to identify 1,175 YSO candidates based on their colors in all 4 IRAC bands (3.6, 4.5, 5.8, and 8.0 µm).

The detection of point sources is incomplete in fields with bright diffuse emission, which is common in IRAC 5.8 and 8.0 µm observations. We desired to extend the YSO selection for sources without detection at the long IRAC wavelengths. The extended criteria are also useful for targets that are observed during the warm *Spitzer* mission with compatible near-infrared (H, K_s) observations.

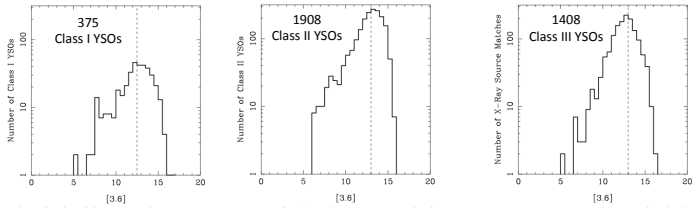
We marked the location of the IRAC-identified YSOs in a pair of H, K_s and [3.6] and [4.5] color spaces. To reduce the number of reddened field stars that the near-IR criteria identify as YSOs we also required the new YSO candidates to fall more than 3σ from the reddened main sequence locus in the near-infrared color spaces. Using these criteria, we identified 1,108 additional YSOs that lacked detection at 5.8 or 8.0 µm.

We matched an additional 1,408 sources with small infrared excess to Chandra X-ray point sources in NGC 6334 (Feigelson 2009), taken to be more evolved cluster members (Class III YSOs).

YSOs in NGC 6334

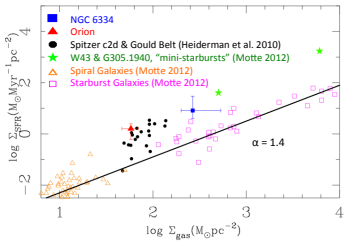


We found the Class I YSOs (left) to be concentrated along the main molecular ridge in NGC 6334. The near-IR / warm-Spitzer YSOs (plusses) reveal a cluster of protostars near one of the 8 µm peaks on the central ridge. The Class II YSOs (right) show greater spread around the central ridge and the near-IR selected YSOs fill in the gaps for the central region that is bright at 8 µm.



The dashed lines in the 3.6 µm magnitude distributions mark the approximate magnitude at which the YSO census is assumed to be complete for each class, at [3.6] = 12.5 for Class I YSOs and [3.6] = 13 for Class II and III YSOs. We used the Robitaille et al. models (2006) to convert the cut-off magnitudes into a stellar mass above which the YSO population census is considered complete. For Class I YSOs we found the $M_{comp} = 0.8^{+0.9}_{-0.6}$ $M_\odot$, Class II YSOs $M_{comp} = 0.3^{+0.3}_{-0.15}$ $M_\odot$ and Class III YSOs $M_{comp} = 1.5 \pm 0.6$ $M_\odot$. We used a standard Kroupa IMF to infer the total mass of the stellar population, $M_{YSO} = 9800$ $M_\odot$, from the observed sample. Assuming a 2 Myr disk half-life we derive the star formation rate 4900^{+3800}_{-2500} $M_\odot$ Myr^{-1} , with $\Sigma_{SFR} = 8.2^{+6.3}_{-4.2}$ $M_\odot$ Myr^{-1} pc^{-2}. We mapped the extinction across the observed field and found the observed portion of the molecular cloud contains ~2 x 10^5 $M_\odot$ indicating the current star formation efficiency is $0.04^{+0.03}_{-0.02}$.

NGC 6334 in the Extragalactic Context



The Kennicutt-Schmidt relation comparing the observed star formation rate surface density and gas mass surface density. The error bars for NGC 6334 (blue box, center) reflect the uncertainty in the mass estimates of the YSO population and the molecular cloud. NGC 6334 has a higher surface density of gas and star formation rate than the low mass star forming regions from Spitzer's *cores to disks* (c2d) and *Gould Belt Survey* (GBS) programs. We used Orion as a comparison for our method of determining the star formation rate, and found Orion falls in the same locus as the low mass star forming regions.

The prototypical "mini-starbursts" W43 and G035.39 (Motte et al. 2012) seem to extend the Kennicutt-Schmidt relation to high gas surface densities, and NGC 6334 falls in between the two regimes. "Mini-starbursts" are identified by SFE > 0.15 and $\Sigma_{SFR} > 10$ $M_\odot$ Myr^{-1} pc^{-2}, conditions found in the main ridge of NGC 6334 where SFE ≈ 0.3 and $\Sigma_{SFR} = 13.0^{+25}_{-10}$ $M_\odot$ Myr^{-1} pc^{-2}.

References

- Feigelson, E. D. et al. 2009, AJ 132, 227
- Gutermuth et al. 2009, ApJ 184, 18
- Heiderman et al. 2010, ApJ, 723, 1019
- Motte et al. 2012, SF2A-2012: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, 45
- Robitaille, T. P. et al. 2006, ApJS, 167, 256

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