Intermediate-mass Young Stellar Objects
Bridging the astronomical gap between
*T Tauri* stars and massive star formation

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Outline

Principal Themes

➢ A Great Divide in star formation astrophysics: High-mass (>8 $M_\odot$) versus low-mass ($\leq 2 M_\odot$)

➢ The M17 SWex giant molecular cloud complex: A laboratory for intermediate-mass star formation

➢ Circumstellar disc lifetimes & building the stellar initial mass function (IMF)

Coda: GLIMPSE meets its best match, UKIDSS
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Formation of a low-mass star in isolation:
An evolutionary sequence
Infrared Spectral Energy Distribution (SED) Fitting Analysis

- O-type star: No IR excess emission
- Young Stellar Object (YSO): Stage 0/I, strong IR excess

A low-mass star like the Sun...
Massive SF Model I: Disk accretion

• Massive cores form massive stars; scaled-up analog of the low-mass case.

• Gravitational and Rayleigh-Taylor instabilities in 3D model enable accretion in spite of feedback.

• Predicts formation of massive binary companions plus multiple low-mass companions from disk fragmentation.

Krumholz et al. (2009)
Massive SF Model II: Competitive accretion and mergers

- Massive clusters form massive stars; no correlation between initial core mass and final stellar mass.
- High frequency of massive binaries and multiples. Mergers form the highest-mass stars.
- Massive star formation cannot be modeled separately from the full cluster environment.

Bonnell, Vine & Bate (2004)
Bonnell & Bate (2005)
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Discovery of an extended (85 pc) molecular cloud associated with the M17 star-forming complex

Bruce G. Elmegreen and Charles J. Lada
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(Received 16 August 1976)

We extend observations of Lada (1976) and report the discovery of a very large (85 pc × 22 pc), massive (∼10⁶ M☉) molecular cloud extended parallel to the galactic plane southwest of M17. CO observations indicate that the cloud contains isolated fragments of enhanced temperature. Since these fragments appear to represent the continuation of an evolutionary sequence described by OB stars northeast of the cloud, we suggest that an extended OB association will eventually form here. We then consider the implications of these observations for several current theories of star formation.

These observations of the “M17 SWex” molecular cloud, along with similar maps of the Orion and W3 complexes, motivated the sequential triggered star formation model of Elmegreen & Lada (1977).
Fig. 1. Contours of peak $^{12}$CO emission near 20 km/sec toward M17. Contours are drawn in intervals of 5 K beginning at 5 K. The contour is a solid line wherever the data were sampled at single- or half-beam intervals while dashed lines are estimated contours where double-beam sampling was made. The four fragments are referenced in the text by letters A–D in order from NE to SW.
IRAS All-Sky Survey, 1983
MSX Galactic Plane Survey, 2000
Red MSX Source Catalog
Mottram et al. (2011a)

MSX Galactic Plane Survey, 2000
Spitzer GLIMPSE and MIPSGAL Surveys: 2003–2007
Spitzer GLIMPSE and MIPSGAL Surveys: 2003–2007

Povich & Whitney (2010)
3 massive YSOs from the RMS catalog
Intermediate-mass YSOs in M17 SWex

488 candidate YSOs:
- 133 Stage 0/I
- 276 Stage II
- 4 Stage III
- 75 with ambiguous classifications

Includes 68 YSOs with excess 4.5 µm emission — outflows?

Povich & Whitney (2010)
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The YSO Mass Function (YMF)

Stellar initial mass function (IMF):
\[ \Phi(\log m) = \frac{dN}{d \log m} \propto m^{-\Gamma} \]

Disc evolution biases YMF. Assuming constant star formation rate:
\[ f_{\text{disc}}(m) \propto t_{\text{disc}}(m) \propto m^{-\delta}; \Gamma_{\text{YMF}} - \Gamma_{\text{IMF}} = \delta \]
The intermediate-mass YMF as a diagnostic tool

- Relates low- and high-mass YSO evolutionary timescales through the underlying IMF
  - “Canonical” low-mass (T Tauri) disc lifetimes are ~3 Myr (e.g. Haisch et al. 2001)
  - Massive YSOs may or may not have stable discs; timescale for embedded phase <1 Myr (e.g. Mottram et al. 2011)

- Challenges
  - Relevant timescales are highly uncertain.
  - Current survey observations do not fully sample YMF.
  - Birth of massive YSOs may be asynchronous with low-mass YSOs in same cloud.
  - Accreting YSOs have not yet reached final mass.
  - Timescales are very sensitive to power-law slopes, but the YMF is difficult to measure accurately, and the intermediate-mass IMF may be uncertain.
The Great Nebula in Carina

1439 YSOs, 410 matched to X-ray sources (+)
- Stage 0/I
- Stage II
- Stage III
- Stage Ambiguous

Contours: CO molecular clouds
Circles: C$^{18}$O dense cloud cores

Povich et al. (2011b)
YSO Mass Function – Carina

1439 YSOs detected, complete to \(~3.1 \, M_\odot\) (~3x M17 SWex)

>20,000 YSOs predicted, with TOTAL mass >16,000 \(M_\odot\), extrapolated to 0.1 \(M_\odot\) (~2x M17 SWex)

\(\Gamma_{\text{YMF}} = 3.2 \pm 0.3\)

\(\Gamma_{\text{IMF}} = 1.3 \pm 0.2\)

Povich et al. (2011b)
Is the intermediate-mass IMF actually Salpeter's?

Figure 2
A representation of the "alpha plot" by Scalo (1998) and Kroupa (2002). We show the derived index, $\Gamma_1$, of the initial mass function (IMF) in clusters, nearby star-forming regions, associations, and the field as a function of sampled stellar mass (points are placed in the center of the log $m$ range used to derive each index, with the dashed lines indicating the full range of masses sampled). The data points are from studies discussed in the text and are not meant to be a complete review of the field. Additionally, we have added a sample of clusters compiled by Kroupa (2002). Open circles denote studies where no errors on the derived $\Gamma_1$ are given, whereas filled circles are accompanied with the corresponding error estimate (shown as solid vertical lines). The observed scatter in the $\Gamma_1$ measurements presented here is likely to be larger than in the literature as a whole, as "outliers" are emphasized in this review. The colored solid lines represent three analytical IMFs: Shown in green is the Chabrier (2003) IMF (dashed line indicates extrapolation into the substellar regime), with a Salpeter (1955) IMF in light blue, and a Kroupa (2002) IMF in orange (which is essentially Salpeter above 1 $M_\odot$).

As well as the mass of a given stellar population. Specific observations (e.g., B-band luminosity, near-IR color, etc.) often preferentially sample a given stellar mass range. For all but the most massive stars, multiple epochs of star formation contribute to each mass range. Hence, a detailed knowledge of the SFH (and metallicity) of the population is needed if one wants to constrain the underlying IMF. These degeneracies between SFH, metallicity, and the IMF, are even more important for unresolved systems and are highlighted throughout this review.

If the IMF varies systematically with environment or metallicity (both of which could depend on cosmic look-back time), then it is possible, even likely, that the inferred SFHs, stellar masses, and, hence, stellar mass-density estimates would be systematically in error. This could strongly bias our understanding of many important topics, from chemical evolution to how galaxies are formed. One important quantity often measured for local and high-redshift galaxies is their present SFRs. By constraining the amount of ionizing radiation emitted by a galaxy (traced by UV, $H_\alpha$, or other...)

Bastian, Covey & Meyer (2010) ARA&A
Competitive accretion model of cluster formation – A mid-heavy IMF in extended, low-density regions?

This model is broadly consistent with the observed YSO spatial distribution and YMF in M17 (possibly also in Carina).
Summary – Principal Themes

✧ Spitzer has revealed intermediate-mass star formation in Galactic giant molecular clouds at ~2 kpc distances.

✧ Intermediate-mass YSOs bridge the gap between studies of low- and high-mass star formation.

✧ Ensemble properties of YSOs in rich star-forming regions (e.g. YMF and spatial distribution) provide new avenues for constraining YSO evolutionary timescales and models of massive star formation.
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Coda: GLIMPSE meets its best match, UKIDSS
2010: 488 YSOs, 2MASS+GLIMPSE
2011: 836 YSOs, includes UKIDSS

Including UKIDSS JHKs photometry increases sample size by ~70%!
110 YSOs not rediscovered in UKIDSS DR4 catalog!

My student, Wesley Orbin, has been re-analysing M17 SWex using a combined GLIMPSE and UKIDSS (DR4 GPS) catalog.
Circles: YSOs in initial UKIDSS/GLIMPSE sample

Squares: original Povich & Whitney YSOs (Stages 0/I, II, Amb.)
Summary – Coda

- 2MASS lacked the depth to detect YSOs in highly-obscured regions. UKIDSS sensitivity is a better match to GLIMPSE.
- Including UKIDSS photometry expands the sample size and may enable us to push the YMF analysis to lower masses.