X-RAYS AND YOUNG CLUSTERS

Membership, IMFs and distances

Feigelson E. D. and Getman K. V.
Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA
edf@astro.psu.edu, gkosta@astro.psu.edu

Abstract

Sensitive imaging X-ray observations of young stellar clusters (YSCs, ages ≤ 10 Myr) are valuable tools for the acquisition of an unbiased census of cluster members needed for Initial Mass Function (IMF) studies. Several dozen YSCs, both nearby and across the Galactic disk, have been observed with the Chandra and XMM-Newton satellites, detecting > 10,000 low-mass cluster members. Many of these samples should be nearly complete down to ≃ 1 M☉. An important additional benefit is that the YSC X-ray luminosity function appears to be universal with a lognormal shape, providing a new standard candle for measurement of YSC distances.

1. Measuring IMFs in young stellar clusters

Measuring the stellar Initial Mass Function (IMF) requires complete and unbiased samples which are often sought in young stellar clusters (YSCs) that have not undergone significant dynamical evolution. We consider here YSCs with ages ≤ 10 Myr where most of the lower mass stars are on the convective Hayashi pre-main sequence (PMS) evolutionary tracks.

A major difficulty in obtaining a reliable census of YSCs is that the few lying at distances d < 400 pc are spatially extended and not strongly concentrated. The richest is the Sco-Cen OB Association with several thousand members, but it subtends several thousand square degrees in the southern sky. Others like the Corona Australis, Perseus or Chamaeleon clouds have dozens of members and typically subtend ≥ 1 square degree. Individual Taurus-Auriga clouds or Bok globules may be smaller, but their stellar populations are too poor for IMF studies.
These large angular sizes require that cluster members of nearby clouds must be efficiently discriminated from the large, often overwhelming, number of unrelated foreground and background stars. This discrimination is traditionally achieved using surveys for stars with Hα emission and/or near-infrared photometric excesses. These methods efficiently select protostars and ‘classical T Tauri’ (CTT) stars, but often undersample the large ‘weak-lined T Tauri’ (WTT) population (Feigelson & Montmerle 1999). As the mass-dependency of disk evolution is not well known, correction to the full PMS population for IMF study is uncertain. Analysis of the K-band star counts towards YSCs can give a more complete census but in an indirect fashion (Lada & Lada 1995). It often requires major corrections for unrelated stars and, as individual members are not individually identified, the IMF is derived by a model-dependent conversion of the K-band distributions to mass distributions.

IMF studies may be advantageous in more distant YSCs, but here additional problems present themselves. The members are fainter than in closer clusters, so that large telescopes with low-noise detectors become necessary to detect the lowest mass cluster members. As distance increases, it becomes increasingly difficult to resolve multiple systems. Both observational and theoretical studies suggest that most stars form in binary or multiple systems. A complete census is also hindered by the wide range of extinctions often exhibited by YSC members.

In light of these constraints, one YSC has unique merits for IMF studies: the Orion Nebula Cluster (ONC). The ONC lies at \( d \approx 450 \) pc, sufficiently close that the best available near-infrared instrumentation can detect objects down to a few Jupiter masses. With \( \approx 2000 \) members concentrated in \( \approx 0.1 \) square degrees, it is easily studied and rich enough to populate the IMF up to \( \sim 45 \) M\(_{\odot}\). Unlike other YSCs in the Orion molecular cloud complex, it lies on the near side of the cloud and has evacuated most of the intervening molecular material, so line-of-sight absorptions are low. While the ONC census suffers some difficulties — mild contamination from unrelated young stars in the background cloud and from foreground dispersed young clusters, incomplete enumeration of multiple systems — it provides a standard for stellar IMF studies that is far above that achieved for other YSCs.

2. The role of X-ray surveys

X-ray emission from PMS was initially predicted from shocks associated with their stellar wind, but studies with the Einstein and ROSAT observatories indicated an origin more closely associated with solar-like
magnetic activity (Feigelson & Montmerle 1999). The emission is 1 − 4 orders of magnitude stronger than typical main sequence levels, exhibits high-amplitude flares and hotter plasmas than expected from wind shocks, and is mostly uncorrelated with the presence or absence of an infrared-excess disk. X-ray surveys discovered many WTTs whose population is comparable to the CTT population even in YSCs associated with active star forming clouds. Although useful, surveys with these early satellites were limited by detector technology: low-resolution gas proportional counters or low-efficiency solid state microchannel plates.

The Chandra X-ray Observatory and XMM-Newton missions are much better adapted to YSC studies with their high-efficiency low-noise CCD detectors. Chandra is particularly useful with its high-precision mirrors giving arcsecond imaging capability, though its field of view is limited to 0.08 square degrees. Together, these telescopes have imaged several dozen YSC populations across the Galactic disk. These include the ρ Ophiuchi, Chamaeleon, CrA, Mon R2, L1551, L1448, Serpens, Cep B and Sgr B2 clouds; populations associated with the Orion, Trifid, Rosette and Carina HII regions; the Cyg OB2 association, η Cha cluster, and various isolated Herbig Ae/Be stars with their companions; star forming regions NGC 1333, IC 348, M 8, M 16, M 17, NGC 281, NGC 1579, NGC 2078, NGC 2024, NGC 2264, IC 1396, RCW 38, RCW 49, RCW 108, NGC 6334, NGC 6530, NGC 6383, NGC 3603, W 3, W 1, W 49, W 51, and IRAS 19410+2336; several Galactic Center YSCs; and 30 Dor in the Large Magellanic Cloud. The most comprehensive study underway is the Chandra Orion Ultradeep Project (COUP) based on a nearly-continuous 10-day pointing towards the ONC and embedded sources in OMC-1. An introduction to COUP, and references for the other regions published through mid-2003, are given in Feigelson (2003a). Figure 1 shows a portion of the COUP image, and some preliminary COUP results are presented here.

X-ray surveys are subject to selection effects which must be carefully considered in the effort to achieve a well-defined YSC census. Most importantly, PMS X-ray luminosities are strongly correlated with a tangle of interrelated stellar properties: bolometric luminosity, mass, stellar surface area and volume. The $L_x - L_{bol}$ correlation has been known for many years, but the linkage with other variables only emerged clearly in pre-COUP studies of the ONC (Flaccomio et al. 2003a; Feigelson et al. 2003b). Though quantitative analysis of the scatter in these relations by the COUP has not yet been completed, we can roughly say that a Chandra observation of a nearby YSC with limiting sensitivity $\log L_x(\lim) \simeq 28.0$ erg/s (0.5 − 8 keV band) will detect > 90% of PMS stars with masses $M > 0.2 \ M_\odot$, and an observation of a more distant
Figure 1. The central $4' \times 4'$ region of the $17' \times 17'$ Chandra ACIS image of the Orion Nebula Cluster, obtained in a $\simeq 10$-day exposure in early 2003 (Getman et al. 2004). Moderate-resolution spectra over the $0.5-8$ keV band, giving an independent measure of line-of-sight absorption, and temporal information on variability are available for each of the 1616 COUP sources. This dataset is the foundation of a wide range of studies comprising the Chandra Orion Ultradeep Project (COUP).

YSC with $\log L_x(\text{lim}) \simeq 29.5$ erg/s will detect $> 90\%$ of PMS stars with $M > 0.8$ $M_\odot$ (Preibisch et al., in preparation).\(^1\)

This result immediately indicates the power of Chandra studies for improving our knowledge of stellar populations in a wide variety of YSCs, and thus studying the IMF in a wide variety of conditions. In most YSCs beyond $d \simeq 1$ kpc, cluster membership is currently limited to a small number of bright spectroscopically-confirmed OB stars and lower mass stars with $K$-band excesses. Consider, for example, the cluster illuminating the HII region M 17 and its the surrounding molecular cloud.

---

\(^1\)A second second selection effect in PMS X-ray luminosities must be considered: the sub-population of CTT stars tends to be a factor of $2-3$ weaker the subpopulation of WTT stars leading to, opposite to traditional methods, a selection bias against accreting stars (Flaccomio et al. 2003b). But this effect is relatively small compared to the 4 orders of magnitude range in PMS X-ray luminosities.
Only a few dozen have optical spectra and while >20,000 have $JHK$ measurements, most of these stars are unrelated to the cloud (Hanson et al. 1997; Jiang et al. 2002). A Chandra image with log $L_x(\text{lim}) = 29.7$ erg/s shows 877 sources nearly all of which are cluster members (Getman et al., in preparation). Such X-ray selected samples should be > 90% complete above a well-defined mass limit, usually around $0.5 - 1.5 \, \text{M}_\odot$ for the more distant YSCs under study.

Analysis of these fields is difficult with hundreds of faint X-ray stars often embedded in structured diffuse emission from large-scale OB wind shocks (Townsley et al. 2003). But sophisticated data analysis methods have been developed (Getman et al. 2004), careful studies are underway and within a few years > 10,000 Chandra-discovered YSCs members should be published. Followup optical/near-infrared photometry and spectroscopy will be needed to place these stars on the HR diagram to estimate masses for IMF analysis. Chandra should thus provide an important boost to comparative IMF studies for many of the YSC clusters listed above.

We caution that it is still unclear whether even the most sensitive X-ray surveys can efficiently detect substellar PMS objects which will evolve into L- and T-type brown dwarfs. Two YSC studies with sensitivities of log $L_x(\text{lim}) \simeq 27.0$ erg/s performed to date give inconsistent results. A deep Chandra image of the Chamaeleon I North cloud found all 27 known cloud members including 3 probable substellar objects (Feigelson & Lawson 2004). This suggests the X-ray census is complete and gives an IMF deficient in stars with $M < 0.3 \, \text{M}_\odot$ compared to the ONC or field star IMFs. But this may be due to mass segregation favoring higher mass stars in the small 0.6 pc$^2$ region covered by the Chandra imager, rather than intrinsically different IMF. The second study with log $L_x(\text{lim}) \simeq 27.0$ erg/s is the COUP observation of the ONC. Here, most of the spectroscopically confirmed brown dwarfs (Slesnick et al. 2004) are not detected, indicating that X-ray surveys will probably be incomplete in this low mass regime.

3. **A new distance estimator for YSCs**

Techniques for measuring distances to YSCs and their natal molecular clouds have hardly changed in a half-century. When a OB population can be studied spectroscopically and individual stellar absorptions are found, then main sequence fitting provides a reliable distance. But when they are too obscured or unavailable, then distance estimation methods are varied, unreliable and inconsistent. Consider, for example, the YSC surrounding the Herbig AeBe star LkHα 101, one of the brightest in-
The X-ray luminosity function (XLF) of YSCs has two remarkable empirical characteristics that should render it an effective and accurate distance estimator for clusters such as this. First, the shapes of different YSC XLFs appear to be remarkably similar to each other, once a richness-linked tail of high luminosity O stars is omitted (Figure 2). Second, the shape of this ‘universal’ XLF strongly resembles a lognormal with mean $< \log L_x > \simeq 29.5$ erg/s (0.5 – 8 keV band) and standard deviation $\sigma(\log L_x) \simeq 0.9$ (Figure 3).

While we do not have astrophysical explanations for either of these YSC XLF properties, the shape of the XLF can be roughly understood as a convolution of the IMF which breaks from the Salpeter powerlaw below $\simeq 0.5 M_\odot$ (and itself is sometimes modeled with a lognormal curve) and the correlation between $L_x$ and mass. These two effects result in a steep falloff in the number of fainter X-ray stars in a YSC. This was dramatically demonstrated in the Chandra studies of the ONC where a factor of 10 increase in limiting sensitivity from $\log L_x(\text{lim}) \simeq 28.0$ erg/s in the early observations to $\simeq 27.0$ erg/s in the deep COUP observation led to only a very small rise in detected lightly absorbed ONC stars.

Figure 2. The universal cluster X-ray luminosity function (XLF) found in Chandra YSC studies. NGC 1333 (77 stars from Getman et al. 2002), IC 348 (168 stars from Preibisch & Zinnecker 2002), and the ONC (1508 stars from COUP data truncated at $\log L_x = 31.5$ erg/s, Getman et al. 2004).

Infrared sources in the sky, which illuminates the nebula NGC 1579. The cluster distance has variously been estimated to be 140 pc, $>800$ pc, $\simeq 340$ pc, and $\simeq 700$ pc (Tuthill et al. 2002, Herbig et al. 2004). If it lies at the nearer end of this range, it is one of the closest YSCs.
Figure 3. The Orion Nebula Cluster (ONC) XLF with lognormal fit given in the text. COUP sample of 1528 sources with absorption corrected 0.5-8 keV luminosities (Getman et al. 2004). All X-ray luminosities are in the 0.5–8 keV band corrected for absorption measured from the X-ray spectrum.

The peak of the XLF at $<\log L_x> \simeq 29.5$ erg/s can be used as a standard candle for distance estimation, much as the lognormal distribution of globular cluster optical luminosities is used as an extragalactic distance estimator (Harris 1991). One counts cluster members in flux units (this is the X-ray log $N$ – log $S$ curve), matches the observed log $N$ – log $S$ to the universal XLF, and reads off the distance from the offset. The table below gives a simple example for a hypothetical cluster at various assumed distances observed with Chandra for 100 ks. The tabulated values are the fraction of sources seen in broad count rate bins assuming typical PMS X-ray spectra and negligible absorption.

### Table 1. Simulated X-ray source counts for young stellar clusters

| log $L_x$(lim) (erg/s) | 28.0 | 28.5 | 29.0 | 29.5 | 30.0 |
|------------------------|------|------|------|------|------|
| Distance (pc)  | 400 | 710 | 1270 | 2250 | 4000 |
| Flux bin (cts) | 500 | 5000 | 5000 | 5000 | 5000 |
| Percent of sources | 500 | 5000 | 5000 | 5000 | 5000 |
| 5 – 50 | 22 | 46 | 60 | 76 | 86 |
| 50 – 500 | 46 | 42 | 34 | 22 | 14 |
| 500 – 5000 | 28 | 12 | 6 | 2 | 0 |
| 5000 – 50000 | 4 | 0 | 0 | 0 | 0 |

The table shows that the observed log $N$ – log $S$ shape will differ dramatically for YSCs at different distances. For close distances or unusually long exposures (as in COUP), most cluster members are quite
bright and few faint ones are seen. For far distances or short exposures, most cluster members are near the detection limit which is $3 - 10$ photons for typical Chandra fields. The principal challenges are corrections for absorption, which can be derived (except for the faintest sources) for individual sources from the X-ray spectrum, and the elimination of extragalactic background sources, which can be achieved by the absence of a stellar counterpart in sensitive $K$-band images. Accurate distances and error analysis would not be performed in broad flux bins as in the table above, but would be based on unbinned sources fluxes using a maximum likelihood method as described by Hanes & Whittaker (1987) and Cohen (1991).

Acknowledgements: We thank Thomas Preibisch (MPIfR) for use of unpublished COUP results. This work was supported by NASA contract NAS8-38252 (Garmire, PI) and COUP grant SAO GO3-4009A (Feigelson, PI).

References
Cohen, A. C. 1991, Truncated and censored samples: theory and applications. New York: M. Dekker
Feigelson, E. D. & Montmerle, T. 1999, ARAA, 37, 363
Feigelson, E. 2003, in Stars as Suns: Activity, Evolution and Planets, IAU Symposium 219, 27
Feigelson, E. D., Gaffney, J. A., Garmire, G., Hillenbrand, L. A., & Townsley, L. 2003, ApJ, 584, 911
Feigelson, E. D. & Lawson, W. A. 2004, ApJ, in press, (astro-ph/0406529)
Flaccomio, E., Damiani, F., Micela, G., Sciortino, S., Harnden, F. R., Murray, S. S., & Wolk, S. J. 2003, ApJ, 582, 398
Flaccomio, E., Micela, G., & Sciortino, S. 2003, A&A, 397, 611
Getman, K. V., Feigelson, E. D., Townsley, L., Bally, J., Lada, C. J., & Reipurth, B. 2002, ApJ, 575, 354
Getman, K. V. and 23 coauthors, 2004, ApJS, accepted
Hanes, D. A. & Whittaker, D. G. 1987, AJ, 94, 906
Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, ApJ, 489, 698
Harris, W. E. 1991, ARA&A, 29, 543
Herbig, G. H., Andrews, S. M., & Dahm, S. E. 2004, AJ, 128, 1233
Jiang, Z., et al. 2002, ApJ, 577, 245
Lada, E. A. & Lada, C. J. 1995, ApJ, 109, 1682
Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, ApJ, 610, 1045
Townsley, L. K., Feigelson, E. D., Montmerle, T., Broos, P. S., Chu, Y., & Garmire, G. P. 2003, ApJ, 593, 874
Tuthill, P. G., Monnier, J. D., Danchi, W. C., Hale, D. D. S., & Townes, C. H. 2002, ApJ, 577, 826