X-ray insights into the formation of stellar clusters

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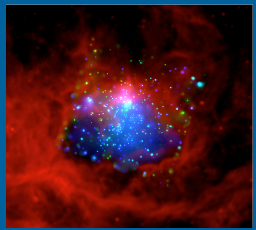
Introduction: X-rays and young stellar clusters

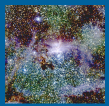
Embedded, high-mass star and cluster formation are usually studied in mm/IR/optical bands where the OB member and Class 0-I-II YSOs are readily found. But disk-free Class III pre-main sequence (PMS) stars, that often dominate the stellar population of young stellar clusters (YSCs), are difficult to study in the IR due to bright nebular emission and bad (factors of 10-100) contamination by older field stars.

X-ray images from the Chandra X-ray Observatory, however, are very effective in detecting large PMS populations with little contamination. Chandra detects nearly-complete PMS populations down to a typical mass limit of 0.5-1 Mo, when obscuration is low (A_V<10). Chandra can penetrate to A_V>100 with reduced sensitivity. A Chandra image of a rich stellar cluster at d~1-3 kpc will typically locate hundreds, and sometimes thousands, of YSO/PMS stars with subarcsecond positions. The X-ray samples are typically dominated by Class III systems, although many Class I-II are also seen, complementing IR-excess samples.

Illustration of X-ray capabilities



Chandra image (blue) on an MSX image (red) of the Pis 24 cluster illuminating the NGC 6357 HII regions. This cluster is dominated by five O3 stars; Chandra finds ~800 PMS members, previously unstudied.



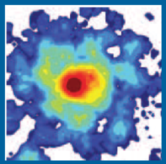
The 2MASS image of the same region (right) shows why it is hard to isolate the cluster population in IR bands.

What X-rays tell us about star formation in rich cluster environments

- Cluster morphologies of rich (N>1000 stars) clusters often resemble the Orion Nebula Cluster (ONC): centrally concentrated with mass segregation. But a few have substructure and no mass segregation.
- YSC stellar Initial Mass Functions often resemble the ONC, but others may show a mid-mass (M~1 Mo) excess.
- Triggered star formation on the peripheries of HII regions is common, and sometimes shows a spatial-age gradient. Triggering may generate a significant fraction of a cloud's stars.
- Star formation has often proceeded for millions of years around YSCs.
- In one YSC, W3 Main, the centrally concentrated OB stars formed ***after*** the broader distribution of PMS stars.
- Interactions between OB winds and molecular clouds are now directly imaged.

A few of the the results are shown below. The Penn State group has published ~16 papers on ~11 clusters since 2006, and other groups are active. A major collaboration has completed 22 papers on the calibrator Orion Nebula Cluster, a new collaboration is working on a Chandra survey of the Carina Nebula complex, and a comparison of ~20 other YSCs is in progress.

Delayed OB formation in W3 Main

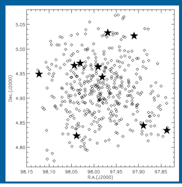


The large-scale (5 pc) structure of the embedded W3 Main cluster is shown in this smoothed source density map (spanning a range of ~10^3) derived from ~900 Chandra PMS stars. Almost all are Class III without mid-IR disks (age ~10^6 yr).

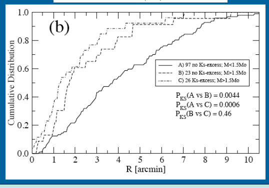
But the inner 1 pc has extremely young OB stars producing radio hyper/Ultra-Compact HII regions (age ~10^4-10^5 yr) seen in this VLA map.

W3 Main is thus a clear case of ***delayed*** OB formation in a cluster core.

Mass segregation

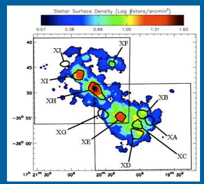


Rosette's central NGC 2244 cluster shows no mass segregation (map with OB = asterisks, X-ray PMS=circles). One off-center O5 star has a subcluster of ~50 PMS stars, while the other off-center O5 star is completely isolated.

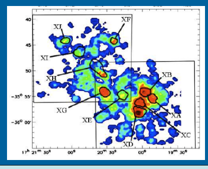


The nearby (d~600 pc) obscured W40 cluster shows clear mass segregation for intermediate-mass stars as low as 1.5 Mo compared to lower mass PMS stars.

Wide age spread in the NGC 6334 complex

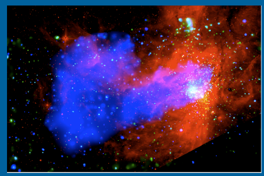


These smoothed maps show the surface density of 1607 Chandra PMS stars over a ~10 pc region of this multi-cluster complex. The top map shows several obscured clusters with A_V>10 (from soft X-ray absorption) previously known from IR maps.



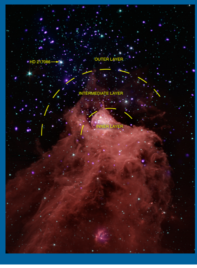
The bottom map shows several clusters of lightly obscured (A_V<10) X-ray stars which were not previously known. This implies that the complex has produced clusters for a considerable time.

The dragons breath in M 17



X-ray panorama of 15 pc in the M 17 complex showing >2000 PMS stars (white), shocked OB winds (blue) collimated by the molecular cloud (red, Spitzer 5.8μm).

Triggering in Cep B



Chandra+Spitzer study image shows ~600 PMS stars in the Cep B cloud and surrounding Cep OB3b cluster. A spatial gradient of disk fraction, from 75% in the cloud core to 25% in the unobscured cluster, demonstrates a long-lived triggering process.

Discussions with Penn State colleagues (Leisa Townsley, Kosta Getman, Pat Broos, Mike Kuhn and Junfeng Wang) is greatly appreciated. References (in ApJ): NGC 6357 (Wang, Townsley, Feigelson et al. 2007), M 17 (Broos, Townsley et al. 2007); W3 (Feigelson & Townsley 2008); NGC 6334 (Feigelson et al. 2008), Rosette (Wang, Feigelson, Townsley et al. 2008-9-10); Cep B (Getman, Feigelson et al. 2006/10); W40 (Kuhn, Getman et al. 2010). Leisa Townsley provided the multiband images of NGC 6357 and M17, and the VLA map of W3 is from Tieftrunk et al. (1997). Work supported by Chandra ACIS Team SV-74018, NSF AST-0809038, and NASA NNX09AC74G.