Finding High Quality Young Star Candidates in Ceph C Using X-ray, Optical and IR Data

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Abstract

This study looked for new candidate young stellar objects (YSOs) within the star forming region of Ceph-C in Ceph OB3. This region was monitored in the infrared (IR) by the YSOVAR project (Rebull et al. 2014) as part of their effort to explore YSO variability. Our search included data in the X-ray, optical, and IR from many places: Chandra, SDSS, IPHAS, 2MASS, Spitzer IRAC and MIPS, and WISE. In this region, the YSOVAR team had identified ~300 YSO candidates from IR excesses, X-rays, and variability. Few other investigations have been carried out in this region to date, so there is limited information about YSOs in this region. We inspected each source in all available images to (a) eliminate artifacts; (b) ensure detections and limits were correct; (c) ensure proper source matching across bands. We constructed spectral energy distributions (SEDs) for each candidate YSO to check on source matching across wavelengths and determine whether the SEDs resembled those of known YSOs or contaminants. We constructed color-color and color-magnitude diagrams and used these in conjunction with images and SEDs to refine our list of candidate YSOs. Our work has identified ~250 likely YSOs. The YSOVAR project will investigate the variability properties of this refined list of YSOs.

Spectral Energy Distributions (SEDs)

+=SDSS u;+=SDSS; △=IPHAS Hα; △=IPHAS r, i; ◇ = 2MASS; ☆=WISE; ○ = IRAC, YSOVAR mean; ○ = IRAC, Cryo-era; ○ = IRAC, GLIMPSE; □ = MIPS; ↓ =limit; - - - = slope; – = Rayleigh-Jeans line to guide the eye, extended from K; vertical lines=error bars.

Ceph C (23:05:51 +62:30:55)

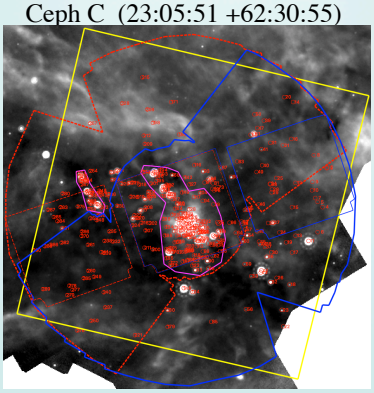

Fig. 1: ↑ MIPS 24 μm background image of region showing X-ray footprint from Chandra (yellow), IRAC-1 (blue) and IRAC-2 (red, dotted) footprints from the YSOVAR time series. A single epoch (pair of boxes) is shown in addition to the coverage of the entire campaign (fanned-out region). Magenta polygons are regions of the brightest nebulosity and densest population of MIR-bright objects ("guilt by association"). Image is approx. 0.35 degrees on a side.

Process

Ceph-C is in the Galactic Plane, so it has been observed serendipitously several times, but there has been little work on identifying specific YSOs in this area. We compiled existing archival data from Spitzer (YSOVAR, GLIMPSE, and cryo-era), WISE, IPHAS, & SDSS. From 27,000+ sources, we obtained 291 YSO candidates through a combination of: a multi-color IR color selection (Gutermuth et al. 2008, 2009); X-ray detection and a star-like SED; variability during the YSOVAR campaign; significant variability between the YSOVAR campaign and cryo-era Spitzer observations; and strong Hα (from IPHAS). We performed an initial image review using POSS, SDSS, 2MASS, and WISE images, dropping any candidates that did not meet standards (e.g., not circular, artifact, mis-matched across bands). We created SEDs (see lower left) for each candidate source including all available data. The SEDs revealed more source mis-matches, missing bands, and detections that were not reliable, as well as SED shapes that are more unusual ("zigzags"). We classified the YSOs based on the SED slope between 2 and 25 μm. Using color-color and color-magnitude diagrams created from all bands (see below), we assessed the location of the candidate YSOs, dropping some as being likely background sources. We noticed regions where poorly populated SEDs were likely a result not of being faint background sources, but instead of being in the IR-bright region with extended emission (nebulosity) and bright sources. We determined that such candidates were likely to be YSOs as well based on position (YSOs are often clustered). We identified sources within the "guilt by association" region (magenta polygon in Figure 1) as likely YSOs, even if they have poorly-defined SEDs; these in particular have nothing but circumstantial (projected position) evidence for being young. The rest of our YSO candidates are likely to be YSOs, but they also need spectroscopy to confirm them as YSOs.

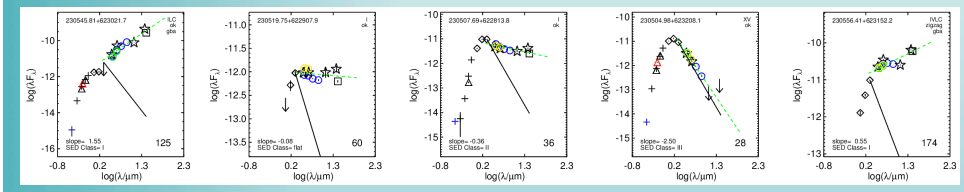

Figure 2: Class I SED showing significant IR excess

Figure 3: Class flat SED, showing a limit in J-band

Figure 4: Class II SED, showing falling slope

Figure 5: Class III SED showing limits in W3, W4

Figure 6: SED pattern we identified as 'zigzag'

Color-Color and Color-Magnitude Diagram Analysis

All sources for the region were plotted in color-color and color-magnitude diagrams. We used these to determine whether particular sources needed to eliminated on the basis that they were not in the right portions of these diagrams to be members of Ceph C (700 pc). These non-cluster members are likely to be either foreground/background stars, or background galaxies. In these plots, the sources in the "guilt by association" region generally have very large IR excesses. The YSO candidates well below the 10 Myr isochrone below are the fainter (likely reddened) "guilt by association" sources.

Using measurements from all available data, we constructed SEDs and compared the sources on individual images to check for quality and reliability of the source matching.

- Sources with data confusion, poorly populated SEDs, or obvious artifacts were dropped as candidates.
- Sources that did not appear in images (but had detections in catalogs) were changed to limits.
- Sources were classified based on slope of line fit to all data between 2 and 22 μm.
- We identified a group of sources that had a similar (and unusual) SED shape : 'zigzags.' These seven sources have slopes indicating Class I, but are not monotonically rising. Further inspection and study of images and relative location of these sources suggest they are young and deeply embedded.
- Some sources have unknown SED classifications due to missing data points (we only have one wavelength in the SED), but are in the "guilt by association" region. These sources require more study for classification, but may be legitimately young because of their proximity to the bright YSOs.

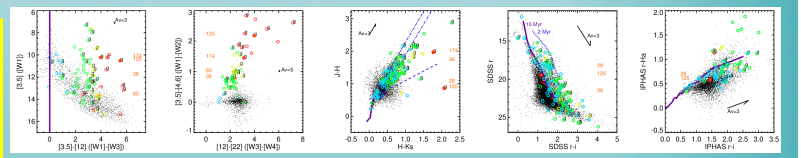

Figure 7: Color-color and color-magnitude diagrams for Ceph-C. Black points are all sources; additional circles: red=Class I, yellow=flat, green=Class II, blue=Class III. SED examples from Fig. 2-6 are highlighted in orange (and labeled on the far left or right of these figures). The sources additionally marked with a "g" are from the "guilt by association" region. Purple lines are the locations of main sequence (MS) stars (at the distance of Ceph-C where relevant). Reddening vectors are as shown (Av affects shorter wavelengths much more than longer wavelengths). In the JHK diagram, the dashed line is the CTTS locus, and the dash-dot lines denote the region in which reddened MS stars fall.

References
Gutermuth, R., et al., 2008, ApJ, 674, 336
Gutermuth, R., et al., 2009, ApJS, 184, 18
Rebull, L., et al., 2014, AJ, 148, 92

We gratefully acknowledge funding via NASA Astrophysics Data Program funds and NASA/IPAC Archive Outreach funds.

Classification Results and Distribution by SED class

27,000+ sources in region
291 selected for investigation
- 46 dropped (16%)

245 candidate YSOs:
- 33 class I (13%)
- 37 class flat (15%)
- 92 class II (38%)
- 76 class III (31%)
- 7 unknown (3%)

Future Work

- Spectroscopy of the YSO candidates would confirm or refute our identification of these stars as YSOs.
- Additional data from longer wavelength surveys (Hershel, SCUBA, etc.) may provide insight into the properties of the most highly embedded candidates in this region.
- The clustering of sources in this region could be further, formally studied to determine if there are sub-clusters within the Ceph-C cluster.
- The results of this survey will support the work of the greater YSOVAR study in its identification of high quality YSOs. Our list of YSOs, in conjunction with time series data (light curves), will lead to better understanding of young stellar and disk evolution, as well as stellar variability.
- Comparison of this region to the other YSOVAR clusters will allow a relative age and variability fraction to be established.