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

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1. Abstract

This study will be looking for new candidate young stars within the star forming region of Ceph OB3, more specifically in a region of this molecular cloud called Ceph C. Even though this region lies in the galactic plane and is included serendipitously in several large galactic plane surveys, Ceph C has not been well studied in the past, and few young stellar objects (YSOs) have been identified there. The YSOVAR team (Rebull et al. 2014) has time-series monitoring data of this region, and in order to understand the diversity of light curves, it is crucial to understand which objects in the field of view are likely YSOs, and which are foreground/background objects. The goal of our study is to identify candidate YSO sources as well as support the greater understanding of the variety, evolution, and variability of young stars. Our search for young stars will use X-ray, optical, and IR data from Chandra, SDSS, IPHAS, 2MASS, Spitzer (IRAC and MIPS), WISE, Herschel, and the literature (including SCUBA data), giving us a wavelength data range from 0.001 to 850 microns. We will merge the catalogs across all available wavelengths. We will make color-color and color magnitude diagrams for the objects in the region, and use IR colors, X-rays, and variability properties to identify candidate YSOs. We will inspect images (where possible) to ensure good matches across wavelengths and to identify (and remove) resolved galaxies. We will also construct spectral energy distribution diagrams (SEDs) for each candidate YSO in order to better assess whether or not the objects are likely reliable YSOs.

2.0 Science Introduction and Context

2.1 Star Formation

Stars form from clouds of interstellar gas and dust that have slowly coalesced with gravity and time. The inward gravitational collapse combined with the rotational angular momentum of the cloud form a cocoon and then a disk around the center mass. The heat generated from this gravitational collapse radiates outward, heating the surrounding dust cloud. The cloud then provides its own IR emission, in addition to that of the star. This excess IR emission causes the YSO spectral energy distribution (SED) to deviate from the standard blackbody emission spectrum, thus providing the IR excess that is characteristic of young stars. These young stars are also rotating fast, accreting high amounts of material, and have active chromospheres, resulting in complex magnetic fields and the emission of high energy X-rays. As protostellar evolution continues, this dust cloud continues to flatten out and the star becomes less embedded. The amount of IR excess measured decreases and the SED becomes more and more like a traditional blackbody spectrum.

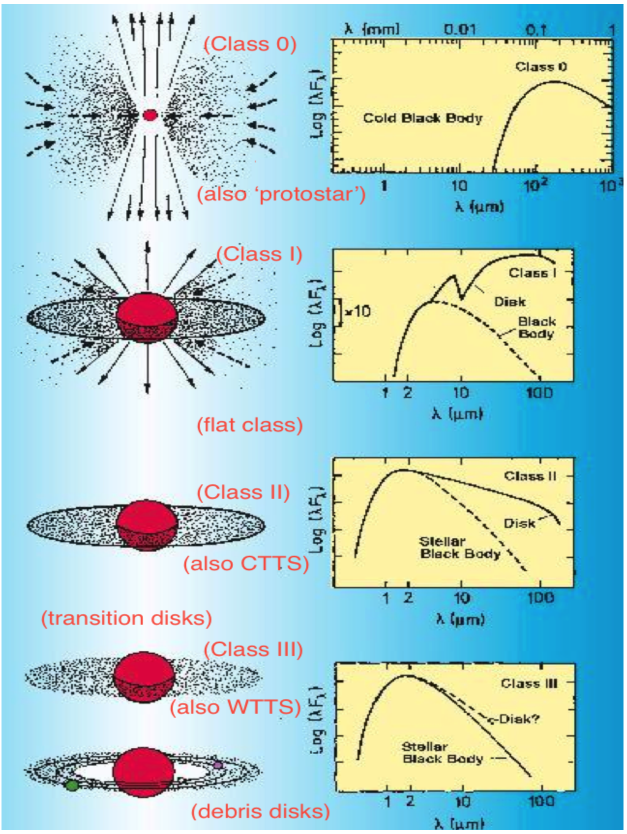

Figure 1: Low-mass star formation with SEDs. (Figure adapted from Bachiller 1996 and Andre & Montmerle 1994.) The illustrations on the left are cartoons of the stages. The plots on the right are illustrative SEDs, showing the IR excess above the stellar blackbody. Nomenclature in this field can be complicated, so a variety of names of stages is provided in the figure. The SEDs are Class 0 (also called protostar), Class I, Flat, Class II (also called classical TTauri stars, or CTTS), and Class III (also called weak-lined TTauri stars, or WTTS). Sometimes 'transition disk' is used to refer to the state between having a substantial disk and having a tenuous disk. The last, most tenuous disk can also be called a debris disk.

An SED is the net energy measured as a function of wavelength. For YSOs, the shape of the SED can be empirically evaluated to help determine the class of the young star (see, e.g., Wilking et al. 2001). Young star classes are interpreted as how embedded the young star is in its formation dust cloud. By comparing the observed SEDs, young stars can be classified and their relative age estimated in terms of the amounts of excess IR energy above the typical blackbody curve. The slope of SED curve in the near to mid IR region (2 - 25 μm) allows us to place the objects in SED classes: Class 0, I, Flat, II, and III (see Fig. 1). It is often assumed that the classification system roughly correlates to evolutionary sequence; Class 0 will transition to a Class 1 as their circumstellar disk is accreted, etc., until the YSO becomes visible in optical wavelengths and becomes a pre-main sequence star. The mapping between SED shape and age may not be so clear-cut (see, e.g., Robitaille et al. 2006, Dunham et al. 2010), but on average, it is thought that YSOs with steep, positive SED slopes are younger than YSOs with stellar (negative) SED slopes.

2.2 Science Background: Our Target

Molecular clouds are dense and compact regions throughout the Milky Way where gas and dust clump together, and it is in these cold regions that stars are born. The Cepheus molecular cloud (located generally in the constellation Cepheus) is a site of triggered star formation due to the interaction of the molecular cloud and the expanding HII region S155. This region, called Ceph OB3, contains individual sub-clouds within the greater cloud, referred to as Ceph A-F (identified and labeled by Sargent 1977). These regions are known areas of active star formation but not well observed from ground-based optical observatories or space based missions in the past. The first photometric study of the entire Cepheus molecular cloud was done by Blaauw et al. in 1964 and identified 40 early-type stars in the cloud at a distance of approximately 725 parsecs. Several other studies in the 1970's (also photometry based) refined the Blaauw list and expanded it to include fainter sources, though sources that are still bright by today's standards.

Figure 2: RGB image of Ceph C region taken from IRSA Finder Chart. Red: DSS2 IR, green: DSS2 Red, blue: DSS2 Blue. Center coordinates 23h05m51.00s +62d30m55.0s Equ J2000. Image size 1 deg x 1 deg.

Even with the availability of modern surveys in the galaxy plane and data analysis techniques, star formation in the region of Ceph C (Fig. 2) has not been well studied; it is the least well studied of all the Cepheus clusters. Hodapp (1994) was the first to discover the embedded cluster in Ceph C. This was a K-band imaging survey of many different molecular outflow sources. Ceph C was just one of many targets, and Hodapp (1994) simply noted that there was an IR-bright IR cluster in Ceph C. Young stars can also be bright in Hα; Mikami & Ogura (2001) identified Hα stars in the region but only one is in our region of interest (see below). Melikian et al. (2014) conducted another Hα survey of the Ceph OB3 region, but none of those targets are in the region we are considering here. Witham et al. (2008) looked for Hα-bright stars throughout the IPHAS survey (which includes this region) but they find only 1 more Hα-bright star in this region we are considering.

More recently, Ceph C was included as one of the star forming clusters studied by the Spitzer Space Telescope (Werner et al. 2004) as part of the Young Stellar Cluster survey (Megeath et al. 2004). This study's goals included understanding clustering in YSOs and was published in Gutermuth et al. (2009; hereafter G09). G09 completed a stellar clustering study that included Ceph C; they presented new automated color selection processes to identify and classify candidate sources comparing IR excess across IRAC data bands. From this, 114 YSO candidates were identified in the Ceph C cloud. DiFrancesco et al. (2008) included Ceph C in a SCUBA (Submillimetre Common-User Bolometer Array) survey, finding 16 sources at 450 and/or 850 μm. The Herschel Space Observatory telescope observed this region in the far infrared, but those data sets have not yet been published.

The YSOVAR project (Rebull et al. 2014, hereafter R14) included Ceph C as one of its targets. This project used Spitzer to monitor a dozen star-forming regions to study the variability properties of the young stars. Ceph C was selected for that study because it includes very embedded stars (objects that would be impossible to monitor from the ground due to their deeply embedded nature), and because it is at a high ecliptic latitude, allowing for a long, nearly continuous observing window (see discussion in R14). As part of that project, some preliminary analysis of the Ceph C light curves has been done, but it is far from complete. Because so little work has been done in this cluster to this point, the work we are proposing to do here as part of NITARP is critical for interpretation of the YSOVAR light curves. Variability characteristics are expected to be different for YSOs of different ages, but the environment may also play an important role. Detailed results obtained for the other YSOVAR clusters thus far (Guenther et al. 2014, Poppenhaeger et al. 2015, Wolk et al. 2015, and Rebull et al. 2015) suggest intriguing differences among the YSOVAR clusters. If we can obtain a list of high-reliability YSO candidates for Ceph C as part of this project, we can better interpret the light curves -- e.g., is this YSO likely to have a big disk, and therefore the light curve more likely to be a result of variations in the disk than in the star. With a well-defined list of YSO candidates, we can thus unlock many more of the secrets hidden in the Ceph C YSOVAR data.

Because young stars are also often bright in the X-rays, even if they don't have any disks left to create an IR excess, X-rays are very useful for identifying the YSOs in a region. The only prior use of X-ray data here is Carkner et al. (1998), using ROSAT data, and they detected nothing in this region. As part of the YSOVAR project, Chandra X-ray Telescope data of this region was also obtained, but has not yet been analyzed. Chandra data are far more sensitive than ROSAT data, enabling detections of YSOs. Because the YSOVAR data is our main motivation for looking for YSOs here, the region over which we will look for YSOs is also the region over which there are light curves; see Figure 3. Rather than trying to follow the complicated polygon of YSOVAR coverage, we will work with a square about 20 arcminutes on a side centered on 23:05:51 +62:30:55.

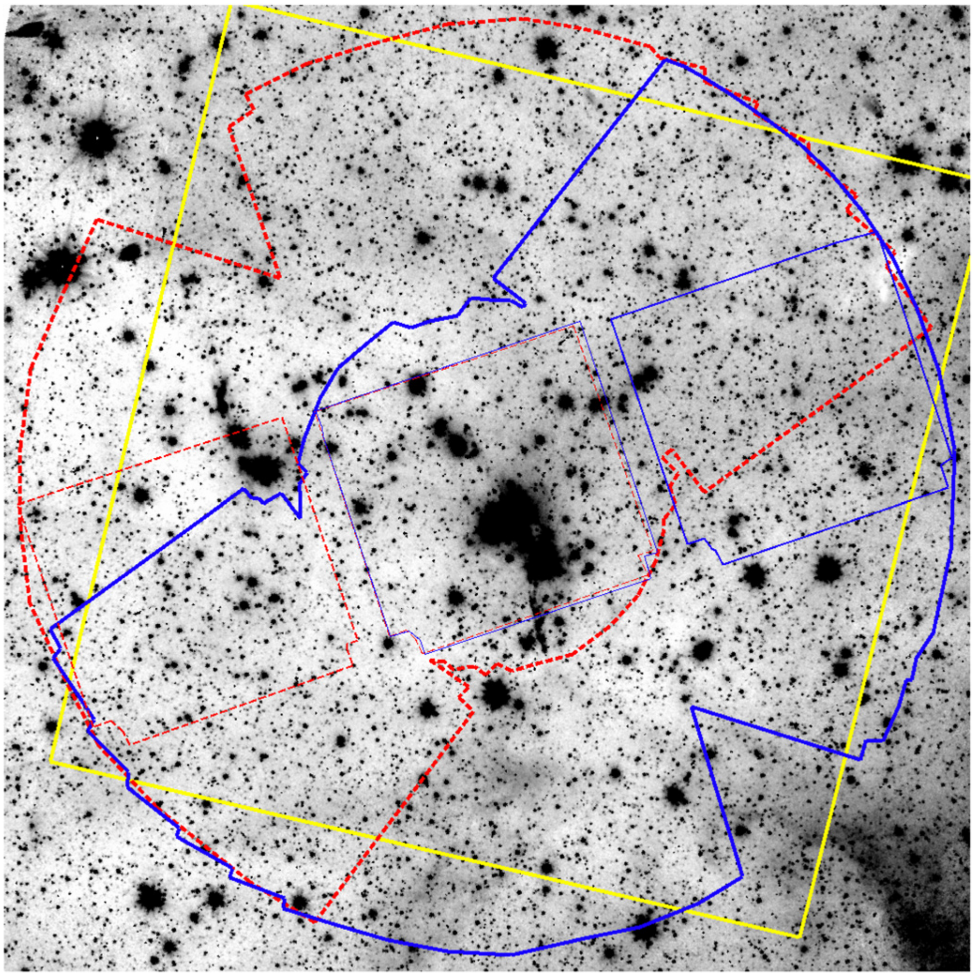

Figure 3: reproduced from R14, showing the approximate sky coverage for a summed-up image consisting of all epochs of YSOVAR Ceph C observations, superimposed on a reverse greyscale image of Ceph C at 4.5 μm obtained during the Spitzer cryogenic mission. The thicker blue solid line is 3.6 μm and the thicker red dashed line is 4.5 μm. A single epoch of observation is also indicated by thinner blue solid and red dashed lines, with the difference between the single epoch and the larger polygon due to substantial field rotation effects (due to the large ecliptic latitude of Ceph C; see R14 for more discussion). The yellow square is the approximate Chandra coverage. North is up and east is to the left; the center is 23:05:51 +62:30:55. The distance between the farthest north and farthest south coverage here is ~20 arcmin. We will be looking for YSOs over this entire region.

3.0 Analysis Plan

3.1 Overview

Our work will focus on using multi-wavelength data for sources in Ceph C, selecting YSO candidates from the IR, X-rays, and variability. For those YSOs, we will visually inspect and assess quality of images, creating comprehensive SEDs, and establishing a reliable list of likely YSOs in Ceph C. Our study will use data from several sources: SDSS in optical bands (*ugriz*; 0.29 to 0.9 μm), IPHAS in the optical (*riHα*; 0.6-0.8 μm), 2MASS in near IR (*JHKs*; 1.2 to 2.2 μm), Spitzer/IRAC in mid IR (3.6, 4.5, 5.8, and 8 μm), WISE in mid IR (3.4, 4.6, 12, and 22 μm), Spitzer/MIPS mid IR (24, 70, and 160 μm), and SCUBA data from the literature (450 and 850 μm). There is also unpublished Herschel data here; by eye in the quick-look images, there are several detected sources. We have been in contact with the NHSC who have agreed to provide us early access to their source lists for those data (70, 100, 160, 250, 300, 500 μm). We also have Chandra X-ray data from ACIS (~0.001 μm).

Since the underlying purpose of this work is to establish a reliable list of YSO candidates in the region where we have YSOVAR light curves, the boundaries of our study are set by this constraint. The YSOVAR region is centered on 23:05:51 +62:30:55. Including the serendipitously obtained ancillary data around the region (see Fig. 3), our study covers the region from 23:04:28.1 +62:21:25 to 23:07:13.4 +62:40:23, which is a box that is about 20 arcminutes on a side.

The analysis process will start with using the 2MASS, IRAC, and MIPS data to identify objects that have colors consistent with young stars following the multi-color approach in G09. The G09 approach uses 2MASS+IRAC+MIPS-24 to select YSO candidates based on a series of color-color and color-magnitude diagrams. Since YSOs are often bright in X-rays, we will include the X-ray data to identify potential young stars that do not have IR excess. Finally, since YSOs are often variable too, we will use the YSOVAR data to identify potential YSOs. The images of all these potential candidates will be examined to assure consistency across many orders of magnitude in wavelength, X-rays through 850 μm. This will be done through visual inspection of each image to assure location matching and determine point source clarity. We will also create optical and IR color-color and color-magnitude diagrams; since the G09 approach uses 2MASS+IRAC+MIPS-24, the IR-selected YSOs are guaranteed to be in the correct place in the IR color-color and color-magnitude diagrams, but the YSOs selected via other means might not be in the same location. The G09 approach does not include the wealth of data from other wavelengths (X-ray, optical, far-IR, sub-mm) that we have, and we will make color-color and color-magnitude diagrams (and SEDs) using those data too to identify high-confidence YSOs.

Table 1 is a summary of all of the data we have already amassed.

Table 1: Existing data

Instrument	Wavelengths	Source	Reduction done by	Number of Sources
Chandra/ACIS	X-Ray (~0.001μm)	collabo-rators	YSOVAR Team	87
SDSS	optical, ugriz (0.29-0.9 μm)	SDSS archive	SDSS archive	3817
IPHAS	optical, riHα, (0.6-0.8 μm	IPHAS archive	IPHAS archive	2219
2MASS	JHK (1.2 - 2.2 μm)	2MASS archive	2MASS archive	1988
Spitzer/IRAC and MIPS	Mid IR (3.6, 4.5, 5.8, 8.0, 24, 70 μm)	collabo-rators	YSOVAR Team	6100
Spitzer/IRAC	Mid IR (3.6, 4.5 μm)	GLIMPSE team	GLIMPSE Team	8271
WISE	Mid IR (3.4, 4.6, 12, 22 μm)	WISE archive	WISE archive	1445
Herschel/ PACS and SPIRE	Far IR (70,100, 160, 250, 300, 500 μm)	Herschel archive	NHSC	several (*)
SCUBA	Sub-mm (450, 850 μm)	DiFrancesco et al. (2008)	DiFrancesco et al. (2008)	16
YSOVAR	Mid IR (3.6, 4.5 μm)	collabor-ators	YSOVAR team	3526
Hα-bright stars	optical (0.656 μm)	Mikami & Ogura (2001); Witham et al. (2008)	Mikami & Ogura (2001); Witham et al. (2008)	2

(*) One can see several sources in the Herschel images, but detailed numbers await a more careful data reduction by R. Paladini and B. Schulz.

In context of R14, our team already has the initial IR, X-ray, and variability YSO selection completed as described there. There are 283 unique objects that are so identified as YSO candidates. Other NITARP teams have worked through lists of comparable length, so we expect that we will be able to make it through image and SED inspection of all 283 sources in a reasonable time.

This comprehensive and detailed process will provide a list of high quality YSO candidates and full SEDs that can be combined with the individual light curve data for a much better understanding of YSO variability within the Ceph C region.

4.0 Education Outreach

The team of educators working on this project represent a wide range of backgrounds and locations. While their teaching experiences and assignments might be very different, they share an appreciation for the effects science research like this has on their students, the school and community as a whole. As this project develops the team proposes to develop a qualitative study into the effects, reach, and influence of the NITARP experience on their students and school. The study will include teacher observations, media activity and response, student comments and level of involvement in science research as a whole.

Ukiah High School (L.Orr)

For this project students in Ukiah School, Pilot Rock, and Pendleton will be given the opportunity to participate in the NITARP LLAMA research as part of an extracurricular project. The bulk of our group work and student participation will be based on remote meeting with several in person workshop type sessions as needed. Over the course of the project students will gain a greater understanding of star formation, but also experience in the research process, data analysis, and scientific communication. In addition to the core components of the NITARP experience, students will present their work to the school boards of each school, at a community library public outreach night, and to the local 4H astronomy club.

Laura Orr, as a NITARP researcher, will use the experience to gain better understanding of astronomical research as well as the process of proposing, conducting, and presenting authentic research. She will share the experience and skills with other middle and high school teachers in her region and state via workshops and professional development presentations including the 2016 NSTA National Convention, OSTA state convention, and to local ESD.

Milken Community Schools, Los Angeles, CA – A. Miller

Several different applications are planned for the NITARP program for Milken Community Schools. A 9th grader plans to use his NITARP experiences to inform his participation in the existing Science Research class. Students at Milken Community Schools in 7th, 8th and 9th grades will participate in weekly meetings where they will work collaboratively to prepare a blog that updates members of not only our school and local community but potentially a wider reaching educational community on the progress of our project. Additionally, students will present a proto science poster and the final science poster at the Milken Innovator Xpo (MIX) in March 2016 and March 2017.

Bioscience High School, Phoenix, AZ- M. Johnson

A team of students will meet weekly to discuss the ongoing research, including latest progress by LLAMA, research and sill development and future planning. Students will learn to use astronomical software for image processing, learn research methods and data analysis. Members of this student team will also travel to Pasadena, Ca during the summer to be trained in data analysis.

The team will also develop communication skills for the purpose of being able to share the scientific work with the public, via outreach events. Outreach events may include presentations for the school board, district-wide science department leaders and school principals. We also plan to present during an event (to be determined) at an Arizona SciTech Festival event in the spring of 2017.

5.0 Resource list

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