Identification of YSOs in the Lagoon Nebula (IDYL)

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1. Abstract

We propose to use infrared (IR) measurements to explore the young stellar population in and around the Lagoon Nebula (M8). There have been more than 50 published articles exploring the young stellar object (YSO) population in and near the Lagoon, but no recent studies have specifically explored the properties of the known YSO population at IR wavelengths longer than 15 µm. By the same token, no searches have been conducted to look for new candidate YSOs in this region primarily using these long wavelengths. In this work, we will assemble a list of known YSOs from the literature and explore their properties in the IR. We will also use the IR to look for candidate YSOs not yet discovered. By assembling a more complete list of member stars, we will have a better understanding of the stellar population in this cluster. This will lead to a better understanding of the mass distribution and age spread, as well as the fraction of stars with disks. We will also contribute to a larger project using K2 (Kepler's repurposed mission) and ground-based telescopes; this project studies time variability of stars in the Lagoon in the optical.

2. Science background

2.1 Star Formation

All stars form from clouds of dust and gas contracting under their own gravity; see Figures 1a and b (from Greene 2001; for more technical reviews of star formation, see the articles in the peer-reviewed proceedings of Protostars and Planets VI, Beuther et al., eds). Since angular momentum is conserved, even if the initial cloud has just a slight amount of rotation (imparted, say, from the rotation of the galaxy itself), then the matter does not continue to fall radially towards the central young stellar object (YSO). Rather, as depicted in Figure 1c, the matter falls onto a relatively thin disk, from which it spirals in and accretes onto the central object. During these early phases, where the accretion rate is high, some of the accreting matter gets ejected in the form of outflows or jets, (likely as a result of strong magnetic fields; see, e.g., Ray 2007) above and below the plane of the disk (see Figure 1c). Eventually, the 'cocoon' of surrounding matter thins as the mass accretes onto the disk or is dispersed by the outflows (see Figure

1d). The YSO continues to accrete from the disk, though at a slower rate as the disk continues to thin. Eventually the outflows cease and protoplanets likely form in the disk (Figure 1e). When the YSO reaches the "young stellar system" stage described in Figure 1f, thermonuclear reactions start in the core turning H into He. Note the sizes and timescales indicated in Figure 1; both the ages and timescales are approximate.

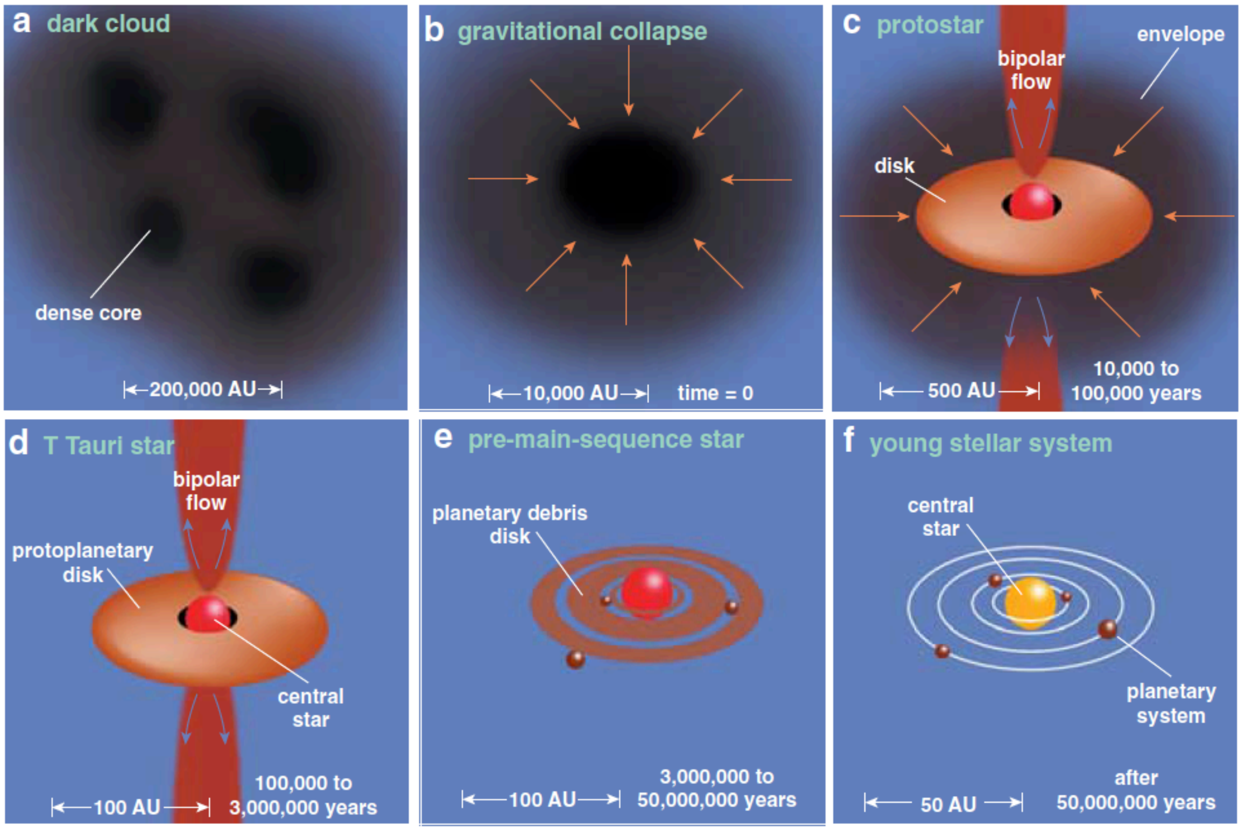

Figure 1. The stages of star formation. Image from Greene (2001).

Figure 2 shows roughly the same stages as Figure 1, but adds more quantitative measures. The right hand side of Figure 2 has example spectral energy distributions (SEDs) of the various phases. An SED shows how much energy is detected as a function of wavelength. At the earliest ages, the central object is not detectable in the optical (~0.3 μm to ~0.8 μm); the cocoon of gas and dust glows as a low-temperature blackbody, detectable only in the infrared (IR) and longer wavelengths. As the matter continues to accrete onto the YSO, the remaining dust around the YSO intercepts radiation from the YSO and re-emits it in the IR. As the circumstellar disk continues to disperse, the central object is revealed. The remaining dust, still heated by the YSO, continues to glow in the IR. Early on, most of the energy emerges in the IR. Later, most of the energy is in the optical, with only a fraction of the energy in the IR. The SEDs in the second, third, and fourth rows of Figure 2 show the stellar contribution as a blackbody. The additional energy emitted by the YSO above the blackbody curve is called the IR excess specifically because it is excess emission above that of the stellar blackbody. The amount of IR excess decreases with time as the disk disperses; as long as there is disk material to absorb energy from the light produced by the YSO, it will reprocess the radiation and re-emit that energy in the IR.

Figure 2 includes some of the nomenclature associated with this process; the nomenclature can be confusing, because different people use the same term to mean different things (see, e.g., Evans et al. 2009b). Class 0 is the earliest phase; these are also sometimes called protostars. Class I, the next phase, still has substantial dust and gas around the YSO. Class I SEDs are rising through the IR; Class II SEDs are falling through the IR. Thus, there must be a stage between Class I and II where the SED is flat, or close to it; these are Flat Class objects. Class II objects are sometimes called classical T Tauris (CTTS); Class III objects are sometimes called weak-lined T Tauris (WTTS). Small amounts of dust remaining near the end of the process can be called debris disks. The viewing angle will also impact the SED shape; a Class II object seen edge-on may resemble a Class I object.

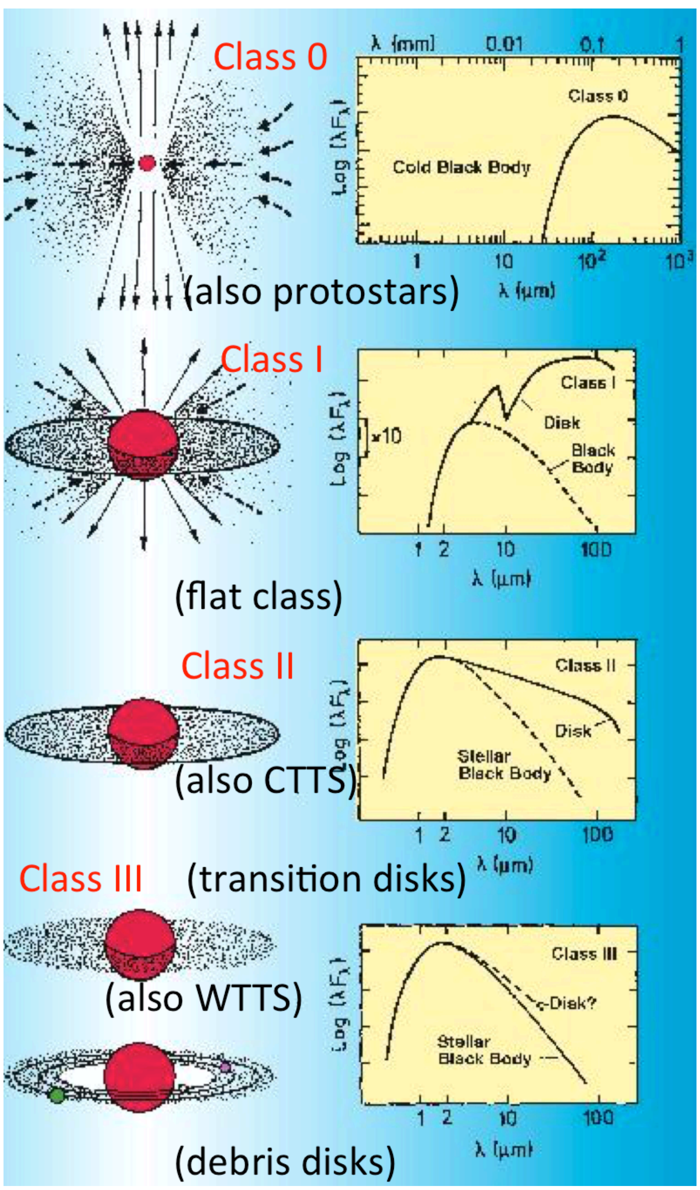

Figure 2. Evolutionary stages of a low-mass YSO (young stellar object). In each panel the physical representation on the left is accompanied by a spectral energy distribution (SED) on the right. Note how the YSO evolves to become a more compact and less dusty object over time. The SED, meanwhile shows the appearance of IR excess, and its relative prominence at each stage, above the stellar blackbody curve. Figure adapted from Bachiller 1996 and Andre & Montmerle 1994. Nomenclature in the study of YSOs can be confusing; see text.

Because all of these YSOs have IR excesses to varying degrees, one obvious way to look for YSOs is to look for objects with IR excesses (see, e.g., Gutermuth et al. 2009,2010 or Koenig & Leisawitz 2014). Indeed, this has proved a very fruitful approach in the Spitzer and WISE eras, with thousands upon thousands of new YSOs identified. Once MIR and FIR data are included, for relatively nearby star-forming regions, to some extent, simple detection of a star in bands of about 20 μm (and longer) may be a strong indication of youth and therefore identification as a YSO candidate. We will be using both of these approaches (simple detection in the MIR/FIR and Gutermuth selection in the NIR and MIR) in our work; see section 3.1 below.

We have thus far emphasized the characteristics of young stars in the IR because the IR will be the focus of our work. However, there are other ways to identify YSOs; all of these methods will be relevant to our work (see more below). Analogous to the IR excess, there can be an ultraviolet (UV) excess, which arises from active accretion. Charged matter from the disk falls into the star along magnetic field lines; as the matter falls onto the star, it creates a shock where it hits the star's surface (see, e.g., Ardila et al. 2013); this shock substantially heats up the gas, which creates the UV excess. YSOs are often bright in X-rays, which come from star spots and flares (e.g., Damiani et al. 2019 and references therein). Hα can also be used to find YSOs; this emission originates in both flares and accretion streams (e.g., Sung et al. 2000 or Damiani et al. 2019 and references therein). YSOs are also highly variable due to accretion and/or circumstellar disks and/or star spots (e.g., Rebull et al. 2018); periodic variability reveals that YSOs often have fast rotation periods (e.g., Rebull et al. 2018).

The current understanding of star formation comes from numerous studies of star-forming regions of different ages in which surveys of all members were used to establish this process and the timescales under which it happens (see, e.g., Evans et al. 2009a). **We plan to look for candidate YSOs in one region, the Lagoon Nebula (also known as M8), to better establish the list of young stars in this region** (this is discussed much more in later sections below). By having a more complete inventory of the young stars in this region, we will have a better sense of the mass function and any age spread, as well as disk fractions. All of these topics have been the subject of recent papers (e.g., Damiani et al. 2019, Prisinzano et al. 2019, and references therein); see next section.

2.2 Connection to the Bigger Picture

In this project, we will characterize the known YSOs in and around the Lagoon Nebula (M8) in the IR, and also use the IR to identify new candidate YSOs. In doing so, we will assemble a more complete list of YSOs in this region. Having a more complete list of YSOs in this region will lead to better understanding of (1) the mass distribution and (2) age spread, as well as (3) the fraction of stars with disks. We will also (4) contribute to a larger project using K2 (Kepler's repurposed mission) and ground-based telescopes; this project studies time variability of stars in the Lagoon in the optical.

Number 1 has to do with having a better understanding of the *mass distribution*. The initial mass function (IMF) is the distribution of stars by mass ("mass function") at the time when they ignite hydrogen ("initial"). Everywhere astronomers have ever looked, there are more low-mass stars than high-mass stars. But the details of this distribution are unclear, such as where the mass function turns over (there are more and more stars for smaller and smaller masses, but there are not infinite numbers of Jupiter-mass objects, so there has to be a turnover). One of the big open questions in star formation is whether or not the IMF is a function of environment (see, e.g., Krumholz 2014 and references therein). One extreme is a high-density star-forming region (SFR) like Orion, where there are a lot of O and B stars and many stars forming in close proximity, such that the "night sky" for any planets there might not be very dark. Another extreme is a low-density SFR like Taurus, where there are no O, B, or A stars, and the nearest neighbor to any given star might be relatively far away. Is the IMF different in a place like Orion compared to a place like Taurus? What if the star formation started by a cloud collapsing under its own gravity, as opposed to having been prompted into collapse by a nearby supernova or UV/winds from O and B stars? In order to answer these questions, a complete inventory of the stellar (member) population in many different SFRs is necessary. Our work will contribute to this inventory in the Lagoon.

Number 2 references the *age spread*. If a cloud collapses solely under its own gravity, then all the stars formed from that cloud could have about the same age. But if a wave of star formation moves through the cloud, prompted, for example, by a supernova on one side of it, then the stars closest to the location of the supernova may be the oldest, and those furthest from it may be the youngest. When YSOs emerge on the optical color-magnitude diagram (CMD), they are well above the zero-age main sequence (ZAMS), and as they age and move towards hydrogen ignition, they move down and to the left to join the ZAMS. But even for a narrow range of masses, they appear on the CMD with a range of luminosities, e.g., an apparent range of ages. Even within a relatively small SFR, we can find stars that appear to be of a variety of ages (e.g., Jeffries et al. 2011 and references therein), despite being in close physical proximity. It is unclear whether this is representative of a true range of ages of the stars or if the spread in luminosity is a result of some other important effect or combination of effects, such as rotation rates, abundances, magnetic fields, or even inclinations of the star+disk system on the sky affecting what we observe. Ages of stars in general are often hard to obtain, and ages of young stars are particularly difficult because of this apparent age spread in young clusters (see, e.g., Soderblom et al. 2014). Here again, in order to answer these broader questions about an age spread, a complete inventory of the stellar (member) population in the SFR is necessary. Our work will contribute to this inventory in the Lagoon. Prisinzano et al. (2019) recently explored the age spread specifically in NGC 6530, a part of the Lagoon Nebula region.

Number 3 above mentions the *fraction of stars with disks*. IR excesses are the observable quantity, which is then interpreted as a circumstellar dust disk. As we understand it, all stars have circumstellar disks at some point in their formation, and the disk disperses when the star is 'old enough.' The fraction of stars with disks is both a function of stellar mass and age, as well as disk lifetime, which itself is certainly related to the star formation process, the size (and density and mass) of the initial disk, the gas-to-dust ratio in the disk, the environment (O and B stars can photo-ablate disks and destroy them faster than if they are isolated), magnetic fields, abundances, and disk chemistry (see, e.g., Ercolano and Pascucci 2017 or Liu et al. 2018). Trying to figure out how long disks last around young stars is a challenge, in no small part because of the uncertainty in ages (e.g., the age spread above). But, this too comes back to a complete inventory of the stellar (member) population in the SFR; for this goal, a sensitive, complete survey in the IR is needed in order to attempt to constrain the number of stars with IR excesses. In particular, the Spitzer and WISE data we will use are both important for this goal, and we will incorporate Herschel and AKARI data where we can (discussed more below).

Finally, number 4 above is a study of the *time variability of young stars*. K2, the repurposed Kepler mission (Howell et al. 2014), monitored thousands of stars with high precision photometry (see, e.g., Rebull et al. 2018, Cody & Hillenbrand 2018, and references therein); other space-based studies have probed variability of young stars specifically in the IR (see, e.g., Rebull et al. 2014). The goals of these time series investigations include characterization of the variability properties of young stars, both disked and non-disked (e.g., Rebull et al. 2018, Cody & Hillenbrand 2018); to determine rotation periods as a function of age and mass (e.g., Rebull et al. 2018); and to look for signatures of disk locking in young stars (e.g., Rebull et al. 2018). YSOs are known to vary nearly at all wavelengths and timescales (e.g., Rebull 2011); accretion is not a steady process, the disk can have warps and other 'texture' (it is not infinitely thin), and multiple processes can result in surface inhomogeneities on the stellar surface, all of which contribute to large variations in YSOs as a function of time.

First, an aside on Kepler/K2: The Kepler satellite had 21 CCD modules covering a total of 116 square degrees on the sky; while some modules were lost during the K2 portion of the mission, a single image of the entire field was still very large. Even though the pixels on K2's CCDs were relatively large (nearly 4x4 arcsec), a single image of the entire field is still a lot of data. There was not enough bandwidth in the Deep Space Network (DSN, which is NASA's network of radio telescopes to communicate with all satellites not in Earth orbit) to download the full 116 square degrees every 30 minutes. So, rather than downloading the entirety of the image every 30 minutes, prior to the campaign, the spacecraft was told to only record and transmit many small "postage stamps" of pixels around each and every planned target, thereby vastly reducing the amount of data that needed to be stored and transmitted. The disadvantage of this approach is that all desirable targets (and corresponding pixels) had to be selected ahead of the campaign, something that had to happen every ~70 d during the K2 portion of the mission. In some places on the sky, there were so many desirable targets clumped so close together that it was deemed worth the bandwidth to download a larger patch of pixels. Since these regions are larger than the other postage stamps, these are called "super stamps."

K2 observed the Lagoon Nebula region as part of their Campaign 9 in April 2016. A super-stamp of the heart of the Lagoon nebula was monitored with K2, as were several postage stamps around likely cluster members further away from the heart of the region. As part of efforts to support that campaign, simultaneous ground based optical monitoring of the region was also obtained. All of these data sets will result in optical light curves (brightnesses as a function of time) of YSOs. These data are actively being reduced now by our collaborators A. M. Cody and L. Venuti, both at NASA/Ames. While time variability is not a primary goal of the NITARP work described here, our work here in NITARP will support this K2 effort by assembling a list of known and suspected cluster members on which they can concentrate in extracting light curves. At this point, no plans are in place to identify new cluster members from variability properties; the master catalog we create, however, will allow easy inspection of the SEDs of any target bright enough to be in the K2 or ground-based light curves.

2.3 Target of study

The study will focus on the area in and around the Lagoon Nebula (also known as M8). The Lagoon Nebula is visible in the sky from mid-northern latitudes (see Figure 3) and lies at a distance of about 1250 pc (Prisinzano et al. 2005). With a net apparent visual magnitude of 6.0, the Lagoon Nebula can be viewed in the constellation Sagittarius with binoculars or a small telescope.

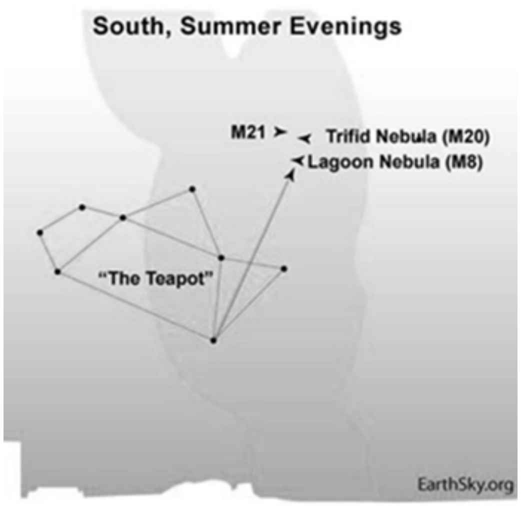

Figure 3. M8 (the Lagoon Nebula) is located right above the "spout" of the "Teapot" in Sagittarius. Image from EarthSky.org.

In looking toward Sagittarius, we will be looking in the general direction of the Galactic center – in Galactic coordinates, ℓ,b~6°,-1°; see Figure 4. (See Appendix 1 for much more information on coordinate systems like this.) Observing in the Galactic plane near the Galactic center results in benefits as well as challenges. The Carina – Sagittarius arm of the Milky Way Galaxy is relatively close and many stars (and clouds of gas and dust actively forming new stars) exist to study. Because the Lagoon is in the Galactic plane, many surveys include this region and therefore have public data that we can use in our work. The main challenge is the sheer number of stars in this direction. When we look in the direction of M8, we see a multitude of stars and most will not be in the nebula, but instead both in the foreground and background, leading to possible source confusion (more on this below). The challenge will be isolating sources which are actually members of star clusters within M8.

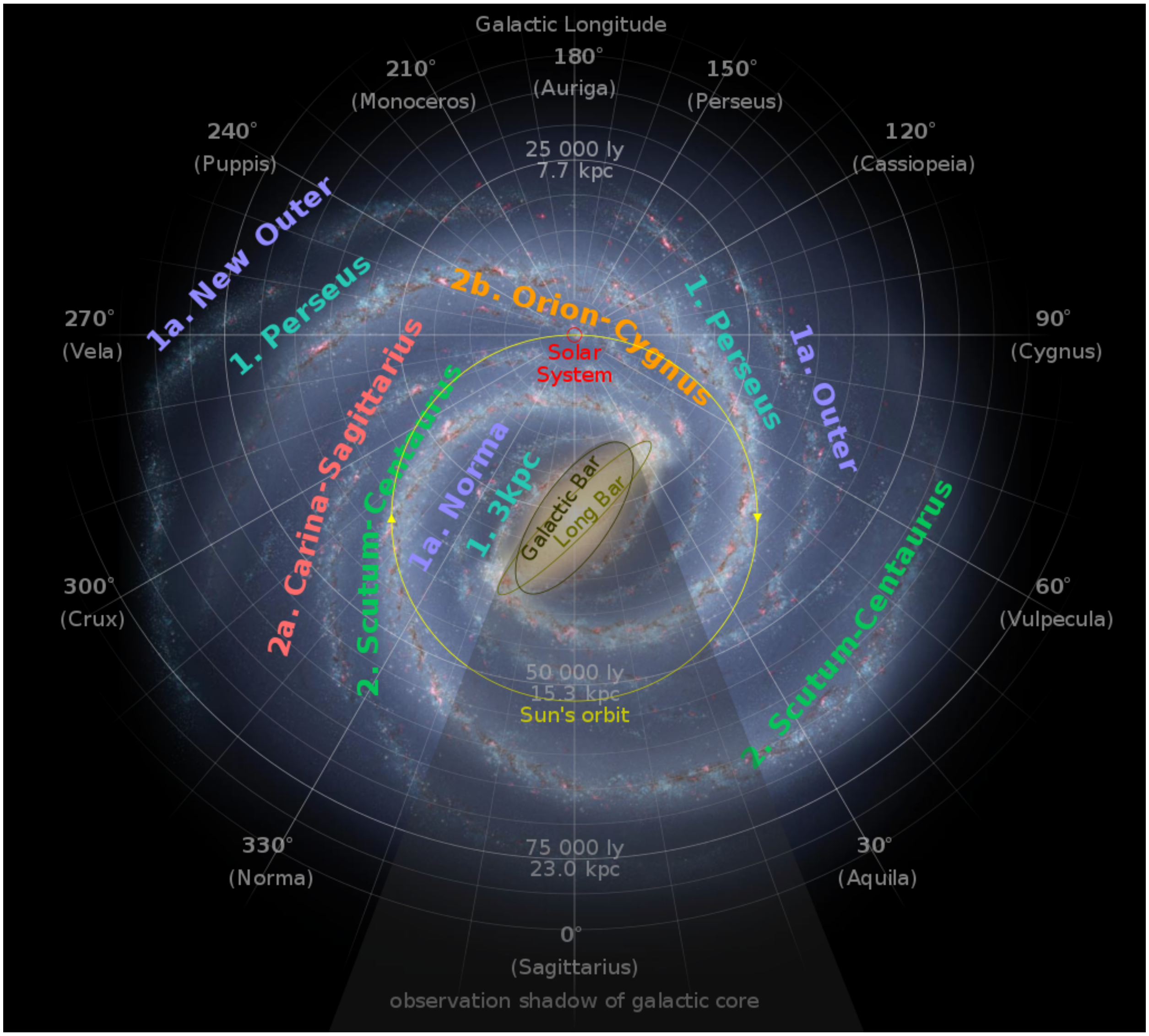

Figure 4. Artist's conception of the Milky Way Galaxy, annotated with color-coded arms as well as distances from the Solar System and Galactic longitude with corresponding constellation. M8 is in the Carina – Sagittarius arm. Figure from NASA/JPL-Caltech/R. Hurt.

Figure 5. A widefield color image, from Tothill et al. (2008), covering M8 (lower right), M20 (the Trifid Nebula, upper right) and Simeis 188 (left). Our target is the Lagoon Nebula, M8, in the lower right of this image. H emission is red and reflection nebulae are blue; north is up and east is to the left; field of view (FOV) 2.5°×2.2°. Image originally courtesy Gerald Rhemann.

Tothill et al. (2008) provides a review of the literature for the Lagoon Nebula region; Figure 5 is a very wide field of view that comes from this Tothill et al. paper. Figure 5 includes M8 (lower right), M20 (the Trifid Nebula, upper right) and Simeis 188 (left). As they point out, nomenclature is difficult and confusing here, with different authors meaning different regions when using the same name. The most important regions identified in Tothill et al. (2008) are called out here in Figure 6, which includes both a DSS2 NIR image, and a 2MASS (also NIR but longer wavelengths than DSS2) image. Features seen specifically in M8 in Figure 5 can also be seen in the DSS image in Figure 6, such as the dark lanes running through the heart of M8. Few of those features, however, are still obvious in the 2MASS image in Figure 6; this is one of the SFRs where the appearance changes a lot between the optical and IR. The annotations provide linkages to the features between the optical and IR images. In Figure 6, the annotations indicate two sub-clusters, NGC 6523 and NGC 6530, the Hourglass Nebula, a region called "M8E" (M8-East), and HD 165052, an O star that may be tied to the name IC 1271 (see Tothill et al. 2008 for more discussion). Our study area is centered on 18:03:37.0 -24:23:12 (RA, Dec; J2000; see Appendix 1 for information on coordinate systems), given by the small magenta circle in Figure 6; the large red circle is our study region, and is 0.5° in radius. The K2 super stamp runs from the east side of NGC 6530 to nearly the west side of the Hourglass.

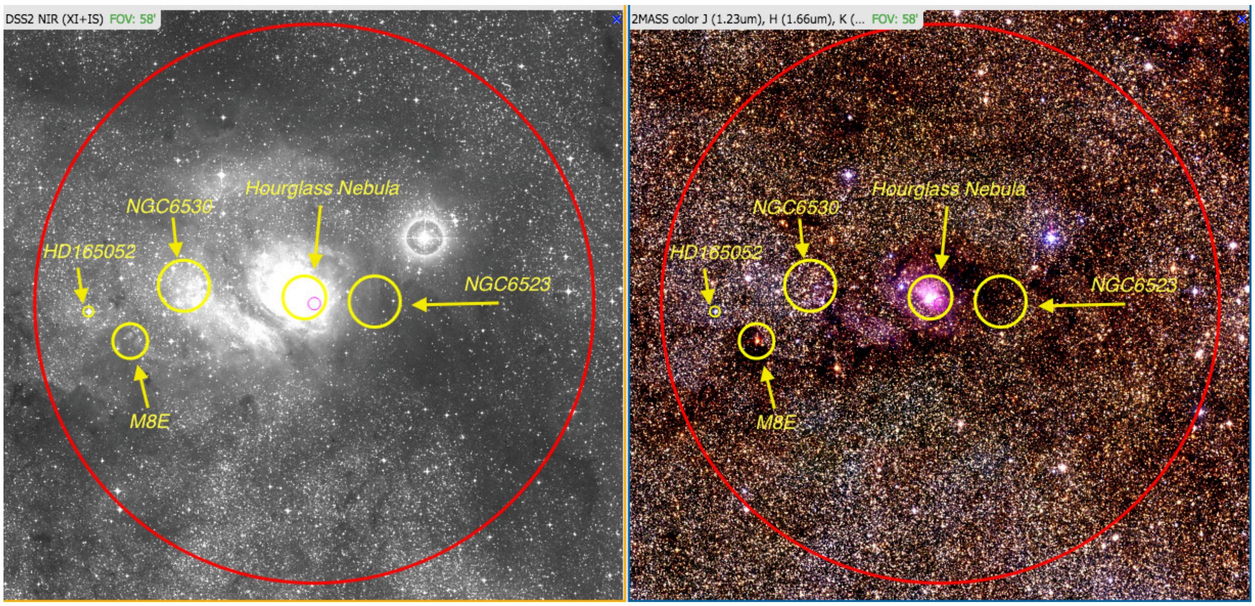

Figure 6. In and around the Lagoon Nebula region, as seen in DSS2 NIR (left) and 2MASS NIR (right). Both images are the same area and are from HiPS images accessible in IRSA Viewer (https://irsa.ipac.caltech.edu/irsaviewer/). Some features seen in Figure 5 can also be seen in the DSS image on the left, such as the dark lanes running through the heart of the region, but are hard to discern in the 2MASS image on the right. The most important regions identified in Tothill et al. (2008) are described here: two sub-clusters, NGC 6523 and NGC 6530, the Hourglass Nebula, a region called "M8E" (M8 east), and HD165052, an O star that may be tied to the name IC1271 (see Tothill et al. 2008 for more discussion). Our proposed study area is the large red circle, 0.5° in radius, centered on α,δ (RA, Dec) = 18:03:37.0 -24:23:12 (J2000), given by the small magenta circle. North is up and East is to the left.

Because the Lagoon Nebula region has been studied for literally decades, there are many papers in the literature, more than 500 in SIMBAD. Based on reading of the abstracts, we culled the list down, limiting ourselves primarily to those relatively recent papers, those papers reporting on point sources (not nebulosity), those using electronic detectors (not photographic plates), and/or those reporting on relatively large surveys of the region (not just a handful of sources). We did not limit ourselves to papers using data from just optical or just IR. We looked at more than 50 papers in detail. Additionally, because the Lagoon is in the Galactic plane (see Appendix 1), there are many Galactic plane surveys that serendipitously observed this region as part of their work. We have more than 35 papers and/or catalogs from which we can draw data relevant to our interests here (which is the stellar population, as opposed to the nebulosity). In the interest of both space and time (both for the authors and readers), we have opted to summarize details of these ~35 papers and/or catalogs in Table 1, found in Appendix 2; the table gives a description of the paper or catalog (including a reference), the focus of the work, whether or not it covers our entire region, how many sources it includes, whether or not member stars (or candidate members) are identified in the paper ("YSO flag"), and the bands which are included. As seen in Table 1, we have data from X-ray, optical, near-IR, mid-IR, far-IR, and sub-millimeter wavelengths. Many of the papers we read (see Table 1 for references) were specifically identifying cluster members via positions and proper motions (PPM), and/or color-magnitude and color-color diagrams; some were conducting spectroscopic follow-up on YSOs identified in other papers (including, e.g., spectral types and Li abundances). Several papers report X-rays (see Table 1 for references). Both YSOs and active galactic nuclei (AGN) are bright in X-rays, but we are in the Galactic plane and near the Galactic center, so no AGN are likely visible through all the constituents of our Galaxy. Thus, we followed the example of several authors and simply took the detection of a star in X-rays as an indication of likely youth and therefore membership. One paper reports mass accretion rates from UV excess (Kalari et al. 2015); several identify cluster members from Hα (e. g., Sung et al. 2000, Kalari et al. 2015). Henderson & Stassun (2012) determine rotation periods for members based on time series monitoring of the region; they report 290 periods, 88% of which are less than 10 days, consistent with periods expected for young stars. There are several surveys of this region in the optical (Gaia DR2, PanSTARRS, VVV, VPHAS, UKIDSS; see Table 1 for references). In the IR, there are 2MASS, Spitzer, WISE, AKARI, MSX, and IRAS data over the whole region (again, see Table 1 for references). Herschel, unfortunately, does not cover much of our region; only about a third of our region, on the northwest, overlaps with the Herschel Galactic plane survey and thus appears in the Herschel HPDP PACS PSC (Point Source Catalog; Marton et al. 2017). SCUBA (sub-mm) covers the heart of the region, from the center of NGC 6523 to M8E, plus three smaller pointings in the area.

Note that the literature covers X-rays through optical and NIR; some literature includes IRAC bands (3.6 to 8 μm). There is very little, if any, work on the point sources using any wavelength longer than 8 μm**. This presents an opportunity: our project will specifically look at the data at 15 μm and longer.** AKARI (9, 18, 65, 90, 140, & 160 μm), MSX (4.29, 4.35, 7.76, 11.99, 14.55, & 20.68 μm), IRAS (12, 25, 60, & 100 μm) and Spitzer/MIPS (24 μm) all contribute data over the whole region; Herschel/PACS (70 & 160 μm) and SCUBA (450 μm limits and 850 μm detections) are available over portions of our survey region. While the spatial resolution of those surveys is not at all comparable to the optical or even 2MASS or IRAC data, these longer wavelength data have not yet been explored in detail for the YSOs in this region, nor have they been fully mined for YSO candidates bright in the IR. **This is going to be the focus of our work here.** We expect to find at least a few hundred candidate YSOs using these long-wavelength data; see section 3.

3. <u>Analysis plan</u>

3.1 Goals

This project has two main goals, both of which are concerned with IR properties of YSOs in and around the Lagoon Nebula.

1. **Literature-identified ("known") YSOs**. Our first goal is to explore the IR properties of the literature-identified YSOs to determine typical IR colors and brightnesses.
2. **New candidate YSOs**. Our second goal is to identify sources bright in the IR (at 15 µm and longer) and identify new YSO candidates in this region based on IR excesses. Because we have quite a bit of ancillary data in this region (including, e.g., distances from Gaia DR2, SED shape, color-mag and color-color diagrams), we can make use of all that data to determine if the newly identified IR-bright sources are indeed likely cluster members.

One important reason for the first goal is that our mentor scientist (L. Rebull) is experimenting with new ways of explaining color-color and color-magnitude diagrams to NITARP teachers and students. In the past, color-color and color-magnitude diagrams have often been covered last in the NITARP year, and participants have struggled in understanding them. By starting with explorations of the known YSOs, the hope is that participants will find these diagrams easier to understand. (Admittedly, this aspect, therefore, is more of an education goal than an astronomy goal.)

For the first goal, scientifically, we expect that the IR color-color diagrams will resemble those found in many other SFRs, with the YSOs bright and red. However, because there are so many X-ray surveys here, we expect a significant minority of sources will have no IR excess; being able to cite a specific number associated with X-ray sources that have no IR excess will shed light on the disk fraction of the stars in the M8 region.

As an additional facet of the first goal, we will investigate the MIR images (at λ >15 µm, where possible) of all the literature-identified YSOs to determine if there are missing detections in the existing catalogs, particularly Spitzer/MIPS-24, the highest spatial resolution and most sensitive data we have at these wavelengths. If necessary, we will do additional photometry to determine the brightness of sources we can see by eye in the images but are not in the catalog. This will extend the SED coverage of the known YSOs to longer wavelengths, and enable more complete assessments of the disk fraction.

For the second goal, scientifically, we expect that most of the objects detected at λ >15 µm are young, but some may be foreground or background objects, and others are too embedded to detect in some of the other, shorter-wavelength studies of this region. Specific details on this are listed in the next section.

There is an additional facet of the second goal as well. As described above in Section 2.1, simple detection of a star in the MIR or FIR may be enough to indicate youth, and this is our baseline approach for the second goal. However, in the context of young stars being studied with Spitzer (and WISE), there have been many methods proposed for identifying YSOs from a catalog of sources in a star forming region with NIR and MIR detections. All of these methods use some combination of color-color and/or color-magnitude diagrams to distinguish YSOs from other objects detected in the IR. Gutermuth et al. (2009, 2010) presents a multi-step method using IRAC and 2MASS. The disadvantage of this method is that it requires all four bands of IRAC, however the advantage is that it can be applied across the whole region relatively easily. If there is time, we will run the Gutermuth color selection algorithm on our catalog to identify additional candidate YSOs. WISE can be used with a similar color selection algorithm, found in Koenig & Leisawitz (2014); the Spitzer data is higher (better) sensitivity and spatial resolution, so in this region of high surface density of sources, we will use the Gutermuth approach with IRAC rather than the Koenig approach with WISE. The MYStIX collaboration (see Table 1) ran their own version of a similar color-based YSO selection using IRAC data on just a subset of our larger region, so a portion of our region is as yet unexplored in this fashion and thus likely to contain additional new YSO candidates.

As a further extension, if our collaborators A. M. Cody and L. Venuti are able to create light curves before the end of 2019 (K2 from space, several other optical bands from the ground), then we will also investigate the variability properties of both the literature YSOs and our new candidate YSOs. Light curve extraction (particularly from the K2 superstamp) in a region of such high source density with such large pixels (~4x4 arcsec) is not trivial. Therefore, the incorporation of the light curves into our analysis may not happen in time for us to include them in the 2020 January AAS poster.

3.2 Scope of the problem

Our region, a cone of 0.5° radius, centered on 18:03:37.0 -24:23:12 (as shown in Figure 6 above), was selected to encompass most of the literature-identified cluster members. A few percent of the literature-identified members in this region are more than 0.5° away from our target center. We chose to limit ourselves to 0.5° radius just for practical terms; there are already a lot of sources in our region.

We have already taken the ~35 literature tables and archival catalogs listed in the Table and merged them together by position. While this is admittedly a first attempt at merging the catalogs together, intermediate tests and spot checks of the final merged catalog suggest that most of the sources are matched correctly, even given the source surface density and the varying resolutions of our constituent catalogs. There are 1.3 million unique sources currently in our merged catalog.

As part of this merging process, we have kept track of those objects already identified in the literature as YSOs (cluster members). There are 4007 such known YSOs. As noted above, the YSOs have been identified by a wide variety of methods. These methods have been applied inhomogeneously across the region because not all surveys cover our whole region (see Table 1 in Appendix), and not every source is seen in every survey. Because of this, not every object will have data at all of the bands, and not every part of this region has been investigated to find members. We will do the best that we can with the available data.

These catalogs come from telescopes with vastly different spatial resolutions. Merging by position through the optical and NIR is relatively straightforward, even with the high source surface density. Incorporating Spitzer/IRAC should also be straightforward, because the astrometry in IRAC is tied to 2MASS positions and therefore highly accurate. The remaining IR data sets, ordered roughly by spatial resolution, are WISE, AKARI, PACS, MSX, SCUBA, and IRAS. Source matching through these bands will be more challenging, particularly for the longest wavelengths, because of the high surface density of stars. To compensate for this, for the sources of interest, we will spend time looking at individual images to make sure that we have made the best possible match across catalogs.

Given our preliminary matched catalog, two-thirds of the known YSOs have IRAC detections, which should be enough for us to explore the IR properties of these known YSOs. However, only ~10% of the literature YSOs have MIPS-24 counterparts. There are sources easily visible in the Spitzer/MIPS-24 maps that are not already tagged as YSOs (goal 2); there are ~300 sources with measured MIPS-24 fluxes in the catalog. We will look at those ~300 sources, but we also suspect that some to-be-determined fraction of the existing set of known YSOs have MIPS-24 detections that are not in our catalog (goal 1 extension). The only MIPS-24 catalog we currently have is from SEIP, which is relatively shallow (only measuring the brightest sources), so it is very likely that some sources visible in the image may not be in the catalog. If we need to, we will do additional photometry on the MIPS-24 images.

AKARI is relatively shallow and has lower spatial resolution than IRAC, but there are detections at 9 and 18 µm through our whole region. There are about 20 sources with AKARI IRC 18 µm detections but not MIPS-24. Because the IRC images have not been publicly released, we cannot check for unreported detections of known YSOs in the IRC images nor do additional photometry. But, we can inspect SEDs and look at Spitzer and WISE data for these sources to assess if the AKARI IRC source is matched to the correct source from the other surveys.

The Gaia counterparts tentatively matched by position to these 'new' objects suggest a wide range of distances. (Not all of the objects in our catalog have a Gaia counterpart.) The Gaia distances for the existing cluster members clump around ~1250 pc (as expected). We will investigate whether the source matching between MIPS/AKARI and Gaia for the IR-bright objects is correct, and investigate in more detail those sources near ~1300 pc as likely candidate members.

SCUBA, Herschel, MSX, and IRAS source matches need more careful individual attention since these surveys are relatively low spatial resolution, with consequently larger positional uncertainties. Matching by position is particularly hard for those sources given the high surface density of objects. We will individually investigate these sources as well, exploring the limitations of the low spatial resolution surveys.

For these kinds of research projects, contamination (sources that look like YSOs but aren't) is frequently important. If only NIR+MIR (e.g., 2MASS+IRAC) data are available, it is easy to be fooled by several different contaminants. However, we have far more data than just 2MASS+IRAC, which will go a long way towards limiting contamination in our final sample of YSOs. Contaminants might include the following :

- Background galaxies forming stars. These objects have the same colors as star formation, because they are forming stars, just not in our Galaxy. AGN are much further away, but certain redshift ranges also result in colors resembling those from galactic star formation. This is not an issue for us, because of the location of our target -- our own Galaxy blocks out background galaxies.
- Background AGB stars. These aging stars produce dust in their atmospheres, so these dusty old stars can thus resemble dusty young stars. Usually AGB stars are far, far brighter than YSOs, but if they are far enough away to be significantly reddened by the galaxy, they resemble dusty YSOs that are much closer. AGB stars are likely to be our main contaminant, specifically because we are working in the Galactic plane. However, with the extensive optical and NIR data we have, we should be able to determine if their SED resembles that from a highly reddened giant or a YSO.

- Asteroids. These objects are very bright in the IR. However, they also move with respect to the background stars, and are largely in the ecliptic plane (see Appendix 1 for discussion on coordinate systems). We are looking in the ecliptic plane, but we have many different data products obtained at many different epochs. Any asteroids that persisted through the existing pipelines for all the IR data we have would therefore manifest as a very bright source appearing at only one band. It is very unlikely that we have any asteroids in our catalogs.
- Foreground and background dust-free stars. Because we are working in the Galactic plane, there are myriad stars that are not part of M8. However, our search for new YSO candidates is driven by IR-bright sources (goal 2). IR-bright sources that have no IR excess in the SED will be dropped as unlikely to be YSOs during the inspection process. Additionally, those with Gaia DR2 counterparts have distances and can easily be assessed; sources that are correctly matched across wavelengths but that have DR2 distances much different than ~1300 pc are not cluster members.

3.3 Specific to-do list

Here is our specific to-do list:

- Merge catalogs. (Done, at least provisionally.)
- Identify literature (known) YSOs in catalog. (Done, at least provisionally.) *(goes towards Goal 1)*
- Make some SEDs and CMDs (using combination of Excel and IDL) of known YSOs with MIR/FIR detections to check whether the catalog matching worked and to explore properties of known YSOs. Explore the limitations of lower spatial resolution data. *(goes towards Goal 1)*
- Quickly go through MIPS-24 images (using IRSA's Finder Chart tool, https://irsa.ipac.caltech.edu/applications/finderchart/) for those ~4000 known YSOs to determine if any are detectable in the image by eye but are missing MIPS-24 μm photometry. In order to assure ourselves that our survey is as complete as possible at the most sensitive and highest spatial resolution long wavelength data we have available. *(goes towards Goal 1)*
- Do photometry at MIPS-24 for any missing objects. (We will use a combination of MOPEX and IDL for this; if there is time, we will do some photometry by hand using Aperture Photometry Tool [APT].) Add this information to our catalog and SEDs. *(goes towards Goal 1)*
- Identify objects that are NOT tagged as YSOs with MIPS-24 and/or AKARI-18 detections. *(goes towards Goal 2)*
- Investigate each object in all available images using IRSA Viewer (https://irsa.ipac.caltech.edu/irsaviewer/) and ds9 (http://ds9.si.edu/site/Home.html). Obtain any missing photometry. *(goes towards Goal 2)*
- Make SEDs for new objects using Excel (and IDL). *(towards Goal 2)*
- Determine based on comparison of catalogs, images, and SEDs whether the source has been matched correctly across surveys, whether it is a point source (or artifact), whether there is missing photometry in any band, and whether it is irretrievably blended in the longer wavelengths. *(goes towards Goal 2)*
- Make CMDs/CCDs using Excel to see if new candidate YSO properties are consistent with literature YSOs. Investigate the Gaia DR2 distances to these sources where available to ensure

that the sources are likely YSOs. Cull the list down to the most confident YSOs. *(goes towards Goal 2)*

- Repeat (if there is time) the prior four steps for a Gutermuth-selected sample of objects not yet identified as YSOs. *(goes towards Goal 2 extension)*

We estimate that this entire process should result in about 300 sources that we will investigate in detail.

4.0 Education and Outreach plans

4.1 Bob Swanson

- While I will be working full-time at Mississippi State University, I will continue to teach online sections of Intro to Astronomy as an adjunct instructor for Itawamba Community College. I plan to develop several video lessons to teach my online students about our NITARP project, and also record video updates about our IDYL work so they can experience vicariously what astronomy research involves.
- As a JPL Solar System Ambassador, I am required to organize and/or participate in at least four astronomy public-outreach events each year. I plan to develop a public program that will focus on our IDYL NITARP research. This program will be presented at either Mississippi State's Howell Observatory or at Rainwater Observatory in French Camp, MS. Assisted by my students, Dionna Huett and Jaydin Walthers, we will develop activities to teach about infrared astronomy to an all-ages general audience.
- I will assist my student participants in developing and scheduling a talk about the NITARP experience (what involvement with active science research has meant to them) that they can present to the Itawamba Community College Science Club as well as to the physics and honors-level physical science classes.

4.2 Danny Mattern

- I will use my on-line astronomy courses taught at Butler Community College to get as many students as I can interested in current research in astronomy. I will use my experience with NITARP to show them relevant research areas in the field and to have them understand why research is important to the sciences. I will try to incorporate the use of astronomical databases like IRSA and the Astronomical Data System (ADS) and Simbad into lab activities so that students can get firsthand practice with finding relevant astronomy resources.
- At the beginning of every semester at Butler Community College we have several Professional Development Days (PDD). Faculty are encouraged to create workshops on any topic of their choosing and then present to other faculty at PDD. Throughout the semester we also have Faculty Second Saturdays where the second Saturday of every month is reserved for faculty

development. The workshops can range from educational strategies in the classroom to individual hobby enthusiasts. They can literally be on any topic that a faculty member has interest in and wants to share with others. My goal is to create a workshop on what we did through the NITARP program with our astronomy research. The main point will be to show that it is possible to include students in active research at the community college level. I will create a presentation to share the results of our research but also include the significance of student participation in the program.

- As a former high school teacher, I still have many colleagues at high schools in the area, especially in the math and science departments. I will reach out to some local schools and share the information about our NITARP experience with any high school staff that are interested. I would really like to get high school teachers excited about the possibility of doing research with their own students in their classrooms.
- The majority of teachers at any level just don't realize some of the opportunities that are open to them. They just need to be willing to look. The NITARP program is a perfect example of that and my hope is that if I can share our success story it will inspire other teachers to get motivated and find their own projects to increase student learning in their own classrooms.

4.3 Mike Bechtel

- The Wartburg team is going to be completing the NITARP research while simultaneously analyzing current Next Generation Science Standards (NGSS) to see how NITARP skills match to the standards, specifically astronomical education within a K-8 classroom.
- From these findings, the student team will then work on writing NGSS-aligned curriculum that can be implemented at various levels in the K-8 education system.
- The Wartburg College NITARP students will connect with current and future pre-service educators. The Wartburg cohort will be working collaboratively with 25 pre-professional education students in an Elementary Science Methods course to prepare, provide, and vet the newly written NGSS-aligned curriculum.
- From the new curriculum, data will be collected to see how the lessons are improving astronomical education within the K-8 environment, and in a greater sense, STEM education.
- The initial student team will also be reaching out to current school districts in the Northeast Iowa area to provide inservice professional development in cross-curricular lessons to further enhance and support their STEM curriculums. We will also be presenting the process at national and international conferences.

4.4 David Strasburger

- I will present the project as an example of student research opportunities to the New England Section of the American Association of Physics Teachers (NES-AAPT)
- I will present the project to astronomy education colloquia at New England independent schools: both Phillips Andover and Phillips Exeter have yearly events.

- I will use the NITARP model as a template for continuing to develop partnerships with local astronomers in Massachusetts with the goal of creating a sustainable school-based student research program in astronomy. I have an existing relationship with the American Association of Variable Star Observers (AAVSO) as a basis to build on.
- I will continue my current work to explore the creation of a non-profit that would act as a regional umbrella organization for such student-teacher-astronomer research partnerships.

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Appendix 1: Coordinate Systems

This Appendix includes a brief aside on coordinate systems, prompted by several questions during the peer review of this proposal.

Any position on the sky can be described in any of a large number of coordinate systems, and astronomers really do have a lot of coordinate systems to choose from. It can be useful in certain contexts to have a coordinate system centered on a (moving) spacecraft, or one in which the Earth is at the center and the Sun is always along the x-axis. However, there are three coordinate systems that are most commonly used to describe the location of any given object: Equatorial, Galactic, and Ecliptic.

Equatorial coordinates. Right Ascension (RA, or sometimes α) and Declination (Dec, or sometimes δ) are basically extensions of latitude and longitude on the Earth, where the zero point of longitude is anchored at the Vernal Equinox. However, since the Earth's poles precess, simply RA and Dec are not enough to specify the unique location of an object; one must also specify the epoch of the RA/Dec coordinate system. All of the RA/Dec coordinates used here are J2000. RA is usually given in hours, minutes, seconds of time (with a total of 24 hours), and Dec is usually given in degrees, minutes, seconds of arc. RA can be converted to degrees; there are 15 degrees in an hour of time (24 hrs = 360 deg).

Galactic coordinates. Galactic latitude (ℓ) and longitude (b) is a coordinate system based on the Galaxy, as seen in Figure 4. The Sun is at the center of this coordinate system. The 'equator' of this coordinate system is the plane of the Galaxy, e.g., where there is the highest surface density of stars on the sky. It is often hard to make observations in or near the Galactic plane because there are so many stars. The Galactic longitude is measured in degrees (of arc) from the Galactic center (where b=0). Galactic latitude (in degrees of arc) is measured above and below the plane of the Galaxy.

Ecliptic coordinates. Ecliptic coordinates are based on the Solar System. The plane of the Solar System is the 'equator' of this system, e.g. where the planets, comets, asteroids, dust and debris, etc. are largely located. It can be hard to observe in the ecliptic plane, because there can be asteroids moving through the field of view. The ecliptic longitude is measured (in degrees of arc) from the Vernal Equinox. The location of the Vernal Equinox also changes with time, so these coordinates also must have an epoch attached to them. Ecliptic latitude is measured above and below the plane of the Solar System (in degrees of arc).

In practice… These three coordinate systems are not coplanar, that is, the ecliptic plane is not the same as the Galactic plane, and both are different than the equatorial plane (where Declination=0). It can be convenient to shift among coordinate systems to indicate succinctly the concerns, constraints, or strengths of observing a given region. For example, "Our target is in or near the Galactic plane," can often mean, "We need to be careful because there are a lot of targets per square degree here." "Our target is in the ecliptic plane," can mean that, "There are a lot of moving targets in individual frames observed in this region, so our observing strategy required that there be many frames taken of this region at different times so that the asteroids can be removed from the final data products." Similarly, "Our target is at about 18h, -24 d," can be interpreted to mean, "We are observing something that is in the southern hemisphere (-24d), so will be relatively low on the horizon at best for most of the continental US, and it will be visible (at night) in the Summer (18h)."

Our work. The center of our region is given by all of these coordinates:

- α,δ=18:03:37.0 -24:23:12 (J2000) (equatorial)
- α,δ=270.90417 -24.386667 (J2000) (equatorial, in decimal degrees)
- ℓ,b= 5.9574678 -1.1666191 degrees (Galactic)
- 270.8236154 -0.9499731 (J2000) degrees (ecliptic)

Our target is in the Galactic plane (near the Galactic center), and it is in the ecliptic plane. So, there are a lot of stars in this region, and any individual frame taken of this region is likely to have asteroids, though essentially all of the data products we will use are combinations of individual frames, so all moving objects should be gone from the images and catalogs. (This might affect the K2 data, which are a series of single exposures!) Our target is not in the equatorial plane; it is in the southern hemisphere, and visible from the continental US in the Summer.

Appendix 2: Table of References for Catalog Data

There are so many papers on this region in the literature, and so many catalogs from which we can use data, that it was much more efficient to list them all in a table than explain them in paragraph form.

(Table 1 starts on following page.)

reference	year	paper focus	# srcs	YSO flag[1]	X-rays	optical	NIR	MIR	FIR, Submm
van den Ancker et al. (1997)	1997	PPM to find members, spty; large area	132	x		UBVRcIc			
Sung et al. (2000)	2000	members via R-H α but did not tabulate H α separately; smaller area	929	x		UBVIc			
Rauw et al. (2002)	2002	X-rays (XMM); smaller area	106		XMM				
Damiani et al. (2004)	2004	X-rays (Chandra) plus archival data from prior studies; smaller area	884		CXO				
Prisinzano et al. (2005)	2005	finding members; new optical data plus archival data from prior studies; smaller area	1429	x		BVIc			
Arias et al. (2006)	2006	tiny field of view	763				JHK		
Arias et al. (2007)	2007	follow-up on a few members	46	x					
Chen et al. (2007)	2007	PPM to find members; smaller area	364	x		B			
Prisinzano et al. (2007)	2007	spectroscopic member follow up (vsini, Li); smaller area	332	x		BVIc			
Kumar et al. (2010)	2010	IRAC for members; smaller area	233	x				IRAC1234	
Henderson et al. (2012)	2012	rotation periods; smaller area	290	x		VIc			

[1] “YSO flag” means “there is a list of objects in this paper that these authors report to be cluster members”, as opposed to just a list of all sources in the region.

Castro (2015)	2015	X-rays (Chandra) plus archival data from prior work; smaller area	1482		CXO				
Kalari et al. (2015)	2015	members from H α, UV excess, derived mass accretion; smaller area	235	x					
Wolk (2019; private communication)	2015	X-rays (Chandra); smaller area	768		CXO				
MYStIX: Povich et al. (2013)	2013	X-rays (Chandra) + Spitzer IRAC; smaller area	953	x	CXO		JHK	IRAC 1234	
MYStIX: Broos et al. (2013)	2013	X-rays (Chandra) + Spitzer IRAC; larger than prior paper; smaller area in general	2056	x	CXO		JHK	IRAC 1234	
Prisinzano et al. (2019)	2019	spectroscopic member follow up (vsini, Li); smaller area	661	x		VIc			
Damiani et al. (2019)	2019	List of members; PPM (Gaia DR2)	3675	x	CXO	many			
WISE/AllWISE (Wright et al. 2010)		catalog; whole area	19,087					WISE 1234	
Herschel/HPDP PSC 70 (Marton et al. 2017)		catalog; smaller area	12						PACS 70
Herschel/HPDP PSC 160 (Marton et al. 2017)		catalog; smaller area	44						PACS 160
AKARI IRC (Murakami et al. 2007)		catalog; whole area	270					Akari 9,18	
AKARI FIS (Murakami et al. 2007)		catalog; whole area	231						Akari 65, 90, 140, 160

MSX (Egan et al. 2003)		catalog; whole area	827					MSXAB1B 2CDE	
IRAS/PSC (Neugebauer et al. 1984)		catalog; whole area (low resolution!)	66					IRAS 12	IRAS 25, 60,100
SCUBA (DiFrancesco et al. 2018)		catalog; smaller area	153						SCUBA 450,850
2MASS/PSC (Skrutskie et al. 2006)		catalog; whole area	92,414				JHK		
Spitzer/SEIP		catalog; whole area	47,030					IRAC 1234. M1	
Spitzer/GLIMPSE (Benjamin et al. 2003; Churchwell et al. 2009)		catalog; nearly whole area	170,867					IRAC 1234	
EPIC (Huber et al. 2014)		catalog - link to K2 data(*); whole area	19,433						
DENIS (DENIS Consortium 2005)		catalog; nearly whole area	81,987			i	JK		
Gaia DR2 (Bailer-Jones et al. 2018)		catalog with distances calculated under Bayesian statistics; whole area	91,118			Gaia BGR			
Gaia DR2 (Gaia Collaboration 2018)		catalog; whole area	142,987						
Bell et al. (2013)	2013	catalog with everything and with member subset; smaller area	14,610	x		Ugri	Z		
PanSTARRS (Chambers et al. 2016)		catalog; whole area	304,340			gri	zy		
VVV (Saito et al. 2012)		catalog; whole area	455,732				zyjhk		

VPHAS (Drew et al. 2014)		catalog; whole area	553,338			ugri, Ha			
UKIDSS (Lucas et al. 2008)		catalog; nearly whole area	836,387				jhk		

(*) Everything with a LC should have an EPIC number, but not everything with an EPIC number has a LC.