A Search for Low-Mass Young Stellar Objects in Star Cluster AFGL 490

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1.0 Abstract

Based on theoretical models and observations, it is thought that most stars form in clusters, although much about cluster formation and evolution is still unknown. Sometimes, young stellar objects (YSOs) are so embedded in envelopes of gas and dust that a complete list of YSOs in a cluster is difficult to obtain. Having a complete list of cluster members is useful in order to compare the cluster's properties to other, older clusters. Our project will be to work toward the development of a complete membership list for the cluster of YSOs emerging from the dust cloud surrounding the high mass star AFGL 490. This embedded cluster of low-mass stars around the high-mass (8-10 $M_\odot$) star AFGL 490 (see Straižys & Laugalys 2008 and references therein), is located within the plane of the Galaxy in the Cam OB1 association. This research will build upon work done by Gutermuth et al. (2009) and Masiunas et al. (2012), who studied this cluster with Spitzer/IRAC (Infrared Array Camera) and MIPS (Multi-band Imaging Photometer for Spitzer), identifying several hundred YSO candidates from their infrared (IR) excesses, which are associated with dust surrounding each of the YSOs. The YSOVAR (YSO VARiability) project (Rebull et al. 2014) also monitored this region with Spitzer/IRAC, but no one has yet explored the light curves (graphs of light variability vs. time) in detail. Since those works were published, several optical databases have become available in this region (Panoramic Survey Telescope and Rapid Response System [PanSTARRS], INT Photometric H-Alpha Survey [IPHAS], and Gaia). We propose to collect all of the literature-identified YSOs, combine several archival optical (PanSTARRS, IPHAS, and Gaia) and IR (Spitzer/IRAC & MIPS, Wide-Field Infrared Survey Explorer [WISE], Herschel/Photodetector Array Camera and Spectrometer [PACS], Akari, Midcourse Space Experiment [MSX]) data sets, and identify new candidate YSOs using IR excesses, g-band excesses, and hydrogen-alpha (Hα) excesses. We will then use the merged data to assess all of the candidate YSOs using image inspection, spectral energy distributions, and color-color/color-magnitude diagrams to identify which targets are most likely to be YSOs. If time permits, we will also explore the variability characteristics of these YSOs in the IR using the YSOVAR data.

2.0 Science Introduction and Context

2.1 Formation and Characteristics of Low-Mass Young Stellar Objects

A nebula is a large cloud of gas and dust. Under the right conditions, star formation can be triggered in nebulae, creating stellar nurseries. Stars have masses between ~0.08 and ~250 solar masses, and are classified by spectral type. Very massive, hot stars are classified as O or B stars. Medium-mass stars are classified as A or F stars. Low mass, cooler stars are classified as G, K, or M stars (our Sun is a G2 star). To form a star, turbulence of the matter within a nebula gives rise to knots which begin to gravitationally collapse, falling towards the center of mass. The cloud is spinning intrinsically, likely from the rotation of the host galaxy. As the gas continues to collapse, the conservation of angular momentum intensifies the spin rate, generating a disk of matter around the dense core as material continues to fall inward (Figure 1). Over time, this disk thins out and can ultimately form planets as matter accretes onto the central object. At the conclusion of this process, the inward push of gravity is finally halted by the process of fusion of hydrogen within the core. This results in a main sequence star, potentially with a planetary system. During this process, from the initial disturbance within the nebula to the time when the star begins fusion in the core, the object is classified as a young stellar object (YSO). In low-mass stars, this process takes on the order of 50 Myr. It is thought higher mass stars probably go through much of this same process at a faster pace; the stars may ignite hydrogen before dispersing the disk.

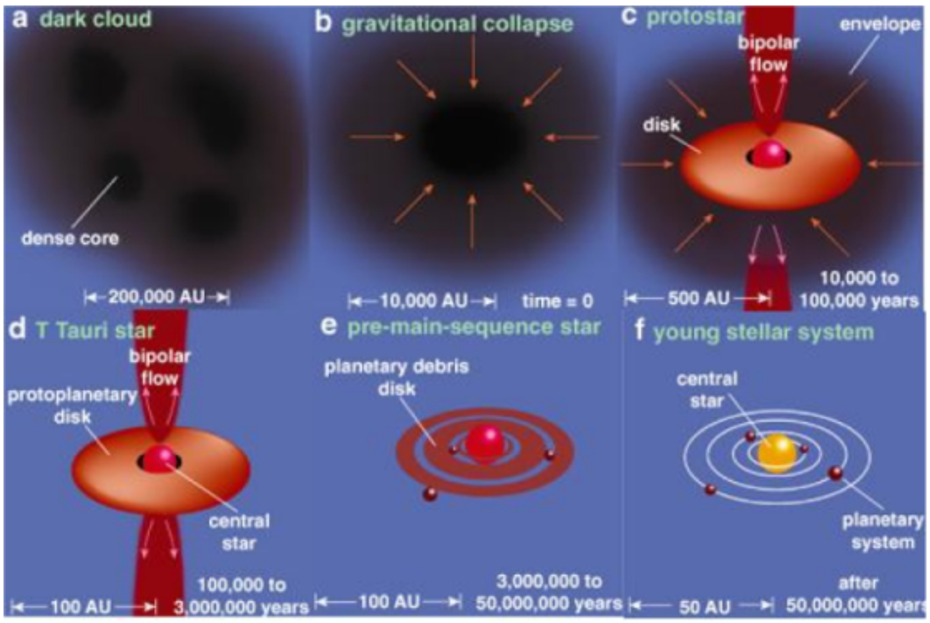


Figure 1: This diagram (Greene 2001) shows the process of low-mass star formation, from YSO to main sequence star.

The dust that surrounds a YSO intercepts energy radiated by the central YSO. It re-radiates this energy in the infrared (IR). Therefore, the dust around YSOs is useful because it makes YSOs brighter in IR than stars that do not have circumstellar dust (Figure 2). Throughout this process, the forming star, or YSO, goes through many phases and each phase is labeled as a class. The YSO classes are defined by their spectral energy distribution (SED) shapes (Figure 3). An SED is a diagram showing the energy density (can be thought of as "brightness") of an object as a function of wavelength or frequency. The amount of IR excess present in a YSO can be seen when the SED is plotted.

Initially, the star accretes most of its mass (the main accretion phase) as the gas and dust are coalescing and the YSO is still cocooned within its natal cloud. This Class 0 YSO is also called a protostar. A Class I YSO already has most of its mass in the central object. It still has a fairly substantial circumstellar disk, though the natal cocoon has started to disperse. As the YSO continues to accrete material and its natal cocoon disappears, it becomes a Class II YSO, which is sometimes called a classical T Tauri star (CTTS). Class II YSOs are surrounded by substantial (optically thick) disks of matter. Because a Class I SED is rising and a Class II SED is falling, sometimes one sees a "Flat" class SED in between Class I and II. As a Class II YSO transitions to a Class III YSO (sometimes called a weak-lined T Tauri star, WTTS), its circumstellar disk thins and matter in the disk clumps together, forming planetesimals and eventually planetary systems (Figure 3).

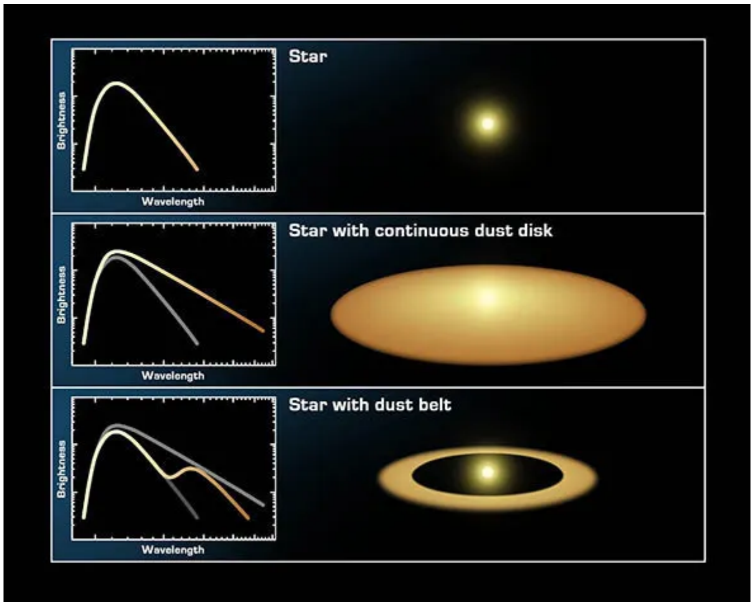


Figure 2: All three images show SEDs (Spitzer press release sig 05-026, NASA/JPL-Caltech/T. Pyle [SSC]). The top row shows the SED of a star. The middle row shows how the SED of a star with a circumstellar disk changes. In the bottom row, there is a star with a surrounding dust ring, which can be approximated as dust at a single temperature. The dust ring does not envelop the star, so the net SED of the star and the dust ring looks like the sum of two blackbodies. The first peak is the warmer blackbody of the star and the second peak is the cooler blackbody of the dust ring.

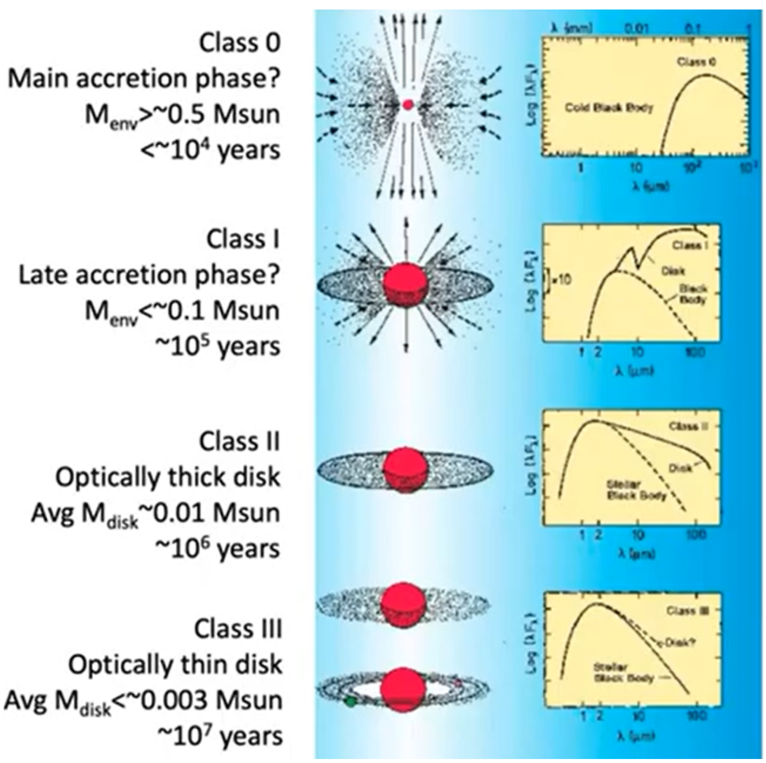


Figure 3: This diagram shows the stages of YSO formation, each class with its corresponding SED. (Figure adapted from Bachiller 1996.)

Variability is one of the defining characteristics of YSOs (Joy 1945). The dynamic nature of YSOs is due to the interactions between the YSO and the disk, the fact that the YSO is accreting from the disk, the fact that the strong magnetic field of the star likely locks its rotation to that of the disk, and the fact that the strong magnetic field of the YSO also makes for large spots and flares. The spots on the central object and the accretion from the circumstellar disk can generate shocks and flares. YSOs can have large ultraviolet (UV) excesses due to these shocks from active accretion (Figure 4). The shocks arise when matter moves along the magnetic field lines from the disk and hits the star. The bright X-rays emitted from flares as well as bright hydrogen-alpha (H**α**) emission lines occurring within the accretion columns generate stellar activities that can result in identifiers for YSOs (Figure 4).

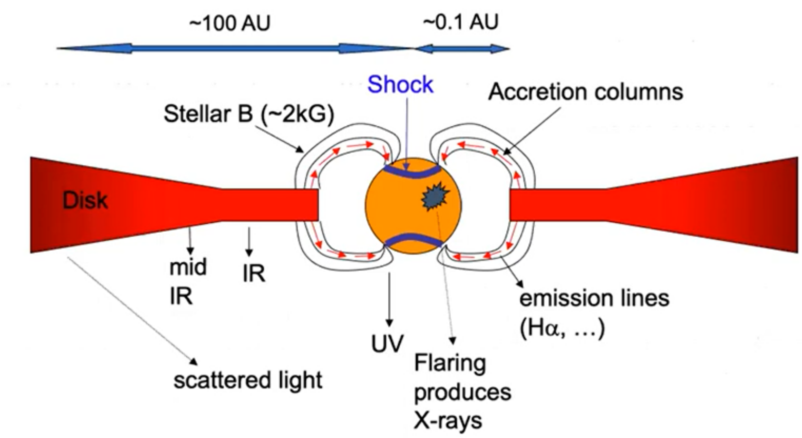


Figure 4: This diagram illustrates the anatomy of a Class II YSO and the various characteristics that can be used to identify YSOs; IR excess, UV excess, X-rays, and H**α** emission lines. (Figure from Rebull 2011.)

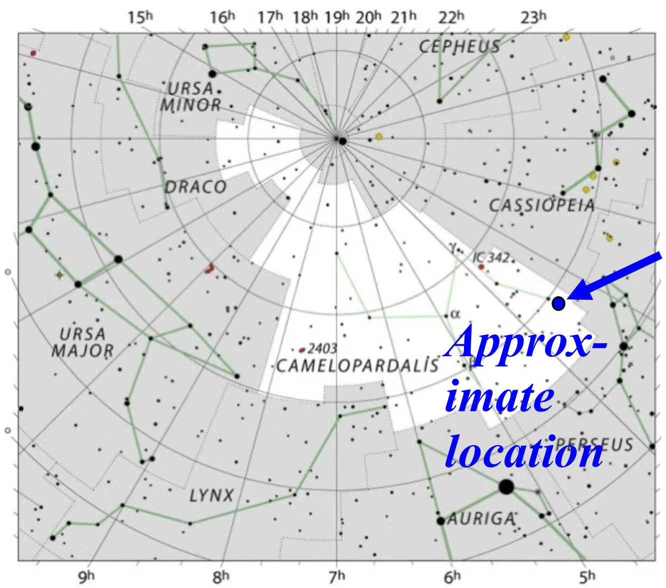
In order to develop an understanding of YSO formation, it is important to study star clusters. As more clusters are studied, more information can be learned about both star formation and evolution as well as cluster formation and evolution. It is important to understand the classes of YSOs because with this information more can be learned about the early stages of a star's life cycle, including how planetary systems are formed. Assuming that stars within a cluster form at the same time, comparisons of data from other clusters can be used to determine the relative age of the cluster as a whole, and then place that cluster in context with others.

If we achieve our goal of developing a more complete list of cluster members for AFGL 490, we can compare this cluster to other clusters and learn more about cluster evolution. AFGL 490 has been identified as an embedded cluster, meaning the cluster is very young because it is still buried within the dust in which it formed. Using archival IR data will help us see through the dust to find the YSOs. However, since dust scatters shorter wavelengths, this may complicate our plans to use optical data to study these YSOs.

2.2 Target Information: AFGL 490

2.2.1 General Location and Characteristics

The star AFGL 490 (sometimes called RAFGL 490 or GL 490) is a massive (~8-10 M⊙) star (see Straižys & Laugalys 2008 and references therein). Hodapp (1994), working in the near-IR, first recognized that there is an apparent cluster of lower-mass stars around the massive star. This cluster of stars has (sometimes confusingly) inherited the name of the massive star. **We will be studying the cluster of lower mass stars around the massive star.** Data suggest this cluster is between 1 and 5 million years old (Rebull et al. 2014 and references therein). It is 900 pc away (Snell et. al 1984), in the Local Arm of the Galaxy (ℓ=142.0° b=+01.82°), in the direction of Camelopardalis, a northern hemisphere constellation (Figures 5 and 6). It is part of a much larger complex, the CamOB1 association (see Straižys & Laugalys 2008 and references therein, and Figure 6).



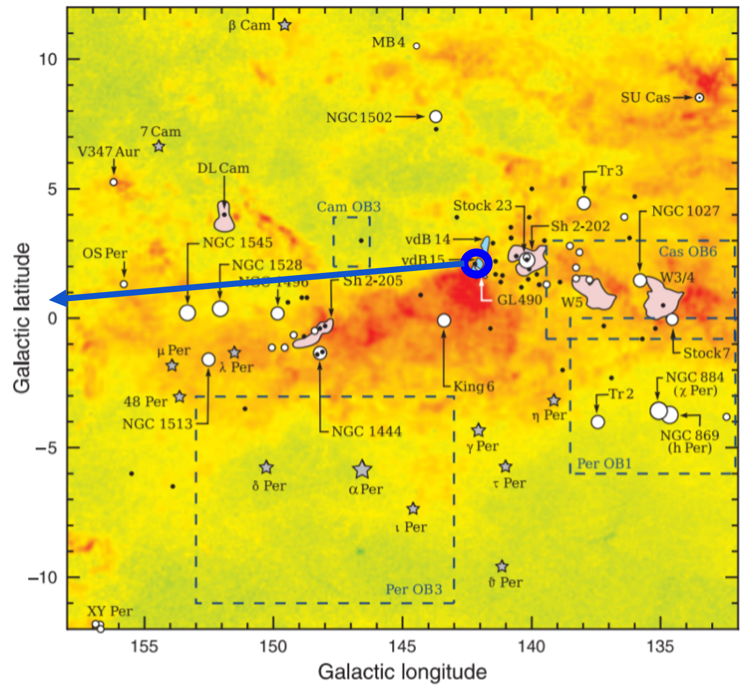


Figure 5 (left) (from International Astronomical Union and Sky & Telescope) shows the approximate location of AFGL 490 in the constellation Camelopardalis.
Figure 6 (right) (from Straižys & Laugalys 2008) shows dust clouds from Dobashi et al. (2005) plotted together with clusters, nebulae and known young objects identified by Straižys & Laugalys (2008). The darker orange/red regions indicate dust clouds. Our research will focus on identifying low-mass YSOs in the dust cloud immediately around the high-mass star AFGL 490 (labeled in Figure 6 as "GL 490" and indicated by the blue circle). For a more detailed image related to the size of the area of study, refer to Figure 8.

The characteristics of the high-mass stellar object that dominates this region, AFGL 490, have been studied using IR data as early as Harvey et al. (1979). However, the cluster surrounding AFGL 490 has been studied in significantly less detail. The first time the AFGL 490 cluster is mentioned as being an area of focus is in a paper by Hodapp (1994) where it was first recognized in near-IR as an apparent cluster of about 100 lower-mass stars around the massive star. Lada & Lada (2003) list this cluster as an embedded cluster. Figure 7 shows the bright star AFGL 490, and the surrounding nebulosity in the IR is immediately obvious.

Figure 7: This is an image of AFGL 490 taken by the Wide-Field Infrared Survey Explorer (WISE). This image shows wavelengths of 3.4 μm (blue), 4.6 μm (cyan), 12 μm (green) and 22 μm (red). North is to the right and East is up. This image is approximately represented by the circle in Figure 6. (Figure from NASA/JPL-Caltech/WISE Team 2010).

2.2.2 Previous Studies of AFGL 490

Straižys and collaborators explored a very large region that encompasses AFGL 490 (Figure 6), the results of which were published in seven papers between 2007-2010. Straižys & Laugalys (2007a) covered much of the region in Figure 6, i.e. much more than AFGL 490, and identified where the dust clouds were located. Straižys & Laugalys (2007b) identified IR-bright YSOs using the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984), and the Midcourse Space Experiment (MSX; Egan et al. 2003), eight of which are in our region. Straižys & Laugalys (2008a) worked more closely with the region surrounding AFGL 490, but still in a region much larger (3°x3°) than we are considering here, such that just 12 of the objects listed there as YSOs are in our region. Straižys & Laugalys (2008b) is a review article about Cam OB1, which has very little information about AFGL 490 in particular, because it covers the very large region seen in Figure 6. Straižys & Corbally (2008, 2009) reported on the spectroscopic follow-up of several YSO candidates, confirming their YSO status, but just four of the objects covered in both of these papers appear in our region. Straižys & Kazlauskas (2010) continued work over the very large region from their first paper, including data from Akari (Murakami et al. 2007) and Spitzer (Werner et al. 2004); 15 of their YSOs are in our region. In Table 1, below, we refer to all seven of these papers together as “Straižys et al.” without a year. There are 21 unique YSO candidates from all of these papers together in our region.

Table 1: *Summary of Literature YSOs*

Bin #	1	2	3	4	5	6
Origin of YSO list	Gutermuth+ (2009) and Masiunas+ (2012)	Straižys et al.	YSOVAR (Rebull+ 2014)	Barentsen+ (2014)	Winston+ (2020)	New identification by us
Method of finding YSOs	IR excess	IR excess	Variability in IR	Objects bright in H**α**	IR excess	H**α** excess, g-band excess, IR variability, optical variability
Number of YSO Identifications	351	21 (3 not already identified in other bins)	254 (125 already in Bin 1)	4 objects (all of them are also in Bin 1)	193 (19 not already in other bins)	TBD, estimate ~20 new
Catalog	2MASS and Spitzer and their own deep JHK data	2MASS, IRAS, Akari, MSX, Spitzer/ IRAC, spectros-copy	2MASS, Spitzer/ IRAC and MIPS, UKIDSS	IPHAS	2MASS, Spitzer, and WISE	*IR:* JHK (2MASS, UKIDSS, Masiunas+), Spitzer/ IRAC & MIPS, WISE *Optical:* IPHAS (H**α**), **Gaia DR2 (distances), PanSTARRS (grizy)**
Tasks to be done here	Candidates will be inspected and refined here (Goal 1)	Candidates will be inspected and refined here; we will reach fainter sources from Akari & MSX (Goal 1)	We will identify new YSO candidates (Goal 1)	Candidates will be inspected and refined here; we will look for new H**α** bright candidates (Goal 1)	Candidates will be inspected and refined here (Goal 1)	We will identify new YSO candidates and refine the list of variables (Goal 2 and Stretch Goal)

Gutermuth et al. (2009) studied the entire list of embedded clusters from Lada & Lada (2003) using the Spitzer/Infrared Array Camera (IRAC; Fazio et al. 2004) and Multi-band Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004), and thus included AFGL 490 in their study as one of many clusters. They discovered that the AFGL 490 cluster extended beyond the region covered in the initial survey, so they went on to survey a larger region with IRAC and MIPS, with additional deep JHK data collected as well. Masiunas et al. (2012) reported on these observations of the region surrounding the high-mass star, AFGL 490, selecting YSOs in this region using IR excesses and the Gutermuth method of selecting YSOs (using JHK and Spitzer bands). They reported ~350 YSO candidates in the region that we are proposing to study here.

AFGL 490 was one of a dozen star-forming regions selected for monitoring with Spitzer as part of the YSO VARiability (YSOVAR) project (Rebull et al. 2014); (Figure 8). While the Spitzer light curves already exist, and some variables have been identified (Rebull et al. 2014), no individual sources have been analyzed in detail. There are approximately 250 variables that were identified in this region.

Additionally, because this cluster is in the Galactic Plane, it has serendipitously been observed by several Galactic Plane surveys, including the INT Photometric H-Alpha Survey (IPHAS; Barentsen et al. 2014) and the Herschel Space Observatory (Pilbratt et al. 2010)/Herschel Infrared Galactic Plane Survey (HiGal; Molinari et al. 2010). Some of these surveys have identified candidate YSOs in the AFGL 490 region. Barentsen et al. (2014) identified four H$\boldsymbol{\alpha}$-bright stars using IPHAS, while Winston et al. (2020) used WISE (Wright et al. 2010) and Spitzer to find ~200 YSO candidates from IR excesses. All of the H$\boldsymbol{\alpha}$-bright stars were identified by Masiunas et al. (2012), and all but ~20 of the Winston et al. (2020) stars were similarly identified by Masiunas et al. (2012). There are also relatively recently available data from the Panoramic Survey Telescope and Rapid Response System (PanSTARRS; Chambers et al. 2016) and Gaia (Gaia Collaboration 2018) that have not yet been incorporated into the analysis of the YSO candidates in this region.

2.2.3 Our work with AFGL 490

Figure 8 is the region we plan to study, and it goes from $\boldsymbol{\alpha}$ =03:25:23 to 03:29:24 and $\boldsymbol{\delta}$=+58:22:54 to +59:03:23.1, so 44 arcminutes by 36 arcminutes = 0.44 square degrees, roughly centered on AFGL 490. Incorporating all of the literature data above, there are ~480 unique literature-identified YSO candidates in this region. There are substantial archival data that have not yet been mined that can be used to further our goal of finding and studying low-mass YSOs. **We will look for new YSOs as well as further confirm/refute the YSO status of the literature-identified YSO candidates.** Based on a preliminary, rough analysis, we expect to find approximately 20 possible new YSO candidates.

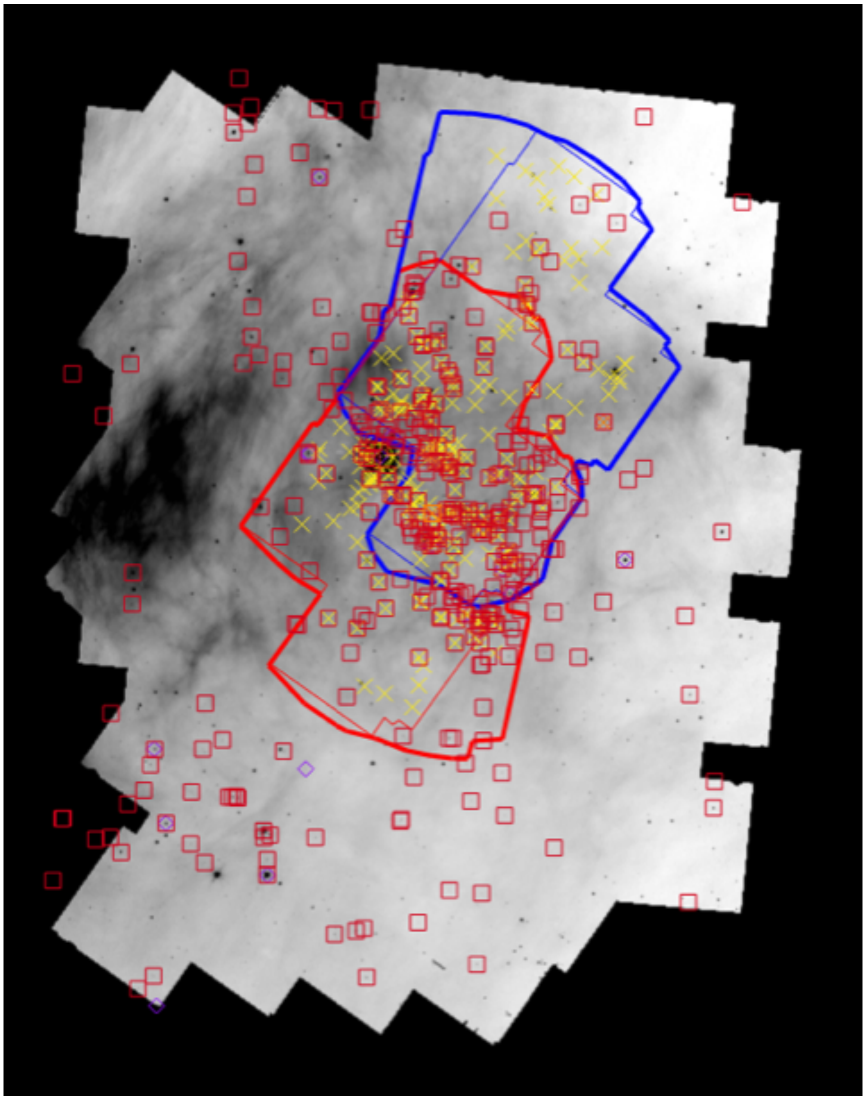


Figure 8: This is the region of AFGL 490 that we will study, building upon previous research by Rebull et al. 2014. The boundaries of this image are 03:25:23 to 03:29:24 and +58:22:54 to +59:03:23.1. The background is IRAC-4 (8 μm). The YSOVAR footprints are represented by red lines indicating data collected by Spitzer IRAC-2 (4.5 μm) and blue lines indicating data collected by Spitzer IRAC-1 (3.6 μm). This image measures 44' North-South by 36' East-West, where North is up and East is left. Using the Gutermuth method of identifying YSOs using IR excesses, the red squares are YSO candidates from Gutermuth et al. (2009) and Masiunas et al. (2012). Using YSOVAR light curves, the yellow x's are variable YSO candidates identified from Rebull et al. (2014). The purple diamonds are YSO sources from Straižys & Laugalys (2008).

3.0 Analysis Plan

3.1 Goals of the Project

Goal 1: There is not yet a complete list of low-mass cluster members in the literature for AFGL 490. We will focus on assembling a list of YSO candidates from the literature, identifying new YSO candidates using several methods, and assessing all of them using all of the newly available data to create a cleaned list of high-confidence YSO candidates.

Goal 2: Explore the variability of the YSO candidates in the IR (IRAC-1 and -2 from Spitzer).

Stretch Goal: Investigate the variability of these YSO candidates in the optical (g- and r-band) from the Zwicky Transient Facility (ZTF; Masci et al. 2019).

3.2 Analysis Specifics

3.2.1 Assembling the Catalog

The complete catalog is summarized in Table 2 and summarized in words here as well. In the context of YSOVAR, Rebull et al. (2014) already assembled a master catalog that merged the entire catalog from Masiunas et al. (2012), not just the published subset, which includes JHK data much deeper than that from 2MASS and from the Spitzer Space Telescope - IRAC and MIPS. Masiunas et al. (2012) built on analysis done by Gutermuth et al. (2009), and published a slightly different list of YSOs in the region in common with the older study. Because it is in the Galactic Plane, AFGL 490 was also part of the GLIMPSE (Galactic Legacy Infrared Mid-Plane Surveys Extraordinaire; Churchwell et al. 2009) survey, which provided another Spitzer data reduction option. The master catalog keeps track of which sources were identified in which study.

Through the development of the complete catalog, we merged catalogs by position from WISE and the AllWISE release, as well as those from CatWISE (Marocco et al. 2021) and unWISE (Meisner et al. 2021) as served by the Infrared Science Archive (IRSA). We also merged by position catalogs from Pan-STARRS DR1 and the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), IPHAS, and Gaia DR2, including distances from Bailer-Jones et al. (2018). To our knowledge, no one has explored in detail the optical properties of the YSO candidates in this region using IPHAS, PanSTARRS, or Gaia DR2. At the time this proposal was written, Gaia EDR3 had not yet been incorporated. We plan on incorporating it into the complete catalog early in our research process.

Additionally, we merged catalogs from IRSA using longer wavelengths. The Herschel Space Observatory surveyed the Galactic Plane as part of the Hi-Gal survey using both PACS (Poglitsch et al. 2010) and the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010). The Herschel PACS Highly Processed Data Products (Marton et al. 2017) provided catalogs from which we can use photometry directly without having to do it ourselves, and we have started from those products. We also merged by position the data products from Akari Infrared Camera (IRC) and Far-Infrared Surveyor (FIS), and MSX. The Herschel/PACS, Akari, and MSX data all have lower (worse) spatial resolution and worse sensitivity than the existing IR data merged above, but can provide useful additional points for the brightest YSO SEDs.

For completeness here, we mention that ZTF also observed this region, but as it is used in our stretch goal, we have not yet investigated how many counterparts there are from this catalog in our region.

3.2.2 Assembling the Literature YSOs

For each of the papers listed above, we merged the YSO identifications by position. Table 1 in section 2.2.2 summarizes the literature YSOs. Masiunas et al. (2012) is the largest catalog of YSO candidates and the easiest list of YSOs to merge, since we are already working from that catalog as a base for the master catalog. There are ~350 YSOs identified via IR excesses from 2MASS+Spitzer bands in this paper. The next largest catalog is from YSOVAR, and this is easy to merge because it is also based on the same master catalog. There are ~250 YSOs identified from variability in the Spitzer bands, though they have not been subjected to in depth inspection. About half of those YSOs are also identified from IR excesses by Masiunas. Just four YSO candidates are identified via extreme Hα excesses; all of them were already identified from IR excesses by Masiunas. Winston et al. (2020) used WISE+Spitzer to tag ~200 YSO candidates based on IR excesses, but just ~20 are not already identified based on other indicators to this point. The ensemble from the Straižys et al.

Table 2: *Summary of Data Sets Included in Master Catalog*
* Point sources in AFGL 490 have not yet been explored in these catalogs
** full Masiunas catalogs are available to us as collaborators with Rob Gutermuth

Source: (Catalog available from survey or literature)	**Wavelengths and/or bands**	**Fraction of catalog that has a match:**	**Number of Sources**
2MASS (ground-based)	Near IR: 2 μm (JHK bands)	~10%	3215
**Masiunas	Near IR: JHK bands (~2 μm) and IRAC	~95%	30612
**Masiunas	IRAC	~95%	30724
Any Spitzer YSOVAR LC	Mid IR: IRAC-1 and IRAC-2	~6%	2025
*GLIMPSE	Mid IR: IRAC-1 and 2 (3.6, 4.5, 5.8, 8 μm)	~52%	16728
*AllWISE (full cryogenic 2010)	Mid IR: WISE-1, 2, 3, and 4 (3.4, 4.6, 12, 22 μm)	~4%	1314
*CatWISE (NEOWISE)	Mid IR: WISE-1 and WISE-2 (3.4, 4.5 μm)	~33%	10601
*UnWISE (NEOWISE)	Mid IR: WISE-1 and WISE-2 (3.4, 4.5 μm)	~34%	10915
**any WISE band, summary*	*39% of our catalog has a counterpart at any WISE band*	~39%	12531
*Pan-STARRS (ground-based)	Optical: grizy	~11%	3597
*UKIDSS (ground-based)	Near IR: JHK (~0.88 - 2.2 μm)	~68%	21835
*IPHAS (ground-based)	Optical - r, i, Ha	~17%	5510
*Gaia DR2	Optical: G, BP/RP (Blue and Red Photometers)	~20%	6666
*Any Herschel/PACS	Far IR: 70, 160 μm	~0.071%	23
*Any AKARI/IRC	Mid IR: 9 and 18 μm	~0.056%	18
*Any AKARI/FIS	Far IR: 65, 90, 140, 160 μm	~0.06%	20
*Any MSX	Mid IR: 8.28, 12.13, 14.65, 21.3 μm	~0.028%	9

papers is hardest to merge because they were working from inhomogeneous catalogs, some of which were low-precision coordinates. However, using conservative coordinate matches, there are 21 matches to sources in our region, three of which are not already identified using other means.

3.2.3 Achieving Goal 1: Looking for New YSO candidates

IR excess. IR excess arises in YSO candidates from circumstellar dust. Several investigators have already looked for YSO candidates in AFGL 490 using IR excesses, but nonetheless there are some gaps in what they have done. To the best of our knowledge, no one has yet explored the Herschel data in this region, and there are obvious point sources visible in the image. The Straižys et al. collection of papers explored some of the MSX and Akari sources, but perhaps not all of the sources in our region. We will explore all of these sources.

Hα excess. Hα excess comes from accretion columns, or from activity, in YSOs (Figure 4). The IPHAS team identified very bright Hα stars from their entire survey, so they were only identifying the most extreme sources. They found only four such sources in our region, and all of them also turn out to have large IR excesses. We will take the IPHAS data in this region and look for the less extreme sources -- those that are brighter than expected for activity typical of field M dwarfs, but faint enough that they have not been identified already.

Blue excess. UV excesses in YSOs come from accretion shocks. While there is no UV data available, a strong enough UV excess will spill over into adjacent bandpasses. The bluest band we have is g-band (visible light of short wavelengths) from Pan-STARRS. An earlier NITARP team (2019) found many YSOs with g-band excesses in M8, the Lagoon Nebula. It is possible that we will find some similar YSO candidates with such g-band excesses in AFGL 490. However, this is also the method for finding YSOs that is likely to be most affected by interstellar extinction (the dimming of a star due to the presence of dust along the line of sight that causes scattering). Since this is an embedded cluster, it may very well be that too few of the stars are even detected at g, much less have unambiguous excesses at g. We will have to investigate.

3.2.4 Achieving Goal 1: Checking YSO Candidates

For each of the literature YSO candidates and the new YSO candidates we have identified, we will use the data we have amassed to determine whether or not we believe that they are really YSOs at 900 pc, the distance of AFGL 490.

SED construction. Given the multi-wavelength catalog we have constructed, we will assemble spectral energy distributions (SEDs) for these YSO candidates over five orders of magnitude in wavelength (from 0.48 μm, g-band, to 160 μm, PACS-red). No sources will be detected at **all** bands between 0.48 and 160 μm, but many will be detected at most bands between the optical and 22 μm. In each case, we will use the SED to (a) determine whether or not our source matching by position across catalogs worked (if it failed, there will be discontinuities in the SED); (b) determine whether the SED resembles that of a YSO or a background galaxy or a reddened asymptotic giant branch (AGB) star; and (c) place the YSO SED in the appropriate SED class; I, flat II, III (Figure 3).

Image inspection. We will use the IRSA tools Finder Chart and IRSA Viewer to inspect the images of the sources to be sure they are point sources. We will particularly investigate those point sources that have been detected at longer wavelengths by Akari, MSX, and Herschel to be sure that they are identified with the correct shorter-wavelength counterpart, and that they still appear to be point-like at all available bands.

Color-color and color-magnitude diagrams. We will create optical and IR color-color and color-magnitude diagrams for the YSO candidates. We will use these diagrams to assess whether or not the YSO candidates are eligible to be YSO candidates, or whether they are, e.g., more likely to be background giants. We will use the JHK color-color diagram to calculate the total reddening, which we then can use to approximately deredden the optical color-magnitude diagrams. We will use PARSEC models (http://stev.oapd.inaf.it/cgi-bin/cmd; Bressan et al. 2012) for isochrones and Gaia distances from Bailer–Jones et al. (2018) to try to constrain the age and distance of AFGL 490 and rule out membership of some of the YSO candidates in the list. There is an additional section below with additional information specifically on color-color and color-magnitude diagrams. Figure 9 shows models with isochrones, demonstrating the concepts associated with the placement of YSOs above the main sequence as a function of age.

Longer term. In order to confirm that these objects really are YSOs and not just YSO candidates, we will need follow-up spectroscopy. That is beyond the scope of this project. The kinds of contamination that we could have in our YSO candidate list include background giants, particularly AGB stars, and quasars/active galactic nuclei (AGN). With as many optical bands as we have, we are hoping to limit this kind of contamination, but spectroscopy is needed.

3.2.5 Achieving Goal 2: Variability

Variability is one of the defining characteristics of YSOs (Joy 1945). The dynamic nature of YSOs is due to the interactions between the YSO and the disk, the fact that the YSO is accreting from the disk, the fact that the strong magnetic field of the star likely locks its rotation to that of the disk, and the fact that the strong magnetic field of the YSO also makes for large spots and flares. All of these characteristics result in variability that can be detected in IR and optical.

The YSOVAR project (Rebull et al. 2014) monitored a dozen star forming regions in the two shortest bands with Spitzer, 3.6 and 4.5 μm. They identified variables in AFGL 490 via a "lights-out" pipeline – that is, they made choices that they felt would conservatively identify targets very likely to be variable, but were unlikely to grab *all* the variables, e.g., unlikely to be complete, and moreover unlikely to have light curves "cleaned" of outliers, e.g., light curves having the best possible statistics.

We will spend some time looking at the light curves from the YSOVAR project to determine which light curves need modification, see if any obvious variables were missed, see if any obvious periods were missed, etc., add any missed variables to the list of literature YSOs above, and complete the above analysis for those missed YSOs if necessary.

Through this process, we will be developing the skills and statistics necessary to move forward with our stretch goals, if time allows. We will be starting from materials that Rebull et al. developed as part of the 2021 NITARP team which started on ZTF and NEOWISE light curves for IC 417.

3.2.6 Achieving the Stretch Goal:

ZTF monitors the sky visible from Palomar at a cadence of about once per night, in the optical, mostly at r-band, with some g-band as well. There are light curves of about 500 points covering about 1200 days available for several hundred stars in this area. If we get to this goal, we will explore whether or not these light curves can tell us anything new about the stars here, beyond what we will learn in our explorations above.

4.0 Additional Background Information

An SED shows the energy density of a source as a function of wavelength or frequency. SEDs can be useful in identifying YSO candidates because the IR excesses are immediately obvious. In an SED, many wavelength points can be plotted for one object at a time. In this way, we can create an SED plot of one target, and through comparisons of the SEDs of different classes of YSOs, use that SED plot to make sure that the SED resembles that of known YSOs, and place the SED in a YSO class (I, flat, II, III).

A magnitude measurement is the brightness measurement of a star (or galaxy or anything else) through a filter (including losses due to mirror reflections or lens transmission and atmosphere transmission if relevant, basically everything the photons went through to get detected). It is really a flux ratio, given the definition of magnitudes:

$$m_1 - m_2 = 2.5log\left(\frac{F_2}{F_1}\right)$$

Note that this is sort of "backwards" in that larger numbers mean fainter sources. The magnitude system was defined to be referenced to Vega, which is defined to be zero magnitude. So, if star #2 in that formula is Vega, m_2 is 0, and F_2 is Vega's flux:

$$M = 2.5log\left(\frac{F_{Vega}}{F}\right)$$

Stars get fainter when they get further away, and the equation for that is:

$$m - M = 5log(d) - 5$$

This is known as the distance modulus equation, where m is apparent magnitude, M is absolute magnitude, and d is distance in parsecs. Note that further away means fainter, which means larger numbers because of the way magnitude is defined.

Flux densities (colloquially often shortened imprecisely to 'fluxes') are energy per unit area per unit time per photon. SEDs are energy densities (energy per "photon"). It is necessary to convert flux densities or magnitudes into energy densities before plotting for SEDs.

If the magnitude of a star (or any other object) is measured in one band, through its calibration it is implicitly compared to Vega. If the magnitude of a star (or any other object) is measured in TWO bands, which are then compared, the Vega flux cancels out. Color, the difference of two magnitudes (shorter wavelength band minus longer wavelength band) is actually a ratio of the fluxes, and then the distance cancels out (along with Vega). Intuitively this makes sense because a red star is red whether the observer is close to it or far away from it. If the star is farther away, it is fainter in blue AND fainter in red. Its brightness in red light divided by its brightness in blue light is something that won't change with distance. What is going to change the color, though, is the temperature of the object. If it is always plotted as (magnitude in bluer band) – (magnitude in redder band), a smaller number will be a bluer color, and a larger number will be a redder color. This is the color index.

A color-magnitude diagram (CMD) shows something that is independent of distance on the x-axis, and something that is dependent on distance on the y-axis. This is useful in some cases. If all of the stars in a cluster, for example, are at about the same distance, the placement of all the stars in the cluster can be used in an optical CMD to estimate the age of the cluster. This is harder for very young clusters, because the young stars have not yet started burning hydrogen, e.g., they are not yet on the main sequence, so uncertainties in distance can result in large uncertainties in age. Figure 9 shows an example of an H-R diagram (luminosity vs. effective temperature), but this is just the theoretical version of a color-magnitude diagram. In an optical color-magnitude diagram; brightness (V) can be converted to luminosity and color (B-V) can be converted to effective temperature. At any rate, Figure 9 shows evolutionary tracks for stars of a variety of masses and ages. The isochrones, or lines of constant age, are the red lines.

For AFGL 490, we are expecting our stars to hover around a line of about 1-5 Myr above the zero-age main sequence (ZAMS) lines expected for a cluster at ~900 pc. We can get those isochrones from models, like the PARSEC models, as described above. CMDs in the IR can be helpful too, but the ZAMS line becomes more and more vertical moving farther into the IR, so they are useful for different things other than finding the age of the cluster -- e.g., finding IR excesses.

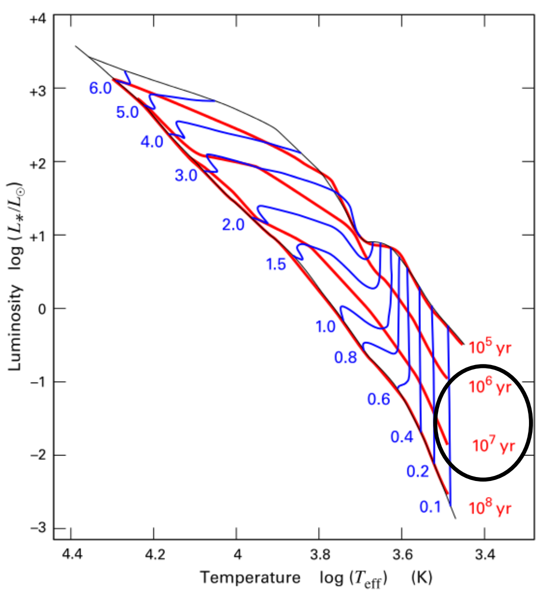


Figure 9: Temperature is a representation of color index and luminosity is a representation of magnitude. Red lines are isochrones (lines of constant age), corresponding to 10^5, 10^6, 10^7, and 10^8 years, as marked. Blue lines are lines of constant mass, corresponding to masses as marked in units of solar masses. The circle calls out 1-10 Myr isochrones. Stars in AFGL 490 shoule be 1-10 Myr, and we are likely to find stars between 0.5-3 Msun. (Figure from Stahler & Palla 2004).

A color-color diagram uses colors on both the x- and y-axes. In those cases, both axes are independent of distance, and specifically, the distribution of points can be used to identify points that are "different from the others." Several examples include the near-IR JHK diagram, which can be used to estimate the degree of interstellar reddening; the mid-IR IRAC diagram, which can be used to identify the stars with large IR excess; the IPHAS diagram, which can be used to identify the stars with large H**α** excess; and a PanSTARRS diagram, which can be used to identify the stars with large g-band excess. For our research, in all of these cases we will need to know where we expect to find normal stars. We can attempt to do this empirically by looking at all of the "not-special" stars in our catalog, or (more reliably) by using a catalog of known main sequence stars. We'll do the latter. In the mid- and far-IR, color-color diagrams are particularly useful because main sequence stars without dust should have zero color (refer to Figure 10). Thus, anything with dust around it stands out.

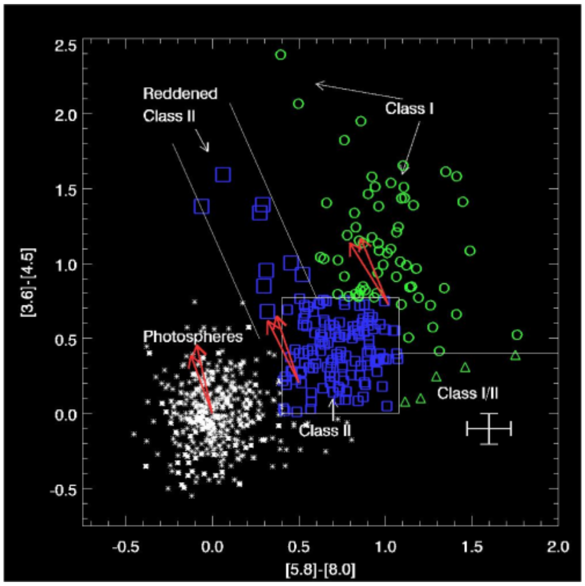


Figure 10: This is a color-color diagram showing targets plotted in two different IR channels. The stars labeled "photospheres" are those with no IR excess, thus their color is zero. Moving up and to the right, the targets become more red, indicating they could be different classes of YSOs based on their redness (Figure adapted from Allen et al. 2004).

5.0 Educational Outreach Plan

5.1 Peoples Academy

Peoples Academy High School, Morrisville, VT
Teacher: Rita Ciambra
Student: Max Kuhnle

Max Kuhnle, from Peoples Academy High School, will participate in all aspects of the research, as well as the winter 2023 American Astronomical Society (AAS) meeting. Throughout the experience, he will meet with me weekly to discuss and review information I have learned in team meetings. He will learn background knowledge and become proficient in utilizing astronomical software to analyze data. He will participate in various outreach activities, such as speaking with the school board, as well as presenting his experience to future astronomy classes where he will share what he did and what he learned.

The importance of bringing real science into the science classroom cannot be overstated. Vermont is a small community and thus I can reach many of my peers. I plan to present my experience to the other science teachers at Peoples Academy High School during professional development time. I will also reach out to other science teachers within Lamoille County and hold a workshop to share information about research I completed and teach the skills I have acquired so my science teacher colleagues can bring more data-driven science into their classrooms.

Since I am a member of the local amateur astronomy group, Lamoille County Star Gazers (LCSG), I will present my experience to that group. LCSG has a robust outreach program, and through the group I will also plan on presenting my experience to the public at an outreach event. Additionally, I am in contact with a local newspaper who has offered to do a series of interviews with me as the project moves along, in order to raise awareness of what I am doing within my community. I will also reach out to the Vermont Astronomical Society (VAS) and offer to present my findings to that group.

5.2 Southeast High School

Southeast High School, Lincoln, NE

Teacher: Ethan Van Winkle
Student: Julia Johnson

I am including a junior student Julia Johnson from Lincoln Southeast High School to be engaged in the research and be present during the summer and winter events. We will discuss weekly about the information presented in the meetings while reviewing concepts and background information. Ultimately they will be a part of the process when we start analyzing the data set and identifying potential YSOs.

In my astronomy class, we use astronomy modeling instruction methods. I teach my students how to use JS9 which is a web-based image processing tool similar to SalsaJ. I have my students learn how to find parallax, do photometry, and filter/colorization of astronomy images. I will include this new found knowledge and methods into my astronomy curriculum. This will give my students a more direct way of understanding the specific concepts being taught in the class under a modeled project.

Beyond educating my students and having them model the techniques, I present topics at a variety of public and teacher events. I am a board member of a local observatory (Hyde) which is organized by the Prairie Astronomy Club and other amateur astronomers. I can present my work to them and the process in which it happens directly to these astronomers. I can also utilize the weekly open nights to talk to the public about astronomy research and our findings to them as well. Outside of reaching the public, I present at conferences and will be engaged in leadership activities for the next five years due to my graduate school requirements. This will provide opportunities to engage with fellow science teachers about NITARP and the process in which this program provided unique research experiences.

5.3 GLAS Education, Nicolet High School

Nicolet High School, Glendale, WI
Geneva Lakes Astrophysics and STEAM (GLAS), Williams Bay, WI
Retired Teacher: Kathy Gustavson
Student: Eliana Tabak

After retirement, I have maintained a strong connection to Nicolet High School Science Teachers and the community. Both Eliana and I will make presentations to the school board and the science department. Presentations will also be made to the astronomy classes, the Independent Science Research class, and any other class that would be appropriate. In Williams Bay, GLAS education is involved in many outreach programs, with frequent community programs and presentations. A NITARP presentation would be included as an authentic research experience.

The most important aspect of NITARP is the experience I am gaining in understanding genuine astronomical research. This experience will allow me to better write online curriculum experiences for the blind and visually impaired (BVI). I am currently involved in projects that are based on the SkyNet Junior Scholars web platform, which use the SkyNet system of automated telescopes, and an image processing program, Afterglow Access, that includes the sonification of data. Incorporating authentic research experience into some aspects of the curriculum is an important goal.

5.4 Jupiter Community High School

Jupiter Community High School, Jupiter, FL
Teacher: Mary Swigert

I teach approximately 150 students each year in my Astronomy Honors class. We cover the full curriculum from origins to cosmology. However, the most interesting part of the year is when we cover projects using real astronomy data. This gives students the confidence to handle college level projects and a taste of real scientific research. We spent a few weeks on pulsar research with data from the Greenbank Telescope in West Virginia. I have been successful in getting several students to attend the capstone and summer workshop in pulsar research. We have also looked at data from Kitt Peak Observatory searching for supernovas. Next year I hope to include some lessons using authentic research using data housed at NASA's Infrared Processing and Analysis Center (IPAC).

Outside of school hours, I conduct star parties to bring students back to the basics of backyard astronomy. I stay connected with the local astronomical society, bringing in guest speakers when possible. I hope to expand these star parties to include the local community, not just students. I look forward to implementing the APT tool and SED website.

5.5 Bay School of San Francisco
Bay School of San Francisco, San Francisco, CA
Teacher: David Friedlander-Holm
Students: (TBD)

The work that I do through this year will be shadowed by my students who are participating in NITARP as well as some students who will not join us for travel. The core of that group are five students who will meet with me weekly (or asynchronously during my parental leave) to prepare for each weekly video conference in the spring and weekly to check in on the progress of their work in the fall. I will make a presentation to the school body in either the fall of 2022 (an in-progress presentation, focused on the structure of science and the application of the scientific method) or the early spring of 2023 (on the arc of our project).

Students will be responsible for an exhibition during one of the several exhibition periods we have at Bay, mirroring the expectations for their ability to present at AAS. We will use the SNAG-490 poster as produced by this team and students will be expected to be able to make both a presentation to those knowledgeable about astronomy (functionally, the same as the AAS preparation) as well as being ready to field questions from those with less astronomy experience--both high school students and teachers.

Finally, I'll be monitoring their progress on their understanding through monthly Likert-scale Google surveys. I'll build these questions in March allowing us to document their understanding of their understanding as time goes on.

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