Cataloging and Analysis of Variability in Young Stellar Objects in the Spider Nebula (IC 417) Using Archival Visible and Infrared Data

Brandon Rodriguez, Crescenta Valley High School, La Crescenta, CA

Robert Anderson, JL Mann High School, Greenville, SC

Benjamin J. Senson, James Madison Memorial High School, Madison, WI

Mentor teacher: Vin Urbanowski, Academy of Information Technology & Engineering, Stamford, CT

Mentor Astronomer: Luisa Rebull, IPAC, Caltech, Pasadena, CA

1.0 Abstract

The Spider Nebula (IC 417) is a star forming region about 2.3 kpc away, in the direction of the Galactic Anti-center. While not in the outer reaches of the Galaxy by any means, IC417 is still further towards the outer reaches of the Galaxy than most well-studied star forming regions. If star formation here is significantly different from star formation elsewhere (e.g., perhaps due to metallicity or stellar density), it might manifest, say, in a different distribution of masses (initial mass function). In order to investigate this, we need to assemble a list of cluster members.

In 2015, a NITARP team studied this region, finding young stellar object (YSO) candidates from IR excesses. In 2020, our team studied this region, identifying new YSO candidates in a part of the nebula called the Nebulous Stream, and assessing all literature-identified YSOs in the optical and IR. At the end of 2020, we had a list of ~600 YSO candidates. In 2021, we will continue our exploration of this region. We will incorporate ~100 more YSO candidates identified in the literature last year into our work from last year, and wrap up a few loose ends from that work, largely related to color-color and color-magnitude diagrams. The bulk of our work this year will explore the variability properties of these ~700 YSO candidates using optical (ZTF and ASAS-SN) and infrared (NEOWISE) light curves.

2.0 Science Background

The 2020 proposal contains a much longer summary of star formation and the pertinent literature for this project. Instead of reiterating all of that background, the most salient points are summarized below.

2.1 Star Formation

Stars form in clouds of gas and dust called nebulae, which act as incubators in which newborn stars form; see Figure 1, which depicts key stages of low-mass star formation. An initial concentration of matter can be triggered into collapse by a supernova shockwave, winds and ultraviolet (UV) light from O and B stars, passing galactic spiral arm density waves, and/or through self-gravity. Throughout the star formation process, gravity relentlessly presses inward (note length scales in Fig. 1). As the matter collapses inward, it falls onto a rotating disk, conserving angular momentum. From this protoplanetary circumstellar disk, matter spirals in to accrete onto the central object. For reasons that are not well-understood (but almost certainly involve magnetic fields), when the mass accretion rate is high, some of the accreting matter gets ejected to form bipolar jets, thought to be along the magnetic axis (which is thought to be most commonly roughly parallel to the rotation axis, Fig. 1c). Eventually the envelope is depleted or dispersed by the jets (Fig. 1d), but the disk is still substantial. As the accretion rate slows, the disk thins out and the jets stop, and proto-planets form from the disk (Fig. 1e). Eventually, the pressure and density in the core of the central object are sufficient to ignite fusion (turn H into He), and it becomes a star. For most of the rest of the star's life, the pressure inward from gravity is matched by the pressure outward from thermonuclear fusion, and the star is stable while burning H.

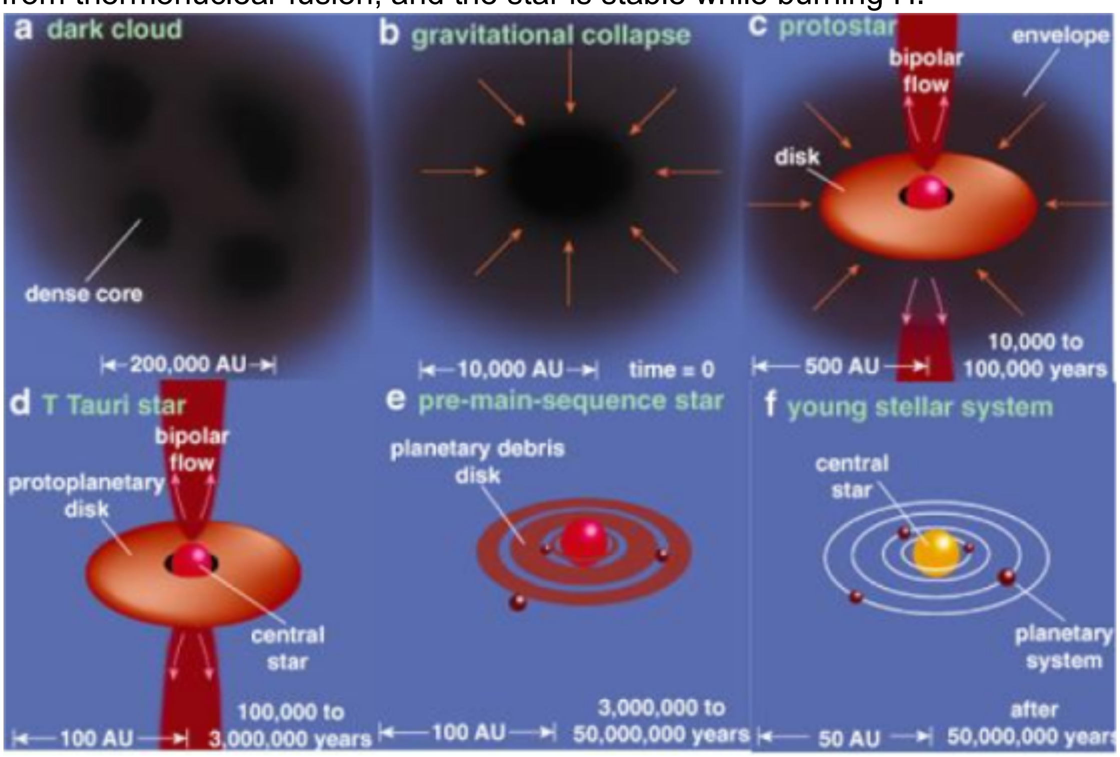

Figure 1: *The process of low-mass star formation (Green 2001). Note the length and timescales in each panel. An AU is the distance between the Earth and the Sun.*

The circumstellar envelope and disk are made from dust and gas. This dust intercepts and absorbs radiation from the YSO, then re-emits it in the infrared (IR). Therefore, we can identify YSOs by looking for stars with an excess of IR emission, e.g., more IR emission than expected for a star that does not have a dusty disk or envelope. IR excess can be used to differentiate the YSO from foreground and background stars that are not dusty. As YSOs age, the amount of IR excess in the envelope and then the disk will decrease (Fig 1e), until it vanishes to trace amounts (Fig 1f). Stars without dust (or with very little dust) have no (or very little) IR excess.

IR excesses in YSOs can be easily recognized in a spectral energy distribution (SED) plot, which is a graph of the energy density emitted by an object as a function of wavelength. As seen in Figure 2, the SED for the youngest YSOs resembles that of a cold blackbody because the object's emission is absorbed by the gas and dust "cocoon" which re-radiates the energy as heat, behaving as a simple blackbody. As the cocoon begins to disperse, and the central source warms up, emission from the central source becomes more apparent. We see this as YSO progresses from Class 0 to Class I and the peak of the SED curve moves to the left (blue-ward), reflecting the greater contribution of radiation from the star itself. Still, the remnant of the dusty cocoon and the dusty disk continues to glow in IR, lifting the right side of the curve off from that of an isolated blackbody -- this is the IR excess. The amount of IR excess continues to decrease as the amount of circumstellar dust decreases and the YSO progresses through the Flat class to Class II (also known as a classical TTauri star, or CTTS). When the YSO reaches Class III (also known as a weak-lined TTauri star, or WTTS), the IR excess has essentially vanished.

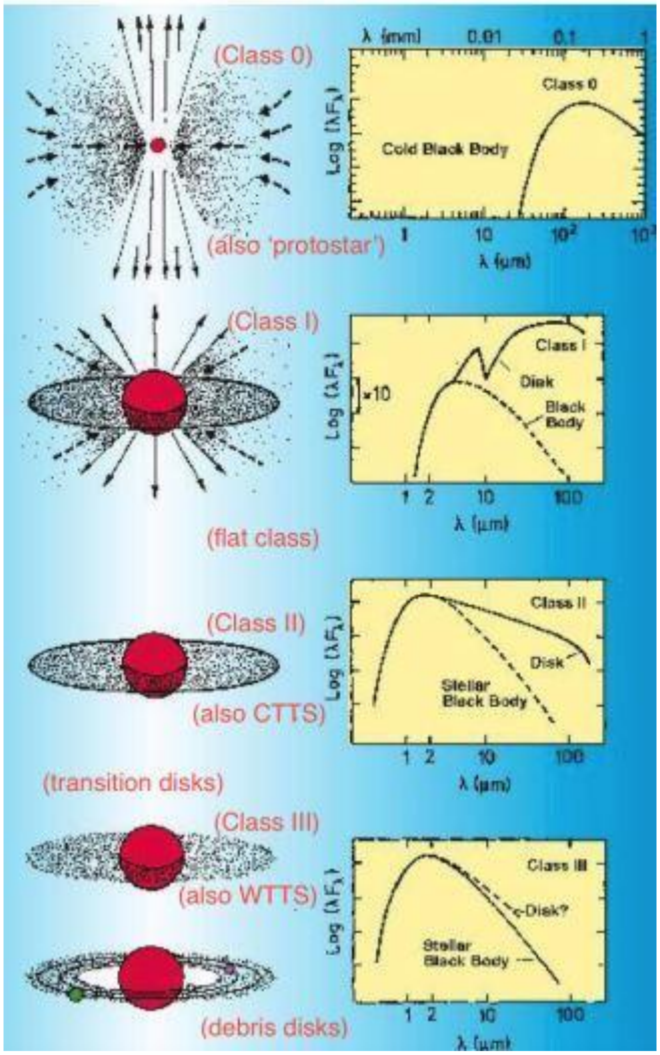

Figure 2: *Low-mass star formation with SEDs illustrating IR excess. Adapted from Bachiller (1996).*

There are other ways in which YSOs are “different than the neighbors,” e.g., different than older stars. Active accretion from the disk onto the YSO creates a shock (where the accretion stream hits the YSO) from which there can be an ultraviolet (UV) excess. This can also be seen in the SEDs, though less obviously than IR excesses. Large accretion rates can create enough of a UV excess that it can affect optical blue bands as well. Accretion streams can create emission lines, most notably Hα; Hα emission line can also be found in stellar flares. Young stars are, in general, rotating quickly, so they are very active as a result -- that is, they have big, cool star spots and flare frequently. Variability is one of the defining characteristics of young stars -- TTauri, the YSO that lends its name to categories of YSOs, has that name because it was first identified as a variable. Variability in young stars can originate from star spots (cool from activity, hot from accretion), variations in accretion rate from the disk to the star, and/or texture in the accretion stream or the disk itself occulting our view of the star. Variability thus can also be used as a way to find YSO candidates.

2.2 The IC 417 Region and Work-to-Date

IC 417 has been studied by a few people, most notably a NITARP team in 2015. Our proposal last year has a thorough review of the literature, but in summary, YSO candidates in this region have been identified in the literature by:

- Finding O and B stars -- O and B stars “live fast and die young,” so by definition, they are young stars.
- Identifying YSOs that are bright in Hα -- these are so bright in Hα that the brightness cannot come solely from flares; they must be actively accreting.
- Selecting YSOs bright in the IR -- YSOs that have an IR excess are likely to have circumstellar dust.
- Selecting YSOs from optical colors and magnitudes -- YSOs that are young and have not ignited H are above (brighter than) the zero-age main sequence (ZAMS), which is defined to be where stars appear in brightness and color when they first ignite H.
- Identifying optical variables -- YSOs that are young are also very often variable (in all wavelengths and on all timescales, provided you measure brightness accurately enough).
- Selecting YSOs based on position -- either those that appear to be clustered or those that appear to be in close proximity to nebulosity. (These must be taken with caution, as we are using proximity in this case to mean “close in projection on the sky” as opposed to truly close in 3D space -- we don’t often have distances to these objects, so that third dimension is hard.)

The NITARP 2015 team collected all the YSO candidates from the literature available to them at the time, and selected new YSOs based on IR excesses. Last year, we collected all of those YSO candidates from 2015, added to them the YSOs that had been identified in the literature between then and 2020, and selected stars in the Nebulous Stream (NS; see Fig.3). For each of the stars in that catalog, we assembled SEDs and inspected both the SEDs and all the images (those to which we had easy access) to weed out the targets that we didn’t think were young. At the end of 2020, we had ~600 targets that we believed, based on our work to that point, to be YSO candidates, e.g., members of IC417.

In the second half of 2020, two papers came out in the literature that identified new YSO candidates in this region, and we wanted to include them in our study this year. Pandey et al. (2020) identified new YSOs based on optical (V,I), 2MASS, and WISE over a larger region that includes IC417; there are 53 stars identified in our region, 49 of which were already in our YSO candidate list. Winston et al. (2020) identified YSO candidates from IRAC, 2MASS, and WISE colors in the whole outer Galactic Plane, including IC417. There are 212 YSOs from this paper that overlap with us, 139 of which were already in our list. Of the four new YSO candidates from Pandey et al. (2020), three are also in Winston et al. (2020). Additionally, we were made aware of data from ASAS-SN (Shappee et al. 2014); Jayasinghe et al. (2019) identified variables over the whole sky from the ASAS-SN (optical) data, 11 of which are in our region, just 3 of which were already on our list of YSO candidates.

From these three new papers, we add about 100 stars to our set of YSO candidates in this region. The region on which we are focusing is shown as the large magenta square in Figure 4, and is given by the box defined by RA=05:29:50.0 to 05:26:31.5 (82.458333 to 81.631250 degrees), Dec=+34:08:50.6 to +34:51:05 (34.147389 to 34.851389 degrees).

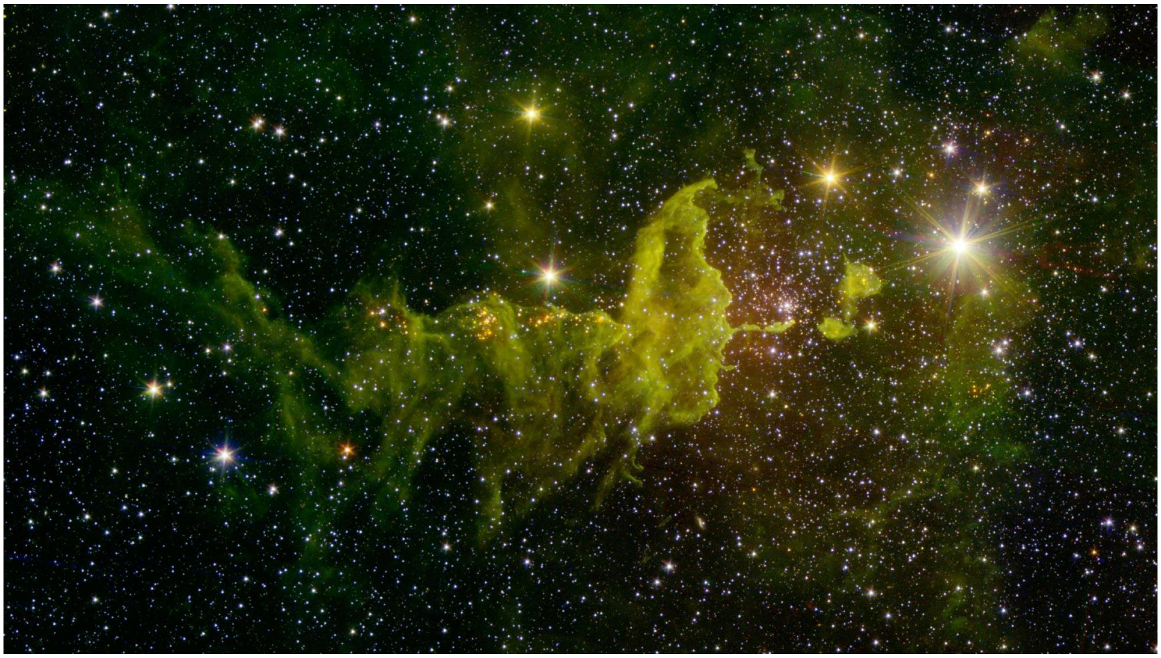

Figure 3: *IC 417 from an image release (2016-04-14/sig16-008; NASA/JPL-Caltech). Red=IRAC-2 (4.5 μm), green=IRAC-1 (3.6 μm), blue=2MASS J (1.3 μm). The text accompanying this image release mentions the 2015 NITARP team. The cluster Stock 8 is held in the "bowl" of nebulosity near the center of the image; the sinuous, "braided" tail to the left (East) of the "bowl" is called the Nebulous Stream (NS), and is where we will focus most of our work. North is very nearly up.*

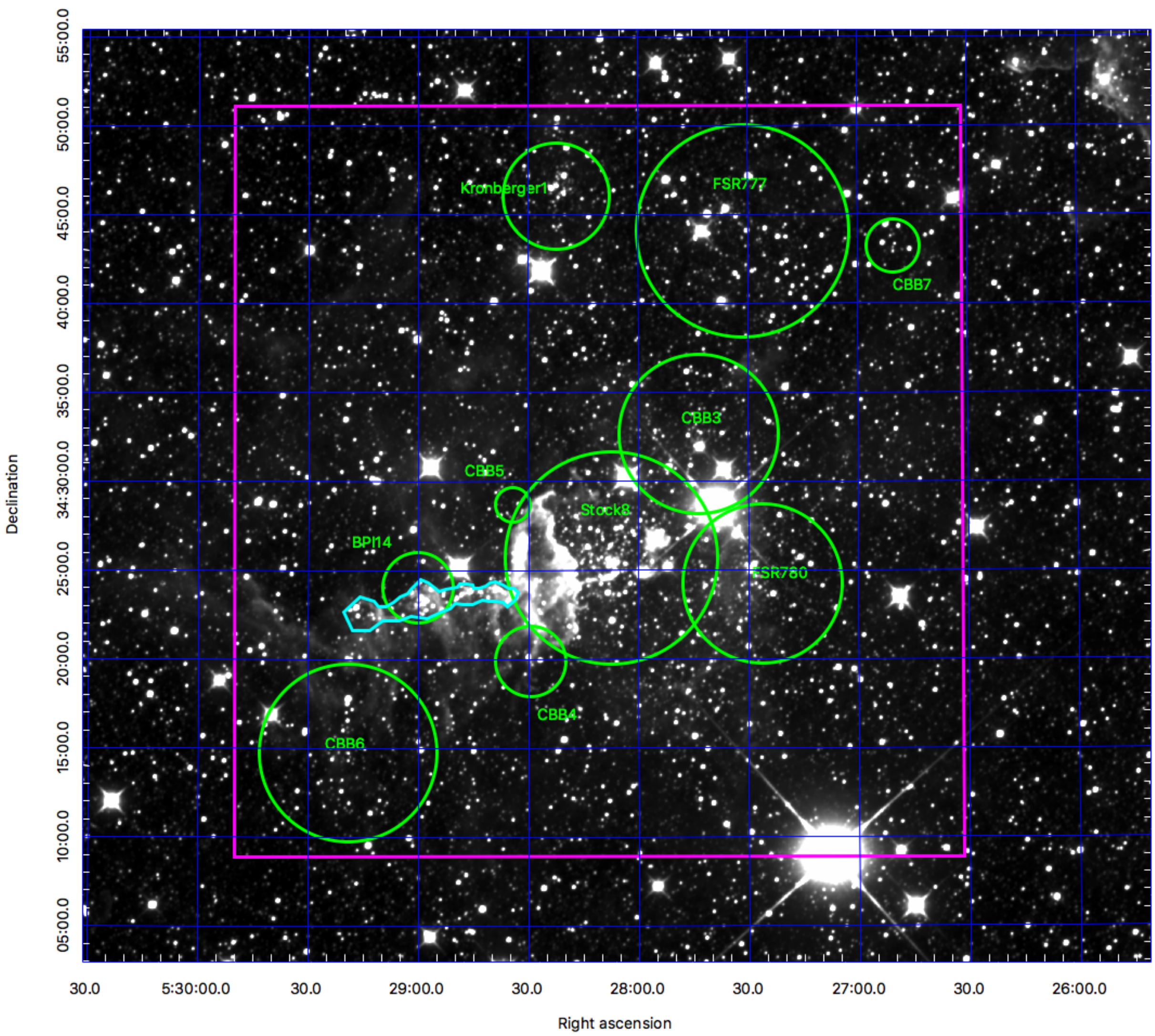

Figure 4: *Updated version of Figure 7 from our 2020 proposal. Image of the greater IC 417 region in WISE-1 (4.5 µm) in grayscale with important annotations overlaid. (IC 417, the "Spider," is the center here; the "Fly," NGC1931, is off the lower left edge of this view.) Equatorial (J2000) coordinates are provided; North is up. We focused on the region enclosed by the magenta square; the 2015 NITARP team studied a slightly larger region. All clusters marked with circles inside this magenta square are clusters identified from NIR clustering analysis (Camargo et al. 2012 and references therein). The small cyan polygon encompasses the Nebulous Stream (NS) originally identified in Jose et al. (2008), and is where we identified new YSO candidates by position in 2020. We explored YSO candidates in the larger magenta square in 2020 but did not identify new YSOs in this wider region. This year, we plan to explore the variability properties of all of the YSO candidates in this region.*

Because the IC417 region is in the Galactic Plane, it has been serendipitously observed by several different surveys. A list of the largest of those surveys, combined with data tables from the literature, is in Table 1.

Table 1: *Summary of data sets included in master catalog*

Survey or literature source	Bands	Fraction of sample	Used in 2015 NITARP team's work?	Used in 2020 NITARP team's work?
2MASS (Skrutskie et al. 2006)	NIR: JHK_s	~40%	yes	yes
Spitzer/ GLIMPSE (Werner et al. 2004; Churchwell et al. 2009)	MIR: IRAC-1 and 2	~86%	yes	yes
WISE/AllWISE (Wright et al. 2010)	MIR: WISE-1,2,3,4	~30%	yes	yes
PanSTARRS (Chambers et al. 2016)	Optical: grizy	~85%	**no**	yes
UKIDSS (Lucas et al. 2008)	NIR: JHK	~70%	yes	yes
IPHAS (Barentsen et al. 2014)	Optical: r', i', Ha	~50%	yes	yes
Gaia DR2/3 (Gaia Collaboration et al. 2019)	Optical: G, Bp, Rp; parallaxes (distances from Bailer-Jones et al. 2018)	~66%	**no**	**partially**
Herschel/ PACS (Pilbratt et al. 2010; Marton et al. 2017)	FIR: 70 and 160 µm	(less than a dozen sources)	**no**	**no**
Akari/IRC (Murakami et al. 2007)	MIR: 9 and 8 µm	(less than 20 sources)	**no**	yes
MSX (Egan et al. 2003)	MIR: 8-21 µm	(less than 40 sources)	**no**	**no**
Jose et al. (2008)	Optical: UBVIc, spty; 2MASS	~20%	yes	yes
Marco et al. (2016)	Optical: stromgren photometry, spty; NIR: JHK	~3%	**no**	yes
Jose et al. (2017)	Optical: VI, NIR: JHK, MIR: I1I2	~4% (just in Stock 8)	**no**	yes
Lata et al. (2019)	Optical: variability and rotation periods	(just 130 sources in Stock 8)	**no**	yes

3.0 Analysis plan

3.1 Adding 82 new sources

At the end of our work last year, we had 616 YSO candidates in our catalog. The literature has provided 82 more sources that we should consider as YSO candidates in this region. We will do the SED and image inspection of these 82 new sources, to integrate them fully into our final catalog of YSO candidates in this region, treating them the same as the objects that survived our culling last year. Our working catalog is thus ~700 objects.

3.2 Remaining Action Items from 2020 Project

Near the end of 2020, we ran out of time (due to COVID-19) to finish absolutely all of our originally planned work. Last year, we got started working with color-color and color-magnitude diagrams, and started work on incorporating Gaia DR2 distances. But we did not complete this work to the extent we had planned to during 2020.

We will spend some time this year to wrap up this work, including in the analysis the 82 new sources above. We will assess each star based on its location in several optical, NIR, and MIR color-color and color-magnitude diagrams, thus strengthening (or weakening) evidence of youth for these objects. We will investigate the distances reported in Gaia for those stars in our list with Gaia counterparts.

3.3 Time Series Analysis

The bulk of our new work in 2021 will be to explore the variability properties of the ~700 YSOs in our working catalog. The rest of this section describes the data, the tools, and the planned work. The term “light curve” means “brightness as a function of time,” and in this context is a synonym with “time series.”

3.3.1 Time Series Data Sets Under Consideration

Three different time series data sets are under consideration for our use in 2021. Two are hosted by IPAC, at IRSA, and one is at Ohio State. Two are optical, and one is IR. We are in the early stages of exploring these data and are likely to narrow the scope of our work if the data prove difficult to work with, given available tools.

Zwicky Transient Facility (ZTF; https://irsa.ipac.caltech.edu/Missions/ztf.html; Masci et al. 2019) – ground-based (1.2m telescope, at Palomar), optical (usually 1 band, r, sometimes 2, g and r), primarily looking for transients. A quick assessment of the currently public ZTF data suggests that we will find ZTF counterparts for about 500 out of the ~700, with several hundred epochs (spread over ~four years). These data are hosted at IRSA, with a new data release planned in Spring 2021.

Near Earth Object-Widefield Infrared Survey Explorer (NEOWISE; https://irsa.ipac.caltech.edu/Missions/wise.html; Wright et al. 2010) – space-based (0.4m telescope, Sun-synchronous polar orbit), IR (2 bands, 3.5 and 4.6 microns). NEOWISE is primarily looking for moving objects, is relatively low spatial resolution, and has very "clumpy," irregular sampling (every ~90 min for a few days every ~6mo, spread over ~9 years), These data are hosted by IRSA and a new data release came out in March 2021. A quick assessment of the public NEOWISE data suggests that we will find light curves for ~350 of our ~700 targets.

All-Sky Automated Survey for Supernovae (ASAS-SN; https://asas-sn.osu.edu/; Shappee et al. 2014) – ground-based (6 groups of 4x0.14m telescopes, distributed across the globe), optical (one band), primarily looking for transients. This project is based at Ohio State. ASAS-SN samples the whole sky every night, approximately. They have already done analysis looking for variables over the whole sky (Jayasinghe et al. 2019). They do not serve pre-reduced light curves for most of their targets; their web interface does photometry on demand for a given position and is not meant to serve bulk requests. We have put in a request for them to give us light curves for our targets but have not yet heard back. We expect that ASAS-SN sensitivity will be roughly comparable to ZTF, e.g., providing counterparts for ~500 of our ~700 targets. If we don't hear back from ASAS-SN, we will probably use their server to generate individual light curves for some fraction of our objects, perhaps selected based on ZTF and NEOWISE variability properties.

3.3.2 Statistical tools

Both NEOWISE and ZTF do photometry for us, but do not necessarily accurately match sources across epochs. Our first step will be to extract (and assemble) complete light curves for each of our targets from IRSA. We will match objects across epochs by position, using a positional radius of 1 arcsec for both surveys. ASAS-SN, if they are willing, will give us ready-to-use light curves. Once we have complete light curves for each of our targets that have counterparts in the corresponding survey, we will investigate the statistical properties of the light curves. Again, we may revise our list based on the properties of the light curves and/or the ease with which we can implement these statistics, but our current plan includes the following metrics:

- **RMS** (root mean square), sometimes written rms.

  $$x_{\mathrm{RMS}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

  RMS, sometimes just called sigma (σ), determines the scatter in the light curve, but not whether or not it is variable, because it doesn't incorporate errors. This is useful to use in context with everything else.
- **Chi-squared test.**

$$\chi^2 = \frac{1}{N-1} \sum_{i=1}^{N} \frac{(\mathrm{mag}_i - \overline{\mathrm{mag}})^2}{\sigma_i^2},$$

Used to answer the question, if the object is not variable (e.g., a flat line with time), then are the variations from that flat line significant? This test takes errors into account explicitly. Larger values of chisq mean the object is more likely to be variable.

- **Fourier** analysis, specifically as implemented for **Lomb-Scargle** analysis. This analysis looks for periodic signals in the data. (If the YSOs have a hot or cool spot on the surface of the YSO rotating into and out of view, then we will see a periodic signature in the light curve.) The IRSA tools include an interactive Lomb-Scargle period search, designed explicitly for use with both ZTF and NEOWISE data.
- **Stetson index.** This metric looks for correlated variability between time series in two different filters.

$$S = \frac{\sum_{i=1}^{N} g_i \times sgn(P_i) \times \sqrt{|P_i|}}{\sum_{i=1}^{N} g_i}$$ where $P_i = \delta_{j(i)}\delta_{k(i)}$ and

$$\delta_i = \sqrt{\frac{N}{N-1}} \frac{\mathrm{mag}_i - \overline{\mathrm{mag}}}{\sigma_i},$$

Larger values mean the variability is more likely to be correlated. Two bands of observation must be taken essentially simultaneously for this to work. This can identify even low levels of variability, since any physical process affecting one band is also likely to affect another nearby band -- we have two NIR bands from NEOWISE, and perhaps two optical bands from ZTF. However, the NEOWISE data, while strictly simultaneous, may be too noisy for this to work, and the ZTF data may not be simultaneous enough. We will have to experiment with this.

- Potentially, **autocorrelation function** (or cross correlation function).

$$\mathrm{ACF}_x(L) = \mathrm{ACF}_x(-L) = \frac{\sum_{k=0}^{N-L-1} (x_k - \overline{x})(x_{k+L} - \overline{x})}{\sum_{k=0}^{N-1} (x_k - \overline{x})^2}$$

This metric looks for repeated patterns in the light curve. If there is a periodic signal, it will find the period, but it will also find aperiodic timescales. Interpretation of this can be complicated, because the data have to be linearly interpolated onto an evenly-spaced time sequence in order to work, and as such may only work for, e.g., one season of ZTF data at a time. We may experiment with this.

3.3.3 Goals of Time Series Analysis

For each of the ~700 YSO candidates in our list, we will determine if they are (a) detected, (b) variable, (c) periodic in the three different light curve data sets. Since variability is often an indicator of youth, this will further help us to refine the list to find the YSO candidates most likely to be real YSOs.

Note that identifying *new* YSO candidates *from variability* in these light curves is a *much* larger project, and beyond the scope of our work here.

3.4 Summary of 2021 Goals

Goal #1: Incorporate new YSO candidates from recent literature into our work from last year.

Goal #2: Finish work from 2020: assess each of the ~700 YSO candidates in color-magnitude and color-color diagrams, in optical and IR. Incorporate distances from Gaia.

Goal #3: Analysis of light curves from ZTF, NEOWISE, and ASASSN for the ~700 YSO candidates. Identify variables and periodic variables. Fold this into the over assessment of youth for the ~700 YSO candidates.

Goal #4: Capture the skills and techniques used in this research through the lens of participating educators in order to construct educational materials for students and teachers interested in astronomical research. Lessons and activities representative of the research experience and reflective of careers in astronomy are detailed in section 4 below.

4.0 Educational Outreach Plan

In order to maximize our educational impact, our outreach plan will consist of two parts: student-led peer-to-peer delivery of infrared astronomy, and teacher-led curriculum development for previous and future NITARP educators.

4.1 Resource Development for the NITARP Community

Educators will develop resources (lesson plans, exercises, labs, or starting points) for the NITARP alumni community, teachers and students. These resources will be located on the NITARP wiki (https://vmcoolwiki.ipac.caltech.edu/index.php/Main_Page) and will be aimed at NITARP alumni, but will be available to anyone.

These resources are astronomy research-themed, each of which represents an exploration that could be done by NITARP alumni in a few hours, using tools and data from IRSA or the rest of IPAC. Ideas include but are not limited to:

- Calculate true velocity of high proper motion star from NITARP 2118 work, and compare it to Gaia results.
- Cepheid distance ladder - find some Cepheids in ZTF, calculate periods, work out distance to LMC.
- Use a list of nearby stars (ex. Gliese-Jariess) and IRSA plotting tools to find local WDs. Do any of them have IR excesses?

4.2 Student Voice in Teacher Curriculum Building

Following up on data collected during the 2020-2021 school year, students will analyze teacher and student perception data after partaking in a series of professional development workshops.

In 2020, participating students from Crescenta Valley High School led several workshops for middle school and high school teachers, including one held at NASA's Jet Propulsion Laboratory (JPL Education 2020a). These workshops included several activities and demonstrations (JPL Education 2020b) that the students identified as the most transformative for their understanding of astronomy. Over a dozen teachers in attendance agreed to partake in a larger study wherein they would be mailed the materials to do these lessons in their own classrooms, and survey their students to measure any impact on understanding and perception towards astronomy.

With several hundred participating students surveyed, NITARP students will analyze the data to measure efficacy of student-led, student-voiced professional development for educators on a wide group of students from varying backgrounds. The findings will be presented as a poster for the AAS Meeting in Utah in 2022.

4.3 Student Leadership in Astronomy Research Based Extra Curriculars

Students at the Academy of Information Technology and Engineering in Connecticut have committed to sharing their experience and expertise to create an Astronomy Research club. This club will utilize NITARP educational resources (see above) to replicate NITARP experiences among students. They will share their work throughout the learning community and at local STEM outreach events.

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