CephC-LABS: Searching for Young Stars in Cepheus C

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1. Abstract

We propose to use archival data to search for, identify, and classify candidate young stellar objects (YSOs) in the Cepheus C region of the molecular cloud Cepheus OB3. Previous work by Gutermuth et al. (2009) identified 114 YSO candidates in Ceph C. The Young Stellar Object Variability (YSOVAR) project (Rebull et al. 2014) identified approximately 300 YSO candidates and work by Orr et al. (2016) refined this list to 245 likely YSOs. More work is needed in this region to identify the youngest Class 0 and Class I candidate YSOs at additional longer wavelengths in the infrared. One purpose of this is to determine which sources are YSOs and which are not, so that time-series data of this region (collected by Rebull et al. 2014) can be interpreted in context to develop a broader understanding of the process of star formation. Our search for YSOs will be driven by longer infrared wavelengths - Herschel (70, 160, 250, 300, 500 μm) and SCUBA data (450, 850 μm). Once we have identified candidate YSOs in these longer wavelengths, we will construct spectral energy distributions (SEDs) for each candidate by aggregating available shorter wavelength data from the region. To further aid our classification, we will construct color-color and color-magnitude diagrams for new and previously identified YSOs in this region. YSO candidacy and categorization will be determined from the shape of the SEDs and the locations of objects on the color-color and color-magnitude diagrams.

2. Science Introduction and Context

2.1 Studying star formation

Stars take millions of years to evolve from giant clouds of gas into churning nuclear “furnaces,” so the process cannot be observed in its entirety. Fortunately, there are lots of stars in the process of forming. Observing many of them at various stages throughout their formation allows us to build up a story about how the process occurs without having to watch the whole process for a single star. Everything we know about star formation comes from light that the stars emit. In the earliest stages of formation, stars are called young stellar objects (YSOs). The amount of light a YSO gives off at various wavelengths and how those amounts vary with time give us clues about nature of the YSO. Recent evidence shows that YSOs are highly dynamic objects. In the past two decades, astronomers have uncovered diverse variations in the brightnesses of YSOs over timescales of days to years (e.g., Rebull 2011 and references therein). These variations help astronomers understand the structure and behavior of stars in the earliest stages of their formation. Large numbers of YSOs have to be observed, categorized, and analyzed so that conclusions can be drawn about individual objects in the context of wider star formation patterns. YSOs also have to be distinguished from foreground stars, background galaxies, and isolated from the gas and dust they are often hiding in. Since the intent of our research is to identify and classify YSOs, it is important to discuss how star formation proceeds, as well as how YSOs are identified and classified.

2.2 Star formation, YSO identification and classification

Stars form out of large clouds of interstellar dust and gas that have been pulled together by gravity over millions of years. The initial gravitational collapse leaves a cocoon of gas and dust surrounding the forming star. All clouds start off with some amount of 'spin', or angular momentum; as gravity pulls the gas together, angular momentum is conserved. This causes the matter to fall into a disk before falling onto the central object. Radiation emitted from the central mass interacts with the surrounding disk of gas. The disk absorbs some of this radiation, heats up, and emits its own radiation which leads to an excess of infrared (IR) emission coming from the vicinity of the young star. As the star ages, the disk eventually thins out and disappears. The radiation from the central star is then free to travel away from the star without being absorbed and reemitted by the disk. Without excess IR radiation, the star's radiation spectrum more closely resembles that of a black body. This process is outlined in Figure 1 below.

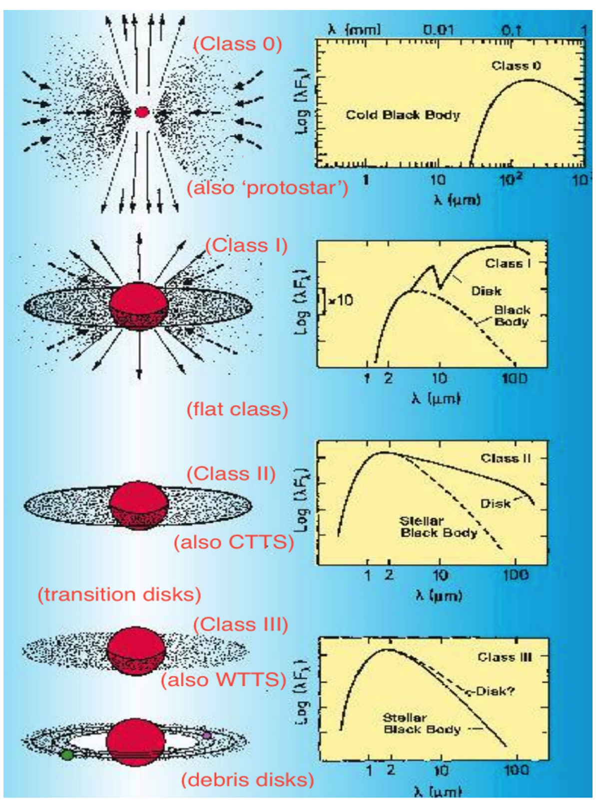


Figure 1: Diagram showing stages of star formation along with predicted spectral energy distribution shapes. Nomenclature used in the field is listed near each stage. CTTS means Classical T Tauri Star. WTTS means Weak-line T Tauri Star. Figure adapted from Andre & Montmerle 1995.

Therefore, a source with excess IR radiation is the sign of a disk of gas and dust that is re-emitting radiation from a central mass. Using different telescope filters, astronomers can capture and figure out how much energy is coming from the YSO at different wavelengths. A spectral energy distribution (SED) can then be constructed to compare how much energy is being detected (y-axis) at various wavelengths (x-axis); see Figure 1. Using the shape of the SED, conclusions can be drawn about how deeply embedded, or surrounded by gas and dust, the YSO is. Generally, the more IR radiation detected, as compared to shorter wavelengths, indicates a more embedded YSO. The slope of the SED graph in the near- to mid-IR (2-25μm), called the 'spectral index', can be used to define various classes - Class 0, I, Flat, II, III (see Figure 1) (Wilking et. al. 2001). YSOs are thought to start out as Class 0s and progress in the order listed until they reach Class III before becoming a star. The age of the YSO is not necessarily known from the SED slope because some YSOs may lose their disks sooner than others (e.g., Robitaille et al. 2006; Dunham et al. 2010). However, in general, YSOs with positive SED slopes in the near to mid IR are probably younger (more embedded) than those with steeper, negative slopes.

2.3 Our target: Cepheus C

Cepheus C is a sub-cloud of a much larger molecular cloud near the Ceph OB3 star association, which lies within the Milky Way Galaxy about 700 pc away (Moscadelli et al. 2009) Though the association stars may not be visible to the naked eye, you can find the approximate location of Ceph C in the night sky by looking near the constellation Cepheus (see Figure 2). "Associations", a term introduced by Ambartsumian (1947), are groups of stars that are much younger than the galaxy of which they are a member. They are often associated with large clumps of gas and dust called molecular clouds, out of which stars can form.

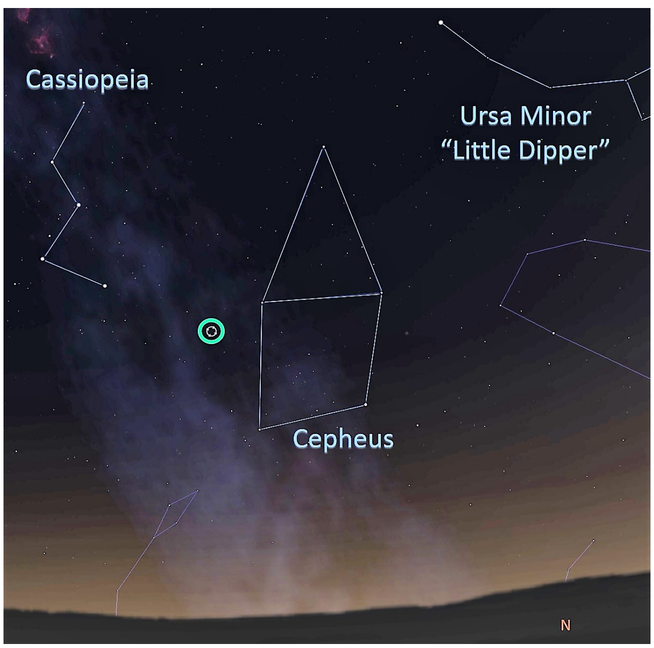
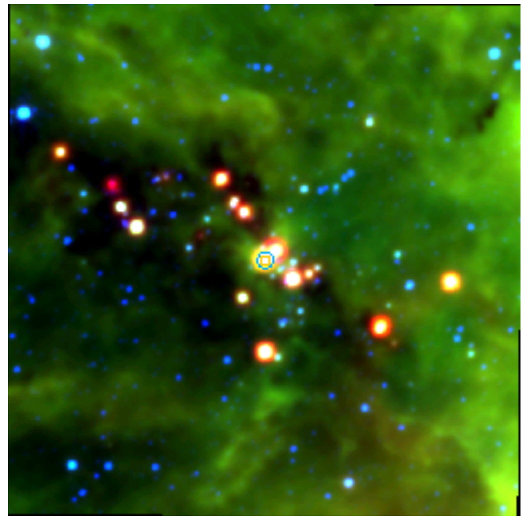


Figure 2: The green circle shows the approximate location of our target in the night sky. (23h5m51s +62d30m55s; J2000.) Constellations are labeled for reference. Image produced using *Stellarium* software.

The images in Figure 3 below show our target region - centered on 23h5m51s +62d30m55s (J2000) with a window of ~20 arcmin on each side in different wavelengths. Note how the two foreground stars in the top left of each image match up. Also note that the bright red sources that are easily visible in the image on the right do not have obvious partners on the left. The red color of these sources suggests that they are bright in longer-wavelength infrared radiation. These sources coincide with the dark region in the DSS image on the left. This suggests that that they may be behind or embedded within a cloud of gas and dust that is blocking visible light. This is the type of region in which we would expect to find YSOs.

Figure 3: Side by side comparison of Ceph C in different wavelengths.

	
Ceph C in DSS - Red: DSS2 IR, Green: DSS2 Optical Red, Blue: DSS2 Optical Blue	Ceph C in infrared - Red: WISE 4, Green: WISE 3, Blue: WISE 2

The first photometric study of the Cepheus association by Blaauw (1964) found approximately 40 stars adjacent to a large molecular cloud. Sargent (1977) mapped the temperature of the adjacent molecular cloud by observing the region in light emitted from carbon monoxide (CO) molecules; Ceph C was originally identified and labeled as one of six regions (A-F) of higher temperature within the greater cloud (see Figure 4 below).

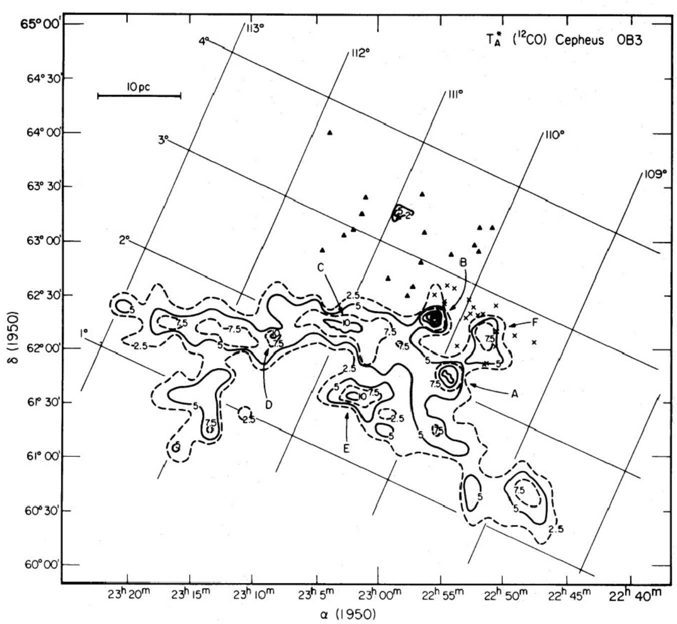


Figure 4: Outlines show a 'topographic map' of CO temperature in the Cepheus OB3 molecular cloud. Ceph C is labeled in the middle. The triangles and Xs show the locations of stars that are part of the OB Association Blaauw looked at in 1964. Overlaid grid shows galactic coordinates. Figure from Sargent 1977.

Though Ceph C has been imaged in many different wavelengths (see Table 1 in the next section) as part of modern telescopic surveys of the Galactic Plane, star formation in this region has not been studied in depth. In 1994, Hodapp discovered that Ceph C was host to a bright IR cluster in the K'-band (~2.1μm). Others have looked for Hα emission in the Cepheus OB3 molecular cloud, but have only identified 2 sources in our Ceph C target region (Mikami & Ogura 2001, Witham et al. 2008, Melikian et al. 2014).

Other recent studies have identified YSOs in Ceph C, but have done so in the context of other pursuits such as determining the properties of star clusters. Using Spitzer, Gutermuth et al. (2009) identified 114 YSOs in Ceph C using mid-infrared color-based methods. DiFrancesco et al. (2008) also identified 16 YSOs as part of a SCUBA (Submillimetre Compact-User Bolometer Array; 450, 800μm) survey.

From 2009 to 2011, the Young Stellar Object Variability (YSOVAR) project observed twelve star-forming regions, including Ceph C, to study how young stars vary over time in the mid-IR. Ceph C was observed with Spitzer during multiple epochs over the course of 42 days for a total exposure time of 18.3 hours at 3.6 and 4.5 μm, and on a single day with Chandra/ACIS for a total exposure time of 44ks (~12 hrs). They obtained light curves for ~1950 objects (Rebull et al. 2014). Some of the light curves for Ceph C have been analyzed, but the process is far from complete. Identifying and carefully classifying the more embedded YSOs in Ceph C will put some of these light curves in context. For example, variations in the light curve may depend on the properties of the YSO disk or other processes that may occur at certain stages of star formation. Orr et al. (2016) began this process by identifying and classifying 245 YSOs in Ceph C. Our research will build upon their work by identifying and classifying more highly embedded YSOs.

3. Analysis plan

Our target region is 20 arcminutes on a side, centered on 23h05m51s +62d30m55s (J2000). We may venture slightly outside this area to include any Herschel sources that will meaningfully contribute to our study.

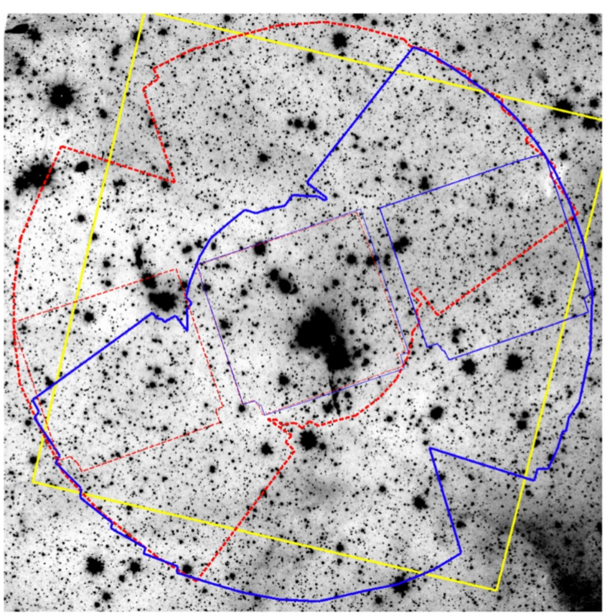


Figure 5: Reproduced from Rebull et al. 2014, showing our target region (~20 arcmin per side) as a reverse grayscale image of Ceph C at 4.5 μm obtained during the Spitzer cryogenic mission. The colored outlines show the regions that were observed during YSOVAR epochs at various wavelengths. The thicker blue solid line is 3.6 μm and the thicker red dashed line is 4.5 μm. A single epoch of observation is also indicated by thinner blue solid and red dashed lines, with the difference between the single epoch and the larger polygon due to substantial field rotation effects (due to the large ecliptic latitude of Ceph C; see Rebull et al. 2014 for more discussion). The yellow square is the approximate Chandra coverage. North is up and east is to the left; the center is 23h05m51s +62d30m55s (J2000).

Our goal is to look for the youngest and most embedded YSOs, therefore, our search will be driven by longer wavelengths - primarily Herschel (70, 160, 250, 300, 500 μm) from two cameras, the Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging Receiver (SPIRE). Despite a recent release of the SPIRE all-sky catalog, our sources reside in one of the omitted regions of the sky and no photometry is available. As a result of last year's NITARP team, we have access to a limited, preliminary source list from SPIRE. This preliminary source list does not include every source we can see by eye, but does provide a baseline to which we can compare our own photometry. As of this writing, the PACS catalog is not yet available; we will watch for its release and make use of it if possible. The Herschel data in the Ceph-C region may be ultimately included by the Herschel infrared Galactic Plane Survey (Hi-GAL), but this region is not included in any of their publicly released catalogs.

Our search in Herschel wavelengths will at least initially be guided by sources identified from MOPEX source detection run on the Spitzer/MIPS 24 μm image of the region, combined with the 16 Submillimetre Common-User Bolometer Array (SCUBA) sources identified by DiFrancesco et al. (2008). Sources that are detected at SCUBA and MIPS-24 should also be detected at Herschel bands. We will inspect the images by eye to confirm whether or not the source detection in these wavelengths is reliable. We will look for any sources that are sufficiently bright and clear compared to the background, are not extended objects, and show up at the same locations in multiple wavelengths (the spatial resolution varies between MIPS, SCUBA, and Herschel). Once we have a reliable list of Herschel sources, we will use any available counterpart data at shorter wavelengths to construct SEDs for each new candidate source. More information about the wavelengths that are available for this region is summarized in Table 1 below.

Table 1: Available data for this region

Instrument	**Wavelengths**	**Source**	**Reduction done by**	**Number of Sources**
Chandra/ACIS	X-Ray (~0.001μm)	collaborators	YSOVAR Team	87
SDSS	optical, ugriz (0.29-0.9 μm)	SDSS archive	SDSS archive	3817
Pan-STARRS	Optical, grizy (0.48-0.91 μm)	Pan-STARRS1 archive	Pan-STARRS1 archive	10269
IPHAS	optical, riHα, (0.6-0.8 μm	IPHAS archive	IPHAS archive	2219
2MASS	JHK (1.2 - 2.2 μm)	2MASS archive	2MASS archive	1988
Spitzer/IRAC and MIPS	Mid IR (3.6, 4.5, 5.8, 8.0, 24, 70 μm)	collaborators	YSOVAR Team	6100
Spitzer/IRAC	Mid IR (3.6, 4.5 μm)	GLIMPSE team	GLIMPSE Team	8271

WISE	Mid IR (3.4, 4.6, 12, 22 μm)	WISE archive	WISE archive	1445
Herschel/ PACS and SPIRE	Far IR (70,100, 160, 250, 300, 500 μm)	Herschel archive	CephC-LABS	several (*)
SCUBA	Sub-mm (450, 850 μm)	DiFrancesco et al. (2008)	DiFrancesco et al. (2008)	16
YSOVAR	Mid IR (3.6, 4.5 μm)	collaborators	YSOVAR team	3526
Hα-bright stars	optical (0.656 μm)	Mikami & Ogura (2001); Witham et al. (2008)	Mikami & Ogura (2001); Witham et al. (2008)	2

(*) One can see several sources by eye in the Herschel images, but detailed numbers await our more careful data reduction.

We will try doing photometry on the Herschel data with MOPEX or Aperture Photometry Tool (APT), and we will use Microsoft Excel to construct SEDs for new candidate sources using available photometry for other wavelengths. The data listed in Table 1, other than Herschel, already has photometry available for our use.

Microsoft Excel will also be used to construct color-color (c-c) and color-magnitude (c-m) diagrams for our new YSO candidates. Our focus is to compare c-c and c-m diagrams in Herschel wavelengths for Cepheus C YSO candidates with Herschel data c-c and c-m diagrams for other star forming regions in the literature. We will also compare c-c and c-m diagrams for our region to c-c and c-m diagrams for an extragalactic region in the literature that has Herschel data so that we can distinguish our YSOs from foreground stars and background galaxies.

To classify our YSO candidates we will use the SEDs, c-c, and c-m diagrams in conjunction with one another. Spectral indices between 2 and 25 μm will be used for classification of the SED, though we plan to include wavelengths beyond 25 μm and will take the extended shape of the SED (and extinction) into consideration when determining classification. We will also compare our SED classifications to the locations of our YSO candidates on the c-c and c-m diagrams to see if they fall where we would expect.

4. Educational/Outreach plan

4.1 Team plan

Collaboration and communication are at the heart of good science. As a NITARP team, we should expect to improve one another's skills and glean ideas that will help us in our educational environments at our home schools. This research experience is an added growth opportunity for each of us. We will be engaged in an element of study that may vary greatly from our normal experience. Our lives will engage in science on two levels - with the classroom pedagogy that we have been honing outside the research environment, and immersed in science research as a player in the scientific research community. This is a unique opportunity for reflection and learning.

As our team compares and contrasts "real" science with "classroom" science, we will tap our educational experience as professional educators, to discern the similarities and discrepancies of the research world to our own classrooms. The adolescent mind and techniques that work best in the education of youth may dictate that there are items that make a direct correlation into the classroom from the world of research, and others that do not. Other items may greatly enhance instruction with appropriate modification. We will work to identify the tools of research and contribute to the understanding of how they best apply to the classroom. In any case, our classrooms will likely never be the same after this experience, and we strive to communicate our growth with other colleagues, so that they can also gain from our new experience.

4.2 Individual plans

Maumee High School, Maumee, OH
Teacher: Sam Evans
Students: Two students TBD

Two students from Maumee High School will participate in all aspects of the research. They will take part in weekly online meetings, travel to Caltech in July 2017 to meet their research team and learn relevant concepts pertaining to the research, reduce and analyze astronomical data, help prepare a poster summarizing their findings, and present their results at the January 2018 American Astronomical Society meeting in Maryland. Throughout the research project, these students will maintain a blog to share what they are doing and learning with others in our community. At the end of their research experience, they will share their work with the public via presentations to the school board and other groups within our district and community. The results of this NITARP experience may also be shared at an annual "Modelpalooza" conference held through Ohio State University each year as part of the American Modeling Teachers Association's modeling workshop series. Comparisons could be made between doing real science and doing science in the modeling classroom.

Sullivan South High School, Kingsport, TN
Teacher: Tom Rutherford
Students: TBD

The following events are planned as venues for sharing information about the NITARP program with others (students will be involved with some of these events):

1) Public presentation to the Bristol Astronomy Club, King University, Bristol, Tennessee
2) Public presentation to the Bays Mountain Astronomy Club, Bays Mountain Park and Planetarium, Kingsport, Tennessee
3) Presentation at the East Tennessee State University (ETSU) Physics Seminar
4) Presentation before the ETSU College of Education teacher candidates
5) Presentation before the King University College of Education teacher candidates
6) Presentation before the Milligan College teacher candidates

7) Staff Development session before the school district teachers
8) Presentation at the 2017 national NSTA (National Science Teacher's Association) meeting, Los Angeles, California
9) Poster presentation at the 2018 American Astronomical Society meeting, Washington, DC.
10) Interviews with local television stations and newspapers

Lake Dallas Middle School, Lake Dallas, TX
Teacher: Olivia Stalnaker
Students: TBD

Students at Lake Dallas Middle School will have access to the research through a Google Classroom as part of their 8th grade astronomy education. Students (including Lake Dallas High School students) that wish to participate directly in the research project will meet after school one day per week to discuss the research and use astronomical software for image processing. Students will present their research process to the Lake Dallas ISD school board as well as at a regional STEAM carnival. Two students of the after school team will travel to Pasadena, California to learn how to conduct the data analysis. Those students will travel to National Harbor, MD, in January to present their findings at the American Astronomical Society meeting.

Elkhart Memorial High School, Elkhart, IN
Teacher: John Taylor
Students: TBD

A team of students will be formed, from students in the research class, those involved in the school physics club, and other students willing to commit to the LABS study. They will meet weekly during our advisory period and/or after school to discuss ongoing research, learn more about astronomical concepts such as star formation, and learn how to use software for image processing and analysis. The team will maintain a shared website to communicate with each other and share progress. From the team, students will be selected to travel to Pasadena, CA during the summer for training, and then to the winter AAS to communicate findings, as well as connect with the local community through various science outreach events.

Our local Physics Club prides itself in community outreach - especially when there is the opportunity to engage younger children in science. Students in the club will be involved in side projects, such as the building of models that can be exhibited at the annual events in which they participate in each year (such as Spooktacular, Scitacular, and the EMHS Open House).

The Memorial NITARP team will be enrolled in the Independent Research class and use their new experiences to enhance the level of studies in the research class, as well as enhance projects that student are engaged in through the local science clubs. It will also work to encourage more science members (students and teachers) at both of the corporation high schools to seek out and join research opportunities for those in secondary education (NITARP, RET, etc.).

5. References

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