YSOs in Perseus with SPHEREx

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Abstract

We propose the continued study of potential young stellar objects (YSOs) within the c2d Survey of the Perseus Cloud, utilizing recently acquired data from the SPHEREx space-based observatory. SPHEREx, launched in March 2025, is conducting a two-year all-sky spectroscopic survey from 0.75 to 5.0 µm. Previous studies have been done on various targets within the Perseus molecular cloud, including the work by Rebull et al. (2007), which flagged 23 objects as likely YSOs, studied using Spitzer's MIPS at 24 µm, 70 µm, and 160 µm. This effort, in combination with studies of the same sources using 2MASS and Spitzer/IRAC, resulted in spectral energy distributions (SEDs) and color-magnitude plots, which helped to isolate potential YSOs from potential galaxies in the field. SPHEREx will provide spectroscopic data of these targets. The spectra from SPHEREx provide 102 channels of wavelength measurement, which provides enough resolution to distinguish background galaxies from YSOs, and moreover permits identification of major molecular absorption species within the spectra. Our goal is to obtain SPHEREx spectra for the candidate YSOs identified in the MIPS survey of Perseus and add them to other archival photometric data released since 2007 to create new SEDs and color magnitude and color color plots to better assess their potential as YSO candidates. We will also develop curriculum units based on all aspects of this work, from literature searching through identification of lines in the SPHEREx spectra. Members of this team teach in wildly different contexts (8th grade through college, classrooms through planetaria), and as a result, our lesson plans will be diverse and flexible.

Key Words and Acronyms: SHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer) - c2d ("From Molecular Cores to Planet-forming Disks"; Evans et al. 2003 - MIPS (Multiband Imaging Photometer for Spitzer) - IRAC (Infrared Array Camera)

Science Introduction and Context

Young Stellar Objects

Star formation is understood to begin in large (both massive and large in scale) molecular clouds of gas and dust outlined below. Parts of the cloud can collapse under the influence of their own gravity. If there is enough mass in the clump, eventually nuclear fusion begins as the star alights on the zero-age Main Sequence (ZAMS). We use the term “young stellar objects” (YSOs) to refer to all stages of this process, from the pre-stellar core through the young ZAMS star. The stages are generally as follows and are more rigorously treated in, e.g., OpenStax Astronomy, or in Carroll and Ostlie (2017):
Basic stages of star formation, with emphasis on stages related to our work.

- Molecular Cloud Formation
  Large, cold clouds of hydrogen gas and dust exist in space. These clouds contain regions of higher density where gravity begins pulling material together. One of these clouds is the Perseus Cloud and includes IC348 and NGC1333; regions of interest in our study. Areas of dense dust like those seen in these clouds are often areas of earliest star formation. Evidence of formation is seen in infrared radiation from young stars and jets or shocks that interact with this surrounding material. STARS will look for this evidence.
- Cloud Collapse & Protostar Formation
  Gravity causes dense regions to collapse inward, forming a protostar. As material falls inward, the center heats up, but fusion has not started yet. In this stage the infrared radiation (IR) is prominent and more than would be expected from a star. IR is also re-emitted from the surrounding dust cloud creating an SED with higher (excess) detections of infrared radiation than optical. STARS will look for this evidence.
- Disk Formation & Rotation
  As the protostar collapses, it spins faster due to conservation of angular momentum. A rotating disk of gas and dust forms around the protostar. This circumstellar disk may eventually form planets. As the dust surrounding the YSO is absorbed, less is re-emitting IR changing the observed SED with peaks in the optical and IR excess decreases. STARS will look for this evidence.
- Young Stellar Object (T Tauri Stage)
  The protostar continues gaining mass from the surrounding disk. Strong magnetic fields and convection develop, and the young star becomes visible as surrounding gas and dust clear away. The observed IR excess

in these sources becomes less prominent and the SED takes the shape of stars.

- Fusion Begins and Star Enters Main Sequence
  The core temperature rises high enough (about 12 million K) for hydrogen fusion to begin. Outward pressure from fusion balances inward gravity, creating a stable star in hydrostatic equilibrium. The star has now entered the Main Sequence stage of its life cycle.

The Perseus cloud is a molecular cloud within our Milky Way Galaxy residing ~250 parsecs away (even though there is some significant distance variation due to the size of the cloud; see Rebull et al. 2007). Star formation is ongoing within the Perseus cloud, permitting opportunities to study a significant quantity of YSOs. The YSOs have circumstellar disks of material including ices, dust, and gas which give off their own thermal signatures as IR excess and reflection from the YSO itself (figure 1 below). Our focus will be on the IR processes of gas and dust detectable from the regions of the disk giving off IR radiation: gas, dust (not UV & not the colder PAHs). Additionally, SPHEREx data provides spectra that will allow for the detection of major molecular absorption species adding more evidence of stellar evolution. Including the new SPHEREx data for sources identified in Perseus, a more complete SED can be created providing more evidence to support YSO identification and estimate ages of these sources.

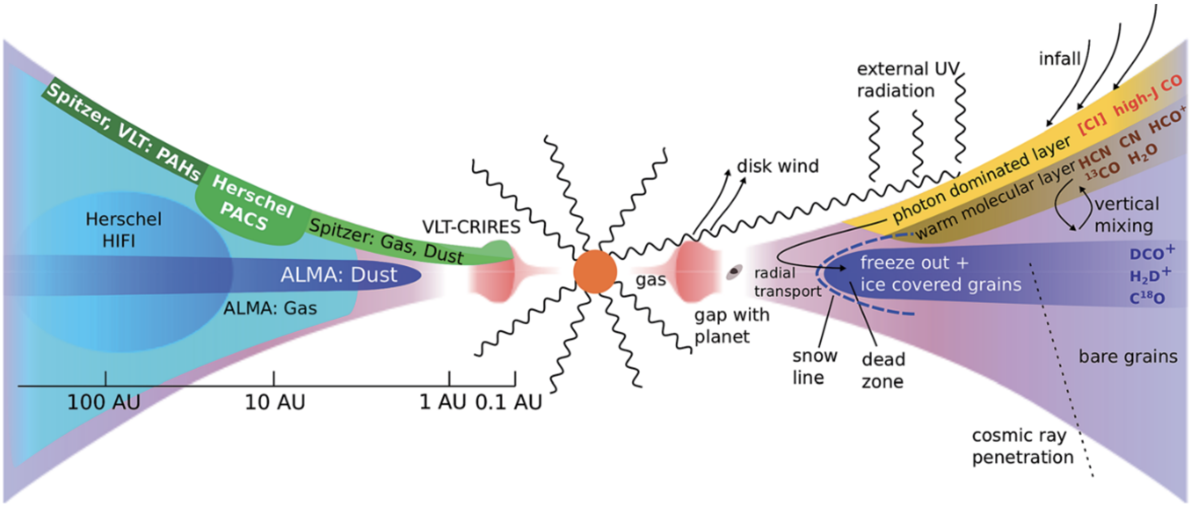

Figure 1: Diagrammatic explanation of the various processes leading to detectable emissions from a YSO. This from van Dishoeck, 2014, *Astrochemistry of dust, ice and gas:* Introduction and overview. SPHEREx is not indicated because the article was published long before SPHEREx was launched, but SPHEREx wavelengths correspond to the inner disk (close to the star, 0.1 AU or thereabouts).

Rebull et al. (2007) published a study of the Perseus molecular cloud using Spitzer/MIPS (24, 70, and 160 um); there were companion papers using Spitzer-IRAC

(3.6, 4.5, 5.8, and 8.0 um; Joergensen et al. 2006, and BOLOCAM (large-format millimeter-wave camera at 1.1 mm, Enoch et al, 2008). These papers identified candidate YSOs throughout the cloud. The STARS study will combine potential YSO sources from several papers to build a catalog within the Perseus Cloud.
The MIPS paper in particular called out a few aggregates of sources bright at MIPS bands that, if they are all co-located in the Perseus cloud, represent YSOs with a wide variety of evolutionary states– deeply embedded though having little to no circumstellar dust, suggesting very different ages. However, it is hard to imagine a situation in which YSOs could be located within 0.1 pc of each other and not be of similar age. This is perplexing specifically because YSO SED shapes have historically been tied to age.

The nature of these objects was left unresolved in the Rebull et al. (2007) paper, since little data beyond 2MASS, IRAC, and MIPS data were known at the time.
Our work will focus on expanding the data points and generating more complete SEDs for objects in this region to better understand the source type, their age, and strengthen existing YSO evidence. This will be done by including more recent data from SPHEREx and post 2007 IR surveys of the region.

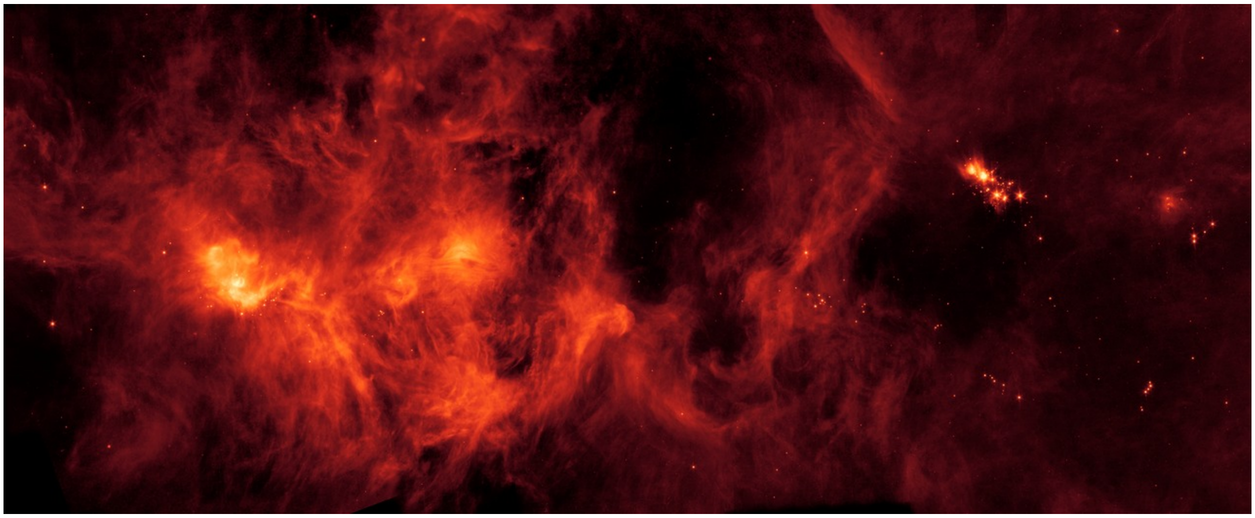

Figure 2: The Perseus Gas Cloud. This is a MIPS24 image of the Perseus Gas Cloud, which contains IC348 (bright clump on left) and NGC1333 (clump of bright sources on the right). North is 21.7° counter-clockwise. This image is from Spitzer press release spitzer_ssc2019-18a; credit: NASA/JPL-Caltech.

SPHEREx

SPHEREx is a space based observatory working in low Earth orbit to survey the entire sky in the optical and near infrared between 0.75 to 5.1 μm over a two-year period. Launched in March 2025, the first all-sky survey was completed in December 2025. The mission continues with new data releases, accessible online tools and advanced data products expected in the coming months. The additional data points will benefit

SED completion and aid in YSO identification. Additionally, the telescope will provide a significant number of wavelengths of data; 102 distinct points with added location markers. This makes the SPHEREx data for a source similar to a high resolution SED or low resolution spectrum.

SPHEREx data does have limitations that could impact the study. The telescope primary's diameter is 20 cm (8 inches) which makes the resolving power of the scope low. This will confine us in some instances when trying to collect data in crowded star fields. We can deconvolve the data for some individual objects, but this has limitations. The smaller diameter will confine us to brighter objects with resolvable space between point sources. There is potential for data contamination due to unintentional atmospheric molecular spectra and the heating of the telescope's shroud. These unwanted signals could skew data and will need to be considered until future data releases provide clarification and correction.

Analysis Plan

We have chosen to list these as bullet points for brevity.

- Table 6 in Rebull et al. (2007) lists 23 objects in "stellar aggregates" and, separately, 21 sources of interest (mostly those detected at all three MIPS bands, some of which are the same as the objects in the "stellar aggregates"). We will initially focus our work on these sources.
- For each of the objects in our initial list of objects of interest, we will check each individual object for additional analysis since the 2007 study using SIMBAD, chasing selected references for each target. We will make a note of additional data that have been published for these targets since 2007.
    - These data include Herschel, PanSTARRS, Gaia (for the least embedded), WISE, Akari, GALEX, and UKIDSS.
- We will merge these catalog data by position and construct SEDs for each target. For each of the objects in our initial list, we will use the existing list of positions and send that list to the SPHEREx spectrophotometry tool. The sources in our initial list are in general, well-separated, but there are a few that are pretty close to each other, so we will pass the entire source list for each aggregate as one list to the SPHEREx spectrophotometry tool so that it can deconvolve the sources where need be.
- We have experimented with some of the sources from Table 6 from Rebull et al. (2007), and in general, the SPHEREx spectrophotometry tool seems to be returning viable, interesting-looking spectra – see Figure 3.

- We will use the web-based tool to examine each of the spectra to determine if the points are saturated or otherwise compromised, or if the spectra are too noisy to be viable.
- We will take the SPHEREx spectra and add them to the SEDs we have accumulated for each source. All of the YSO candidates on our lists should have some sort of IR excess (because IR excess led to their identification as YSO candidates), but the SPHEREx spectra may provide a more complete or new understanding from previous data alone.
- We will examine the spectra for specific emission and absorption lines that suggest YSO disks – for example, water ice commonly has an absorption feature at 3.05 μm and carbon dioxide ice has an absorption feature at 4.25 μm.. Water vapor has a bandhead just short of 2 μm.
- We will be able to construct color-color and color-magnitude diagrams of the YSO candidates based on the newly assembled multi-wavelength catalog based on archival photometry, but we will also be able to explore color-color and color-magnitude diagrams using photometry constructed from SPHEREx data.
- These combined data analysis processes and evaluations will help to provide evidence or increased understanding to the nature of previously identified sources (YSO, galaxy, or other) and stellar evolutionary age or stage in relation to other cloud members.
- Additionally there are 387 YSO candidates that the c2d team identified in the Perseus Cloud (based on 2MASS+IRAC+MIPS), which, time permitting, we will expand our work to include. Some of these sources may be in regions that are too dense with sources for SPHEREx to obtain good spectra; we will assess these sources individually with respect to the data quality, observed embeddedness of the objects, and resolution limits.

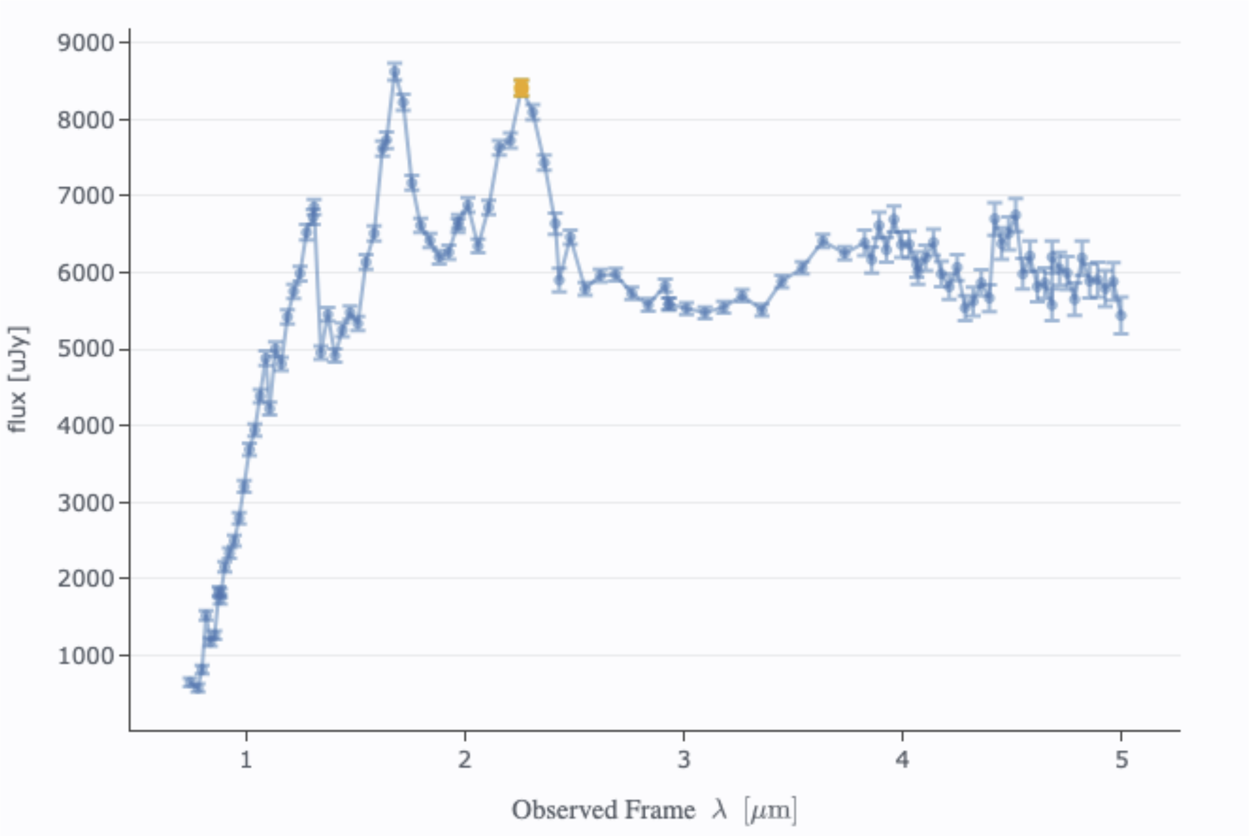

Figure 3: Example result from the SPHEREx spectrophotometry tool for one of the sources from Rebull et al. (2007) table 6. Sufficient signal-to-noise is apparent, along with prominent emission/absorption lines.

Educational/Outreach Plan

Combined Summary of Education Components:

With diverse educational backgrounds, our team aims to create resources connected to this project that can be used in a variety of contexts. This project includes many subtopics, concepts, and physical science skills that can be taught or expanded upon through an astronomy lens. A goal is to develop lesson plans and resources that are effective in the classroom at varied levels and subjects, highlight the use of real science data, tools, and processes in the classroom, and are accessible to educators.

The lessons will be created at a secondary level and be “translated” to include additional supports and scaffolds for middle school. The resources will be housed on a public NITARP CoolWiki site that includes a mechanism for teachers to provide feedback about the lessons. Those of us who teach astronomy courses will embed these lessons and resources into our curriculum.

Outreach is incredibly important to advancing exposure to authentic science processes, tools, and lessons to classroom teachers and public educators. The STARS research team will advocate and present this work at various local, regional, and national conferences to help further their reach. The intended audience will vary with each educators strengths, available resources, and location. All will present this work in a Science and Education Poster session at the 2027 AAS conference.

Individually, the educators involved with this project will be working towards the above goals as noted in their statements which follow below:

John Blackwell: I am a physics and astronomy teacher with some 150 students each year taking the three astronomy electives available at our school. We are fortunate to have an observatory on campus permitting nighttime labs and data collection for astrometry, spectroscopy and photometry. I will be using the material learned in this study with my selected topics in astronomy and advanced astronomy methods courses at our school. I currently use IRSA tools to investigate CM diagrams with my introductory students, so the IRSA interface will not be new to those in the more advanced classes. Extending their understanding of astronomy leaning heavily into data science has been my major shift in the past 10 years, and this type of research falls right into that category. At the observatory, this information can be shared with many visitors who ask how astronomy is done, and demos could also be provided along with information about the NITARP CoolWiki site. At our biennial astronomy teaching conference, attendees will be exposed to this study among others done through NITARP. Their exposure to real data and the very existence of NITARP will help them grow as educators and feed new people into the NITARP program.

Michael Bechtel: Best known as Bec, is the Professor of Science Education at Wartburg College who teaches courses in biology, chemistry, and physics to his Pk-12 pre-service educators. All elementary education undergraduates create lessons, laboratory experiences, and ancillaries for science lessons to be used in their future classrooms. NITARP provides an avenue to bring astronomy into educational settings in easily digested and incorporated instruction for all students. We will be creating a shared collaborative folder with vetted lessons that can be used by any engaged STEAM educator. Furthermore, we will be presenting the NITARP process and the folder at the NSTA national education conference.

Olivia Kuper: I am a physics, chemistry, and scientific research teacher at a small rural Appalachian high school in East Tennessee. I plan to use the NITARP educational materials in my coursework to engage students in authentic science learning experiences and to conduct original research using IPAC data. I plan to share these materials and implementation strategies with other educators through presentations at the Society for Science Research Teachers Conference, Society for Science Advocates, and the University of Texas EXES astronomy teachers group.

Laura Orr: I am a career educator and district superintendent for a small school district in rural Eastern Oregon. I intend to use this program, its experience, and generated resources to support student learning in the classroom and support the use of research as a tool for greater student and staff engagement in learning. This will be shared with students directly in my classroom as a research project for our astronomy and computer science students. As an administrator I intend to use the program and experience to advocate for similar programs in our schools to support science literacy and skill growth for both students and teachers. This work will be shared at the state level in educational and administration level groups with over 500 Oregon school administrators being served as well as those engaging with the AAS poster sessions in 2027.

Ace Schwarz: As a middle school science teacher, I value providing students with opportunities to analyze and interact with authentic astronomical data. I will be “translating” the lessons created for secondary and university students into scaffolded lessons that work for middle school students. The middle school lessons and labs will be freely accessible via the NITARP CoolWiki site. I teach at an independent school in Bryn Mawr, PA, and our astronomy unit reaches over 50 students per year. The NITARP program allows me to bring middle school students along on research projects which further encourages and develops a love of astronomy and formal science education.

Ben Senson: Ben Senson is the Planetarium Director for the Madison Metropolitan School District (MMSD) Planetarium in Madison, WI. He has been an educator for more than 35 years as a classroom teacher of the Earth sciences, physics, aerospace engineering and astronomy. At Madison College he is a senior part-time instructor for physics and astronomy. His work has included numerous published activities in curriculum projects including National Project WET and Project Lead the Way Aerospace Engineering. The processes and results from this research experience will be integrated into the two most requested interactive planetarium experiences offered at the MMSD Planetarium. This will expose approximately 6000 students in elementary grades, across southcentral Wisconsin, to the science of SPHEREx and young stellar objects. Mentioning the NITARP program in these programs will expose 240 educators to the possibility of their direct participation in the program. Both of these impact numbers are on an annual basis.

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