fIRes Final Proposal

Looking for Infrared Excess in Class M Stars: A Step Toward Determining How a Host Star Influences the Development of Rocky Planets.

1. NITARP Team

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2. Abstract

M class dwarf stars are the most common type of star but relatively little research has been conducted to determine the abundance of terrestrial exoplanets orbiting them. An approach to establishing the prevalence of terrestrial exoplanets is the detection, using infrared excess (IRXS), of a debris disk orbiting the star. A survey of the Spitzer Enhanced Imaging Products (SEIP) catalog, a collection of nearly 42 million point sources obtained by the Spitzer Space Telescope during its 5+ year cryogenic mission, is an excellent place to start a search for infrared evidence of debris disks. In this study, we will examine isolated sources in the SEIP with a signal-to-noise ratio (SNR) greater than 5 in four IR wavelength channels (3.6, 4.5, 8, and 24 microns) to search for sources with IRXS in order to obtain a large and reliable set of candidates. Using Gaia distances we will refine the search to main sequence M stars in the SEIP. This selection of M stars with an infrared excess will create the largest catalog of red dwarf stars with debris disks to date for potential follow up for the presence of rocky exoplanets.

3. Introduction

Since 1992, over 5,000 confirmed exoplanets have been discovered, but few of these discoveries have been terrestrial planets (less than or equal to 2 Earth radii) (See https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html). The limited number of terrestrial exoplanet discoveries has raised questions regarding the frequency of such planets particularly around the most common type of star: the M class red dwarf (Dressing & Charbonneau 2013, Kopparapu 2013, Su, Ford, & Terrien 2020). This study aims to significantly expand the number of potential systems harboring terrestrial planets by looking exclusively at red dwarf systems.

A method of narrowing the search for rocky exoplanets is the detection of debris disks potentially formed by collisions of rocky material around stars. These collisions release dust into the system that then absorbs light from the star. This warmed dust radiates infrared in excess of that predicted for the star alone, generating an *infrared excess.* Figure 1 illustrates what such a system with a debris disk (middle and bottom) would look like compared to a bare star alone (top), as well as their corresponding spectral energy distributions (SEDs) on the left side of the diagram (Aumann et al 1984, Werner et al 2006, Wyatt 2008).

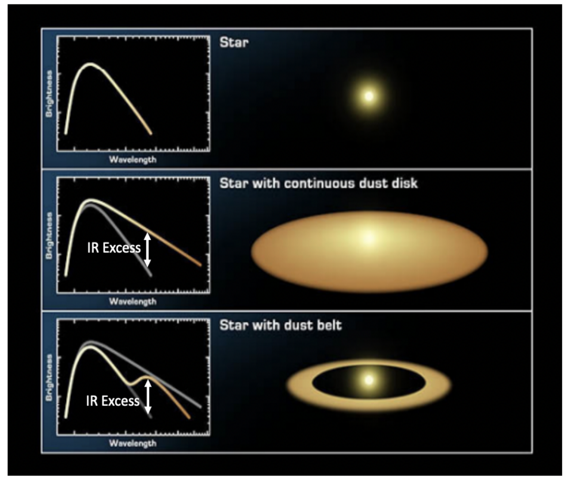

Figure 1 Dust surrounding a hot body results in a Rayleigh_Jeans tail with slope different from that of a single temperature black body. (Artist rendition by T. Pyle (SSC)). IR excess noted with white arrow.

An infrared excess can also be seen in the SED of P1121 (Meng et al. 2015) shown in Figure 2 as an example. Based solely on the 6000 K surface temperature of the star making it a G class star, the blackbody curve in green is expected, showing very little relative emission in the longer wavelengths of infrared. Actual measurements of the infrared emitted by the system are marked from the Spitzer Space Telescope (Werner et al. 2004) and the Wide-Field Infrared Survey Explorer (WISE, Wright et al. 2010) missions with the purple line representing the modeled curve that best fits the data points. As can be seen, this system is clearly emitting an excess of infrared, well beyond that predicted for the star alone shown by the purple curve above the green curve.

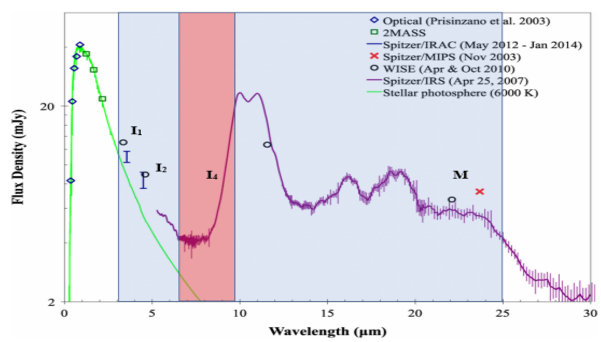

Figure 2. An SED of P1121 showing an infrared excess in the I4 and M bands.

Of particular interest are debris disks containing dust with blackbody temperatures having a range of 150-500 K, which would place the disk in the habitable zone of the star. Dust of this temperature should emit an infrared excess in the 5 - 25 micron range, making the Spitzer Space Telescope and its SEIP (Teplitz et al. 2012), with its cataloged wavelengths of I1=3.6 μm, I2 = 4.5 μm, I3, 5.8 μm, I4 = 8.0 μm, and M1 = 24 μm, ideal tools with which to discover candidate systems of interest. (Although WISE covers similar spectral bands, the 22 micron data from WISE is not suitable because of its coarser spatial resolution and lower sensitivity resulting in fewer reliable detection (Kennedy & Wyatt 2012)).

A wide range of data has already been collected spanning many stellar types and ages from the Spitzer Space Telescope (Rieke et al. 2005; Gautier et al. 2007; Bryden et al 2009;

Morales et al. 2009; Lawler et al. 2009; Chen et al. 2014; Cotton & Song 2016 & Silverberg et al. 2018). This data primarily focused on classes F - K stars, but few of the single most common type of star in our galaxy: M class stars. Gautier et al. (2007) examined a total of 62 M-stars for infrared excess and found none. Even though red dwarfs account for approximately 75% of all stars in our galaxy, their infrared excess has had limited exploration because of the difficulty in distinguishing class M dwarfs from class M giants by their temperature alone. With most of the stars in our galaxy being M stars, finding or not finding debris disks around these red dwarfs will give a new insight to planetary formation and its dependence on stellar type.

Fortunately, the recently available Gaia Early Data Release 3 (EDR3, Gaia Collaboration 2021) allows a method to distinguish these red dwarf stars from their larger and more luminous red giant brethren. By correlating the distances given by Gaia EDR3 with the large database of the SEIP, the incidence of warm dust excess around M dwarfs can be identified, yielding potential sites of terrestrial exoplanet existence.

To construct blackbody curves, determine measured infrared emissions, and visually identify infrared excess for each potential source in the SEIP would be a daunting task, to say the least. Color-color diagrams are therefore used to simplify the identification of potential systems with an infrared excess. Although ideal blackbodies of varying temperatures will emit proportionally varying intensities of light, the *ratio* of intensities at two different wavelengths will be consistent across all temperatures in the long wavelength tail (Rayleigh-Jeans) portion of the spectra. Comparing the magnitudes of two different wavelengths of a source thus provides an easy way to determine if it deviates from an ideal blackbody and, if it does, it has an infrared excess. The color-color diagram in Figure 3, for example, compares the magnitudes of I2 and I4, as well as I4 and M1 for a sample of nearly 8,000 sources found in the SEIP. The large cluster of points at 0,0 represent sources that have zero deviation from the expected magnitude differences for an ideal blackbody source; these stars show no infrared excess. Sources located in the blue oval show emission in I4 that is greater than expected for an ideal blackbody, sources located in the red oval show emission in M1 that is greater than expected for an ideal blackbody, and sources located in the green rectangle show an excess of both I4 and M1. Using such a color-color diagram, therefore, is a quick and simple way to identify sources with infrared excesses using only a handful of wavelengths rather than an entire spectroscopic curve. For our purposes we will be looking at the M1 excess sources (red oval) and the I4 and M1 excess

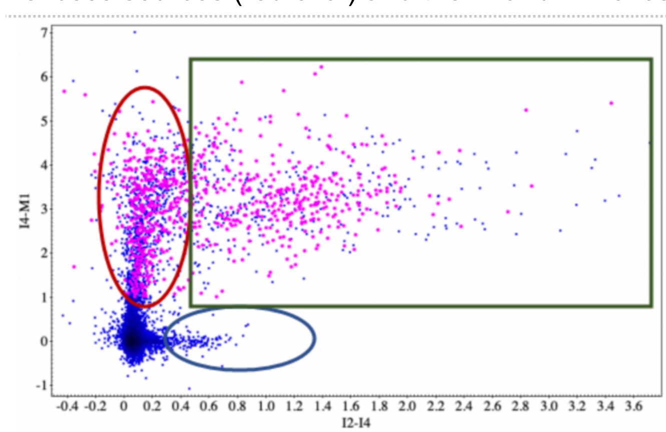

Figure 3. A color-color diagram of 8,000 sources in SEIP. Sources at 0,0 show no IR excess, while sources in the ovals and rectangle show excesses of varying degrees.
Geometric shapes are qualitative.

sources (green rectangle). Sources with only I4 excess (blue oval) are unlikely to be the result of a debris disk and more likely to be an instrumental anomaly.

The final consideration of potential sources is the cause of the infrared excess. As discussed earlier, the likely source of any detected infrared excess is a dust disk in the system that is warmed by the shorter wavelengths of starlight. Of course, gas and dust may also be the remnants of a young star's cocoon or its formation disk, rather than the debris from collisions of terrestrial type objects. An efficient way to separate these occasions of infrared excess is to ignore sources found in or near known star-forming regions and to look beyond the galactic plane into the wider field where older, more mature (>1 Gy) stars are likely to be found.

4. Analysis Plan

Our objectives for this project include combining the SEIP data and Gaia EDR3 to generate a catalog of IR excess red dwarfs and measure the frequency of debris disks located in terrestrial planet zones. We will do this by systematically narrowing our field of focus, first by cross-referencing the SEIP and Gaia EDR3 databases and applying a suitable SNR threshold, then by selecting only the red dwarf systems using H-R diagrams, and lastly, by using color-color diagrams to filter out red dwarf systems that show an infrared excess. Once that is established, then each target will be examined visually to determine if it is truly an M star on the main sequence and the infrared excess is reliable. This process is shown schematically in Figure 4, with preliminary populations included at each stage.

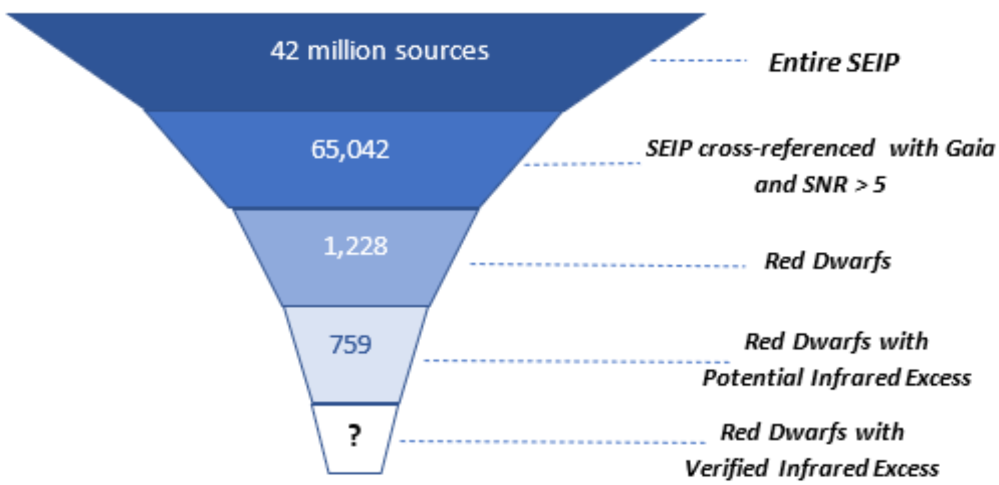

Figure 4. The selection process.

In order to compile a catalog of Class M dwarfs, we will first query the SEIP catalog, which contains point sources detected in all images taken during Spitzer's cryogenic mission using the Infrared Array Camera (IRAC, 3.6 to 8 microns, Fazio et al. 2004) and the short wavelength band of Multiband Imager and Photometer for Spitzer (MIPS, 24 microns, Rieke et al. 2004). Because of the large (5' x 5') field of view of these instruments, observations of intended targets also typically included tens to hundreds of additional sources which were imaged but not analyzed. To examine these serendipitous sources, we will select sources that have a signal-to-noise ratio of greater than five in all four distinct bands as shown in Table 1. Note, due to the varying exposure times of the images that were used to create the SEIP, the SNR >5 yields varying brightness limits across the sky. We are intentionally excluding I3 because of the low sensitivity of this channel. The selected bands will probe the star's photosphere of short wavelengths and dust emission at longer wavelengths. This spectral region also indicates mega-impact collisions releasing dust close to their host stars, similar to the Theia impact that formed Earth's moon.

Table 1: Band selection for the initial query of SEIP data:

Instrument	**Wavelength**	**SNR**
IRAC I1	3.6 microns	>5
IRAC I2	4.5 microns	>5
IRAC I4	8 microns	>5
MIPS 1	24 microns	>5

Once we have identified the sources from the SEIP that meet the wavelength and SNR criteria, we will combine distance information from Gaia EDR3, using a SNR of greater than 3 for the parallax detection. Using these distances we can derive the absolute magnitudes from the selected sources. We can then plot a color-magnitude diagram, as shown in Figure 5, in which we can locate Class M dwarfs from our sample by their color and positions on the plot.

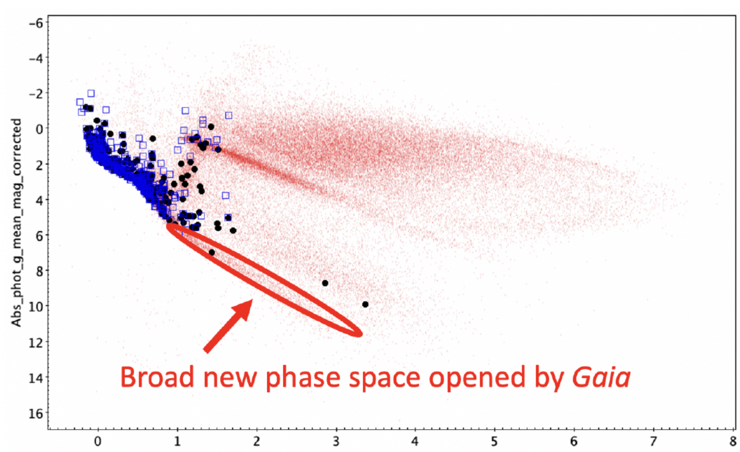

Figure 5. IR excess sources from previously identified debris disks identified by Spitzer (blue) and WISE (black) superimposed on the SEIP HR diagram. The broad new phase space of main sequence red dwarf stars for this IRXS study is noted by the ellipse.

Once we have identified our red dwarf sources, we will develop a color-color diagram, like Figure 3, to determine which stars exhibit an infrared excess at 8 and 24 microns. The limiting threshold of the IR excess will be determined dynamically based on the quality of the data. For sources that exhibit a rising flux trend from 4.5 to 8.0 microns and continuing to 24 microns, we can have high-level confidence that there is infrared excess. Sources that exhibit only excess in 24 microns will require follow-up imaging or spectroscopy. Visual inspection of the images is also necessary to rule out a false IR excess due to aberrations or artifacts.

As the final step in our selection process, M stars that are viable candidates for IR excess that fall on the main sequence band will be plotted on the sky in order to eliminate stars that are in areas of young star formation identified in recent Gaia papers (Figure 6). Young stars have IR excess due to dust remaining from their formation, which is not what we are looking for in this project.

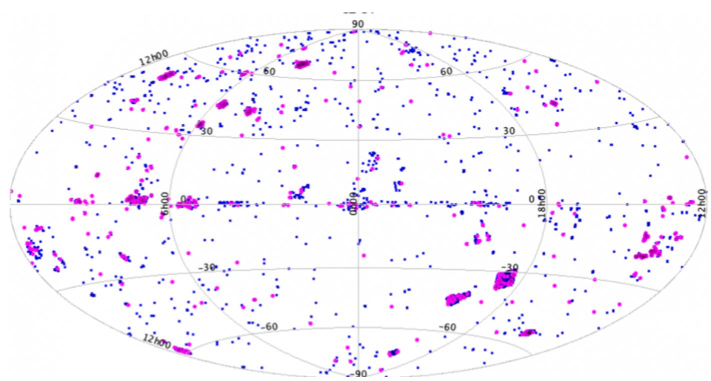

Figure 6. Skyplot of main sequence stars (blue) and M-type main sequence stars with IR excess (magenta). Areas of young star formation will be eliminated from the data set in order to focus on open field stars with IRXS.

By excluding both red giants and any M-class stars found in known star-forming regions, as well as including only sources that have a signal-to-noise ratio of greater than 5 (SNR > 5), this preliminary archival search considerably narrows the 42 million sources in the SEIP to a more-manageable potential 759 red dwarf systems that show promise of an infrared excess. Future studies could further explore these systems by using black body curves to confirm the existence of terrestrial planets, adding to the known 1501 terrestrial planets ($R \leq 2R_{Earth}$) currently found in the NASA Exoplanet Archive.

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6. Outreach

Jeff Benter:

I anticipate that my NITARP experience will significantly expand my “sphere of influence”. Turning inward first, it has already increased my interest, confidence, and understanding of astronomy. I continue to scour my newsfeed looking for astronomy news and have recently subscribed to *Sky & Telescope* magazine. Thanks to my early experiences in astro research provided by NITARP, as I read these articles, I find myself particularly interested in the methods used by the researchers and have already related a few of them to our fIRes work, such as references to signal-to-noise ratios and the filtration and selection of data based on key qualifiers such as location in the sky and source distance. I am also looking forward to more observing opportunities as the weather warms and the skies hopefully clear. I will certainly be thinking of magnitudes, infrared excesses, photometry, and much more as I gaze at the stars.

My NITARP experience will also enhance and expand my classroom teaching. Already I have brought in some of my new knowledge simply talking about the electromagnetic spectrum in a run-up to relativity. The kids were so engaged in our discussion about light that I had to spend an extra class period on it. As I re-tool our physics sequence in the near future, I hope to add a unit on the spectrum and optics and believe that NITARP will be a valuable source of information that the students find interesting and engaging. I would also like to open the archives up to the students in some way, possibly mimicking (on a small scale) previous NITARP or literature studies and possibly even having the more motivated students pose their own questions and attempt their own research. I also plan on hosting after-school sessions to discuss our fIRes project and to get students looking at some of our data and helping in its analysis. I have one student in mind to bring with me to our summer camp; he's currently planning on being a CS major, but he has a great interest in astronomy and I'm hoping we may be able to convert him to an Astro-CS major. I have a second student in mind for our AAS presentation; he's an accomplished physics student who shows initiative and has already expressed interest in our project.

Lastly, I hope to cast my net farther by venturing into the community, as well. From the amount of attention that my limited press releases have garnered, it's obvious that the public has a deep respect and admiration for NASA, the work that it does, and the people who do it. I hope to leverage this respect as a way to start a conversation with the public about astronomy and the many different areas of NASA research. Already, for example, the mom of one of my older boy's friends read the article about my NITARP experience. She approached me at a recent wrestling meet and said that her son has always been interested in astronomy and viewed with his grandpa in his backyard. I messaged him to describe our research project and to invite him to an observing session sometime. He seemed very interested. I already host star parties for my own students; it would only involve a little more preparation to expand the invite list to my son's school and to the public at large. Of course, there's no need to entirely reinvent the wheel: there is already a local astronomy club at our nearby college-town that would be a wealth of information to our community. I would like to join and possibly serve as a liaison between the club and my community.

In conclusion, though my time with NITARP has been short so far, it has already born the first of what I hope will be many fruits, and I look forward to making the most of the investment that NITARP has made in me.

Janine Bonham:

- Presentation of NITARP activities during STEM Showcase at Oley Valley High School (May 2023)
- Presentation of NITARP activities to Oley Valley students, local astronomy clubs, and museums
- Use IPAC and other archived data to do a variety of space science projects
- Follow-up our fIRes catalog findings with further astronomical research with Oley Valley High School students.
- Presentation of NITARP activities to Hawaii Technology Academy astronomy students and Mid Pacific Institute students

Anna Karsten:

With the knowledge and skills I gain through this program, I plan to transform some of my classroom lessons to follow a more authentic process, less like the rigid labs with predictable outcomes. I also plan to share with the community what I learned through a series of library talks. The standards in Minnesota are changing, which requires the sixth grade to increase their Earth Science curriculum. I will help them with the transition and hope to include the lessons I learn in this program. Finally I will reach out to the state science associations to present at their yearly conferences with both my experience and potential lessons and activities. It is possible that the random stranger may get a detailed lecture also. My main objective is to learn how to use data from the telescopes to have students complete an activity.

Olivia Kuper:

- Presentation by my students and myself to the Board of Trustees monthly meeting Greene County Schools

- Presentation by my students and myself to the Bays Mountain Astronomy Club

- Student presentation to the North Greene High School Science Club

- Share this information with the EXES Astronomy group at the University of Texas

- Share this information on Teaching Astronomy, a Facebook group that I administer

- Present a talk at a National Science Teaching Association meeting

- Present a talk at the Phillips Exeter Academy Astronomy Conference

- Present a talk at the Society for Science’s Research Teachers Conference