Classification of Compact Submillimeter Sources in the *Planck* Archive

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Abstract

The *Planck* satellite is a third-generation space-based cosmic microwave background (CMB) experiment with greater resolution and broader frequency range than its predecessors, *COBE* and *WMAP*. The completion of the first high-sensitivity submillimeter all-sky survey in April 2010 allows a unique opportunity to study the classes of astronomical sources which are foregrounds to the CMB. This project will use the *Planck* Early Release Compact Source Catalog (ERCSC) to classify compact objects which have not previously been seen by IRAS. In an effort to avoid the effects of confusion from the high density of sources in the Galactic plane, we will confine our survey to $|b|>20°$. We expect the approximately 4000 previously unidentified sources to be classified into extragalactic radio sources, star-forming galaxies, stars within a dust shell, cold stellar cores or asteroids. Teachers and students from four schools will be active participants in the data analysis process to bring authentic research into the classroom.

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Scientific Research

Goal

The *Planck* satellite is in orbit around the Earth-Sun L2 Lagrange Point in order to minimize the contamination of the infrared radiation from the Earth and the Moon. It has completed the first all-sky millimeter/submillimeter survey that has detected thousands of galactic and extragalactic sources. Many of these sources are new and their counterparts at other wavelengths, including IRAS, have not been identified. While *Planck* observes at nine frequency bands with high sensitivity, our study will focus on the highest frequency (857 GHz), where the beam full width at half maximum is ~5'. This particular frequency has been selected as it is very close to the peak emission frequency of the dust which may surround some of the objects we are working to identify.

The first step is to search the *Planck* database for compact sources away from the Galactic plane (|b|>20°). Once a target without a known association with an *Infrared Astronomical Satellite* (*IRAS*) source is identified we will search the recently released full-sky, higher spatial resolution (6-12 arcseconds), *Wide-field Infrared Survey Explorer* (*WISE*) dataset to identify the short-wavelength (3-24 micron) counterpart of the object. We will use the morphology of the object in the *WISE* data to aid us in determining if the object is within our galaxy or is an extragalactic source. We will also generate spectral energy distributions of objects (i.e., the relative brightness of a source at different wavelengths) by combining the *IRAS*, *WISE* and *Planck* flux densities to constrain the temperature of the source that will provide further clues as to its nature. Our ultimate goal is to define the nature of the previously unidentified *Planck* sources. They may be asteroids, stars, interstellar medium features, nearby galaxies or distant galaxies. The challenge is to distinguish between these different scenarios.

Motivation

WISE and Planck are both space-based telescopes that have recently mapped out the entire sky in the mid- and far-infrared. The full WISE dataset was released in March 2012. Planck released its first all-sky catalog in 2011 and will have a second all-sky release in 2013. In combination, the data from Planck and WISE present an unprecedented opportunity to locate and identify unusual candidate sources.

The 350-micron (857 GHz) band of the Planck Telescope's High Frequency Instrument (HFI) is particularly well suited to a search for dusty galaxies. By observing at wavelengths where dust in galaxies strongly emits, Planck can help constrain the total mass of large dust grains in the galaxies. Furthermore, the sharpness with which WISE can see will pinpoint the location of a Planck source.

The properties of distant dusty galaxies are an active area of ongoing research. These galaxies have been shown to be sites of prolific star formation, creating new stars at rates up to 1000 times that typical of galaxies similar to our own. The characteristic ultraviolet emission of the hot, massive stars being formed is absorbed by the envelope of dust surrounding these regions and re-radiated in the infrared. For distant galaxies, this infrared light is further redshifted until the peak wavelength of emission lies in the submillimeter range. Identifying the number and distribution of these distant dusty galaxies can help astronomers understand their contribution to star formation in the early universe. Previous efforts to study these submillimeter sources have been limited to ground-based telescopes or surveys, which only cover a portion of the sky. Ground-based instruments must contend with relatively high levels of thermal emission and turbulence due to the atmosphere, while partial sky surveys do not sufficiently address questions related to population or distribution.

Other classes of sources that the synergy with Planck and WISE can reveal may include asteroids, stars, or structures within the interstellar medium. Our approach will allow us to differentiate between these sources, as they will have different spectral energy distributions, with stars and asteroids showing temperatures hotter than those expected from distant dusty galaxies, and components of the interstellar medium (including molecular clouds) radiating at lower temperatures than the distant galaxies. Furthermore, objects like asteroids would have moved and so would have no counterpart in WISE. By choosing to look above and below the Galactic plane, and taking the source size and temperature into account, we will be able to discriminate between the various classes of submillimeter sources. Some of this work is also being undertaken by the Planck project, where follow-up high resolution data on these sources is being taken using telescope facilities such as the Caltech Submillimeter Observatory. However, that work will only study a few 100 sources due to the limitations of obtaining telescope time, while this study will use archival data to constrain the nature of the majority of unidentified Planck sources.

Methodology

By searching the *Planck* space telescope data archive for sources which have not been previously studied in other catalogs, a better understanding of the nature of what is in the cold, distant regions of our universe will be gained. Specific sources of interest will be selected at submillimeter wavelengths at a frequency of 857 GHz (350 microns) from the *Planck* database. The Planck catalog includes known cross-identifications with IRAS and radio catalog. Sources which do not have cross identifications will be selected and compared to sources seen at 3, 4, 12 and 22 microns in the *WISE* database, which will facilitate the classification of previously unidentified compact sources.

Planck has a beam of 5 arcminutes compared to WISE, which has a beam of 6-12 arcseconds. *Planck* will therefore have flux density contributions from multiple *WISE* sources within its beam (Figure 1). The flux density of a source from *Planck* will be compared to the flux density within the *Planck* beam retrieved from *WISE*. First a search will be conducted in the *WISE* catalog for sources within a radius of 150 arcseconds of the source seen by *Planck*; this radius is matched to the spatial resolution of *Planck*.

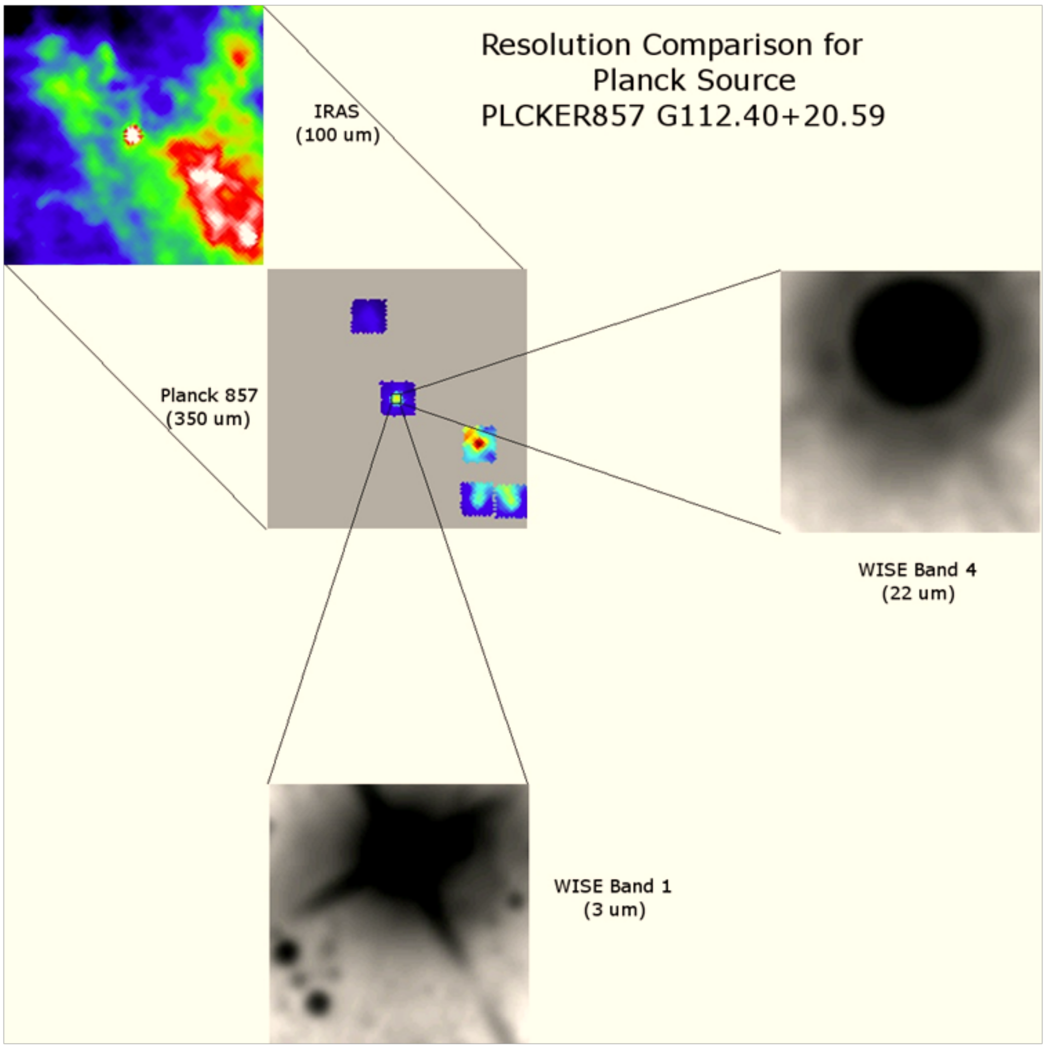

Figure 1: Comparison of data from IRAS (100 μm), Planck 857 (350 μm) and WISE Band 1 (3 μm) and Band 4 (22 μm) for PLCKERC87 G112.40+20.59 showing the ability of data from WISE to more accurately locate and resolve multiple sources seen as a single source in the Planck catalog. Note also the predominance of a single source in the WISE Band 4 versus Band 1.

The study will be limited to sources outside the Galactic plane. This is a result of source confusion that the large Planck beam induces within the Galactic Plane. To avoid this, galactic latitudes greater than 20° and less than -20° will be examined. However, we will not necessarily disregard objects of interest inside our own galaxy if they are outside the Galactic plane.

Typically, there are between 15 to 30 WISE objects in the search radius. Flux from *Planck* is available through public catalogs, but to obtain the flux from *WISE*, the magnitudes of the objects will be recorded at different wavelengths (W1 at 3 microns, W2 at 4 microns W3 at 12 microns and W4 at 22 microns) and translated to a flux density using the *WISE* zero points and the following formula:

$$Flux\ density = (zero\ point\ flux\ density) \times 10^{\frac{-magnitude}{2.5}}$$

The individual flux densities of all *WISE* sources within the search radius are added. This gives all possible contributors to the Planck source flux; in reality there are often 1 or 2 sources at 22 micron which dominate the *WISE* flux density which are the most likely counterparts of the *Planck* source. The *WISE* 22 micron band is most relevant since it traces warm dust emission which tends to be co-spatial with the cold dust emission that *Planck* can see.

Once the flux from the *Planck* and the sum of the flux values from the different sources at each *WISE* wavelength are determined, the measurement of the ratio of *WISE* flux to the *Planck* flux will perhaps tell us about the temperature of the object we are studying (Figure 2). The ratio of the *Planck* flux with the composite *WISE* flux sum is compared to blackbodies of different temperatures. The fit to our data of a typical blackbody curve will determine the temperature of the object. The black-body spectrum is determined by temperature alone not the source’s shape or composition. Uncertainties in the flux densities and resultant flux ratios will be propagated to ensure that the uncertainty in the derived temperature is robust which in turn will lead to a robust classification.

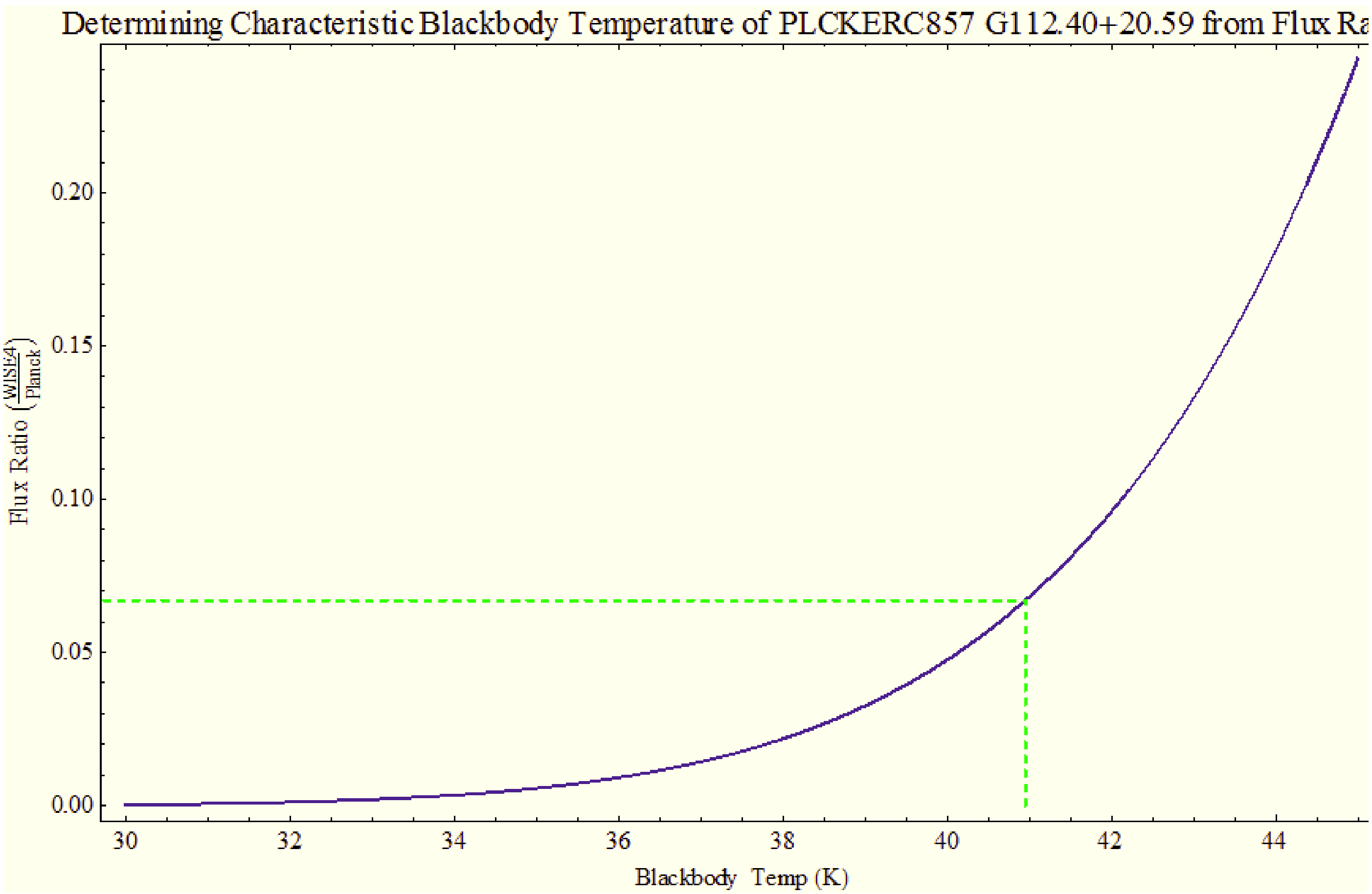

Figure 2. The WISE 22-micron to Planck 350-micron flux ratio is shown as a function of blackbody temperature as the solid line. The corresponding ratio for a particular Planck source is shown on the y-axis. A dust emissivity factor of (frequency)$^{1.6}$ is adopted. Its resultant derived far-infrared color temperature is ~41K which suggests that it is most likely dust emission from a star.

Including *WISE* in the study is important because the shorter wavelengths from *WISE* have a sharper image and pinpoint a location of an object with greater precision than *Planck*. They are both space-based platforms with a full sky viewing area. If possible, in the future, *Akari*, *Sloan* and *IRAS* measurements (mostly upper limits in the case of the latter) of these sources will be added to the *WISE* and *Planck* data to construct a full spectral energy distribution (SED).

Since various infrared frequencies are used, it is helpful to categorize the sources using an SED, which is a plot of the brightness at different frequencies. The use of the SED for each source will determine what the sources could possibly be. For example, sources could be identified as distant star forming regions that have young stars surrounded by significant gas and dust, protostars that are completely covered in a disk of gas and dust, asteroids or clumps in the Galactic interstellar medium. For example, identification of a central star with a more prominent accretion disk around would be a compact source and display as an exaggerated curve above the stellar photosphere in the infrared in our SED plot. A nearby galaxy on the other hand, may be extended in *WISE* and show an SED peaking at ~100 microns corresponding to a temperature of 20K.

It is important to note that the *Planck* sources have a size from a Gaussian fit that are not larger than the *Planck* beam of approximately 5 arc minutes full width at half maximum. The study is also limited to looking at the relatively clean areas outside our Galactic plane. A larger source suggests that the Planck source may be associated with cirrus emission from our galaxy. The fact that the Gaussian size is similar to the Planck beam means that the source is far enough away that it is not extended relative to the *Planck* beam and, therefore, may not be Galactic emission.

Timeline

The team assembled for the first time in January 2012, at the American Astronomical Society 219th meeting in Austin, Texas. The name Cold Spotz was selected as the name for our research team. The team was introduced to the NITARP program and was given an overview of the research associated with *Planck* data. Regular teleconferences were scheduled to communicate with the team members. At the conclusion of the AAS meeting each team member was assigned the task of searching the *Planck* data to locate potential new sources. Each member was assigned to locate ten possible sources from the *Planck* data and then using the WISE data to calculate the flux from the magnitudes of the objects at different wavelengths (W1, W2, W3, and W4). The ratio of the *Planck* flux to the *WISE* flux was obtained. Blackbody curves have been generated to reveal the average dust temperature of the objects; these will be used to classify the object.

The proposal has been completed as a team effort and was submitted by the deadline on March 26th

By the end of March, Dr. Chary taught the team the basic tools (Excel, spectral energy distribution including blackbodies, generating figures) to analyze the sources we have found. During the months of April and May, each teacher will select the students to participate in the NITARP program and help the students become familiar with the research tools needed to work with the *Planck* data.

June 10-15 the teachers and students will travel to the California Institute of Technology in Pasadena, CA to work with Dr. Chary. The students will work directly with the *Planck* data and learn how to use the tools in the research. They will specifically work with Dr. Chary on the details of SED fitting.

June through January 2013, the teams will use the techniques learned to pinpoint the location of and classify high Galactic latitude sources in the *Planck* archive. Candidate asteroids will be identified as warm sources close to the ecliptic plane. The timestamp of a source in the *Planck* catalog defines when *Planck* saw the source; these can be used to identify which asteroid it might be by searching the *Horizons* solar system object database.

Teleconferences will continue on a regular schedule. Two posters will be prepared for presentation at the 221st American Astronomical Society meeting in Long Beach, California. One poster will detail the research the team accomplished. The second poster will highlight the education process experienced while performing the research.

Educational Applications

A firsthand experience can be a key component in science and math education. Many times students lack motivation because they do not see how it can relate to the world around them, and therefore them personally. Having an authentic database research project in front of them, and a hands-on approach to discovering things that no else knows the answer to, can give them a sense of accomplishment and motivation for learning.

Specifically, our research with the *Planck* telescope will help the students to better understand the electromagnetic spectrum and even more specifically, infrared wavelengths, infrared astronomy and why these sources we are looking at in particular are better viewed at this wavelength. Students will also learn the importance of space-based telescopes like the ones we are using, *Planck* and *WISE*.

Educating teachers is also an important part of having better educated students. By having educators with firsthand experiences as noted above, they will have a better vision of and possibly even more motivation for the importance of training students for careers in science and technology. It will help them to better prepare students for STEM careers because they have had an experience in just exactly what it takes to work in these fields. Teachers will be better able to convey the excitement of these learned sciences and mathematics as they themselves become more involved in this type of authentic science.

Following our participation in this NITARP project, teachers can then speak to others in their community through professional development conferences (e.g., Texas Collaboratory, state-wide science conferences) and local media outlets about the importance of training students for careers in science and technology.

Communication is an important tool in science education. Modeling the collaboration of scientists across the world, students will use the CoolWiki to post their queries and hold on-line discussions about their analysis methods and subsequent results. The CoolWiki is designed to provide a place for teachers, students, and scientists to interact and share the materials they've developed, work on new materials, and collaborate on current projects. The wiki also provides a resource for other teachers to learn how to use the materials we've developed. The wiki is a dynamic place, constantly changing and growing.

Maui Prep (C. Border)

One of the biggest failings in scientific education is the desire to clearly deliver scientific content without providing students authentic opportunities to experience the trials and tribulations of the scientific process itself. Students conducting canned labs or following pre-printed procedures are not exposed to truly scientific pursuit of answers - the way has been paved for them from start to finish. While we may pay lip service to error analysis and experimental design, we frequently try to give students too "clean" an experience. Confusion, frustration and dead-ends are all part of any process of human inquiry, and are important milestones in our learning.

The NITARP program is an excellent opportunity for students to have a richer, more meaningful experience in learning and doing science. Not only are student working with authentic data, exploring novel questions of real import, but they become part of a larger community of science, a community they will be expected to share their results with.

It is hoped that students participating in this project will develop a deeper understanding of science through an increase in content knowledge and practice in process skills. Specifically, students will work to understand the tools, data and science they use to carry out the research goals of the group and answer the following questions:

TOOLS:

1. What is the scientific benefit of locating *Planck* where it is?
2. What is the relationship between the physical design parameters of a telescope, its detectors, the wavelengths at which it operates, and the physical limits of its resolution (in other words, what is *Planck* designed to see, and how "well" can its data be used for our purposes)?

DATA:

3. What is the relationship between flux, magnitude and energy of a source seen in the *Planck* catalog?
4. How do the measured emissions of an object at different wavelengths inform us about properties of the source such as composition or temperature?

SCIENCE AS A PROCESS:

5. How do scientists use their reasoning and judgment to determine criteria when evaluating data?
6. What does the public release of scientific data say about the culture of the scientific community?
7. How have your ideas of what science is, or how science is done changed as a result of this experience?
8. How do we fit our results into the larger ideas of astronomy - in what ways have we moved the understanding of humanity forward?

Student researchers will explore these questions as a natural part of the process of conducting and preparing our research. Prior to our summer meeting students will work through a "scavenger hunt" in the *Planck* and *WISE* catalogs as well as the Sloan Digital Sky Survey (which is not an all-sky map) to understand the ways in which various sources look at various wavelengths, and also to relate aspects of telescope design and placement to performance. Students will attend weekly meetings at which they will gain process skills and conceptual understanding of the techniques we use to both filter and analyze data. We will work to include students of other grades and experiences in our work through presentations at assemblies or helping students to explore archived data.

Lokelani Intermediate School (K. O’Connor)

Kathryn teaches 8th grade mathematics and has an afterschool astronomy club. The students at Lokelani have not had upper level math or science as they are in intermediate school and thus these levels of knowledge are not in the curriculum. Kathryn’s goal is to inspire her students through the basics of astronomy so that the students go on to investigate more in this field in high school and ultimately find careers in science and technology. She continues to collaborate with scientists and amateur astronomers with access to the Faulkes telescope and, using the knowledge she has learned from NITARP, she can better inform her students how data is gathered and analyzed from the Faulkes telescope and thus what discoveries or knowledge has been or can be acquired from this instrument.

It is important students feel comfortable working with data in spreadsheets such as Excel and creating example spectral energy distributions with excel.

Madisonville High School (D. Rothrock)

Denise Rothrock from Madisonville, Texas, a physics and astronomy teacher, will be able to share many educational learning opportunities by participating in the NITARP program. Bringing in real research to my students is very important to stimulate the student’s interest in the STEM subjects. The research the students will participate in will allow them to see and experience the research process from start to finish. They will learn the importance of communication between team members, good note-taking skills and writing skills that communicates the research in a clear and organized manner. There are many Texas Essential Knowledge and Skills (TEKS) that will be learned through the research in the NITARP program. A few are listed below:

- Characterize star formation in stellar nurseries from giant molecular clouds, to protostars, to the development of main sequence stars;
- Identify the characteristics of main sequence stars, including surface temperature, age, relative size and composition;
- Research and describe the historical development of the Big Bang Theory, including redshift, cosmic microwave background radiation, and other supporting evidence;
- Analyze the importance of ground-based technology in astronomical studies;
- Recognize the importance of space telescopes to the collection of astronomical data across the electromagnetic spectrum; and
- Demonstrate an awareness of new developments and discoveries in astronomy.

After the research is complete I will share this experience with other educators by scheduling workshops through various venues. I would like to team up with the Texas Regional Collaborative that offers workshops to teachers throughout the year. I will share my experience within my school district. The local museum has astronomy nights and I will contact them for possibly joining their group for a presentation.

Breck School (C. Johnson)

Similar to involvement in previous NITARP projects, a small cadre of Breck School juniors and seniors will work together on this project. Beginning with tutorials on the general principles of submillimeter astronomy, on the relationship between blackbody curves and temperature, and on compact vs. extended sources, journal articles will be read and discussed in weekly “brown-bag discussions” (see reading list in next section). Once the students feel comfortable with the material, the team will be divided into pairs to work cooperatively on the data analysis. The Breck students will collaborate with other student teams to produce a scientific poster and an education poster to be presented at the January 2013 AAS conference.

Reading List

Articles specific to the *Planck* mission.

Refereed journals

- *Planck* Early Results. I. The *Planck* mission. A&A 536: A7 (2011).
- Planck Early Results. VII. The Early Release Compact Source Catalog. A&A 536, A7 (2011).

Scientific American magazine

- *Planck* Telescope sees Universe's cool stuff. *http://www.scientificamerican.com/article.cfm?id=planck-telescope-sees-universe*

- *Planck*'s new view of the cosmic theater *http://www.scientificamerican.com/article.cfm?id=plancks-new-view-of-the-cosmic-thea*

Sky and Telescope magazine

- *Planck*'s view of the Universe *http://www.skyandtelescope.com/community/skyblog/newsblog/97960234.html*
- *Planck* sees first light *http://www.skyandtelescope.com/community/skyblog/newsblog/60242112.html*

Astronomy magazine

- *Planck* steps closer to the cosmic blueprint *http://www.astronomy.com/News-Observing/News/2012/02/Planck%20steps%20-closer%20to%20the%20cosmic%20blueprint.aspx*

Astronomical Society of the Pacific - Astronomy Beats!

- Issue #24. *Planck* Flies! 01 June 2009.

Articles tailored to astronomy concepts

- Submillimeter astronomy: *http://www.astronomycast.com/2009/04/episode-131-submillimeter-astronomy/*
- Flux density: *http://web.njit.edu/~gary/728/Lecture1.html*
- LaGrangian points: *http://www-spof.gsfc.nasa.gov/Education/wlagran.html*
- Blackbody radiation: *http://www.egglescliffe.org.uk/physics/astronomy/blackbody/bbody.html*
- Distant, Dusty Galaxies: *http://www.scientificamerican.com/article.cfm?id=distant-dusty-galaxies* and *http://www.universe-today.com/10312/spitzer-finds-hidden-galaxies/#.T0LgpC-Alao.mailto*

Star formation: *http://www.sciencedaily.com/releases/2009/04/090422085832.htm#.T0LdoixLPbs.email*