Draft version May 5, 2023
Typeset using LaTeX default style in AASTeX631

The Search for Laser Emission Lines in Tau Ceti

Alicia Roberts[1] and Howard Issacson[2]

[1]Department of Astronomy, 501 Campbell Hall, University of California, Berkeley, CA 94720, USA
[2]Berkeley SETI Research Center University of California, Berkeley, CA 94720, USA

ABSTRACT

We present the results of our study on the injection and recovery method using the NEID spectrograph to analyze the normalized spectrum of the star Tau Ceti. The NEID spectrograph is a high-resolution spectrograph located at the Kitt Peak National Observatory, designed to detect small Doppler shifts in stellar spectra. We injected laser lines into the spectrum of Tau Ceti intended for recovery. Our study highlights the methods used in injection and recovery and showcases the framework necessary for successful injections of laser lines.

1. INTRODUCTION

A star's emission spectra can tell as many things about its composition. With its features giving us insight into properties such as its chemical composition, radial velocity, and temperature. Using these natural occurring phenomena, we can begin to analyze abnormalities and see if these could be due to natural causes or due to intelligent extraterrestrial life forms.

The three types of spectra are continuous, absorption, and emission.

A continuous spectrum is a spectrum void of breaks in the observed flux values for all wavelength values. These types of spectra are emitted by an ideal blackbody, an object that emits in all wavelengths with its peak wavelength as a function of temperature. Incandescent light bulbs are an everyday example of an object that emits a continuous spectrum.

Emission spectra is measured through heating up a gas so it emits photons with energies equivalent to the characteristic wavelengths of the elements that make up the gas when excited to different energy levels. Atoms have multiple energy levels that take different energy values to emit a photon; the emission spectrum highlights these values and can be analyzed to determine the chemical makeup of a gas mixture or cloud.

Absorption occurs when a blackbody's radiation is interfered by a cold gas that then absorbs photons at its emission wavelength values and thus causes dips in the observed flux values over its wavelength range. This occurs when the blackbody radiation from the center of a star is then intercepted by the cooler gas of the star's surface. These absorption features then show us the chemical makeup of the star when we analyze the location of these dips in its normalized spectrum as a function of wavelength.

Through the use of the NEID spectrograph located in the Kitt Peak National Observatory, we obtained the raw spectrum of the star Tau Ceti to analyze its properties. Tau Ceti is a G type star in the constellation Cetus. It is a sun-like star, being slightly smaller and slightly cooler in temperature. It is located a distance of 3.6 parsecs away from Earth.

Through normalizing its spectrum, we then analyzed the median dispersion of its thin-width absorption features to obtain its Point Spread Function width (PSF). The PSF width is a measure of the resolving power of the instrument used to collect the light emitted from stellar objects. Knowing this PSF width, we can inject laser lines into our normalized spectrum of Tau Ceti and determine a threshold of accuracy of recovery of these injected laser lines. With sufficient enough accuracy at values close to the continuum, we can analyze features that were not injected and determine if they could be due to natural causes such as cosmic rays, or the hypothesis of intelligent extraterrestrial life forms emitting lasers of their own into the Cosmos.

2. IDENTIFYING FRAUNHOFER LINES IN A SUN-LIKE STAR

2.1. *Fraunhofer Lines*

The Fraunhofer lines are named after Joseph von Fraunhofer, who made detailed observations of these lines and mapped them out in detail. They are now widely used in astronomy to study the chemical composition of stars and other celestial objects.

The Na D lines are a specific set of Fraunhofer lines that are caused by the absorption of light by sodium atoms in the Earth's atmosphere. There are two Na D lines, known as the D1 and D2 lines, that are located at wavelengths of 589.0 and 589.6 nanometers, respectively. These lines are often used in astronomy to measure the radial velocity of stars, as they can be easily detected and are relatively strong in the spectra of many stars.

The Na D lines have also been used in atmospheric science to study the concentration of sodium in the Earth's upper atmosphere. The lines can be used to measure the density and temperature of the atmosphere, as well as the winds and turbulence in the upper atmosphere (Fraunhofer).

2.2. *NEID*

NEID comes from a word translating to "see" in the native language of the tribe that inhabited where the Kitt Peak National Observatory is located in Arizona and is a 3.5 meter telescope that was deployed in 2019. Its goal is to create high-precision information on nearby star's doppler shifts and exoplanet information through astronomical spectrography. NEID is co-ran by NASA and the National Science Foundation (NSF).

The NEID spectrograph uses a technique called "Doppler spectroscopy" to measure the radial velocity of stars. It does this by analyzing the star's spectrum to look for tiny shifts in the wavelengths of its spectral lines, which are caused by the star's motion. These shifts can be used to determine the star's radial velocity, which in turn can reveal information about the star's mass, orbit, and other properties.

Data is collected on stars by taking spectra of them over a period of time. These spectra are stored in an archive that we accessed for analysis of spectral features. The archive includes both raw data and calibrated data, which has been processed to correct for instrumental effects and other sources of noise.

We accessed the NEID archive through the NEID Data Explorer, which is a web-based interface that allows users to search for and download data from the archive. The archive includes data on a wide range of stars, from nearby stars to distant exoplanet systems.

2.3. *Methods*

NEID data comes in the form of a fits file that contains a 2D image of the star. Extracting the image into 1D arrays that contain information on the wavelength and flux value of Tau Ceti for different sections of the image, we can then normalize the 1D data to begin identifying Fraunhofer lines.

Figure 1 shows the raw 1D extracted data from the 2D image of Tau Ceti for the given wavelength range. There are very clear drops in the trending curve that show sharp absorption features. We hypothesized these to the Na D lines when we began our analysis as the lines fall roughly in the expected wavelength range, and any deviation is expected to be due to the doppler shift due to Tau Ceti's movement relative to Earth.

The echelle blaze function is a technique used to normalize stellar spectra, which is the process of removing the continuum level from a spectrum so that only the absorption lines remain. It is used specifically for high-resolution echelle spectra, which are spectra that have been obtained using a specialized instrument called an echelle spectrograph. Echelle spectra are characterized by a series of overlapping orders, which can make normalization more challenging.

The echelle Blaze function was used to normalize our absorption spectrum by identifying the most luminous pixels in the 95th percentile of our specific bin size of 200 pixels. Figure 1 shows the selected pixels for the most luminous as dots on our raw spectrum. As the dots appear to lie on a sufficiently smooth curve, we can transition to curve fitting. Figure 2 show the fitted curve using our echelle blaze values. We can then divide our raw data by this fitted curve to create a normalized result.

The first normalized version of our flux shown is acceptable, but it can be improved by further again dividing our normalized data by an echelle blaze function fit with an increased threshold of the 98th percentile. The secondly normalized data shown in Figure 3 is now more centered at one, and thus much easier to analyze. There is a bit of an upward tail at the left end of the spectrum that is most likely due to the very small variations in flux values at the left end of the spectrum being exaggerated once normalized.

To properly identify Fraunhofer Lines, the spectrum must be shifted to account for doppler shift. Doing so requires shifting the data to be in constant RV space. To do so, we implemented an algorithm that transforms our data to be in terms of velocity instead of wavelength. This is to make the doppler shift identification much more accurate, as

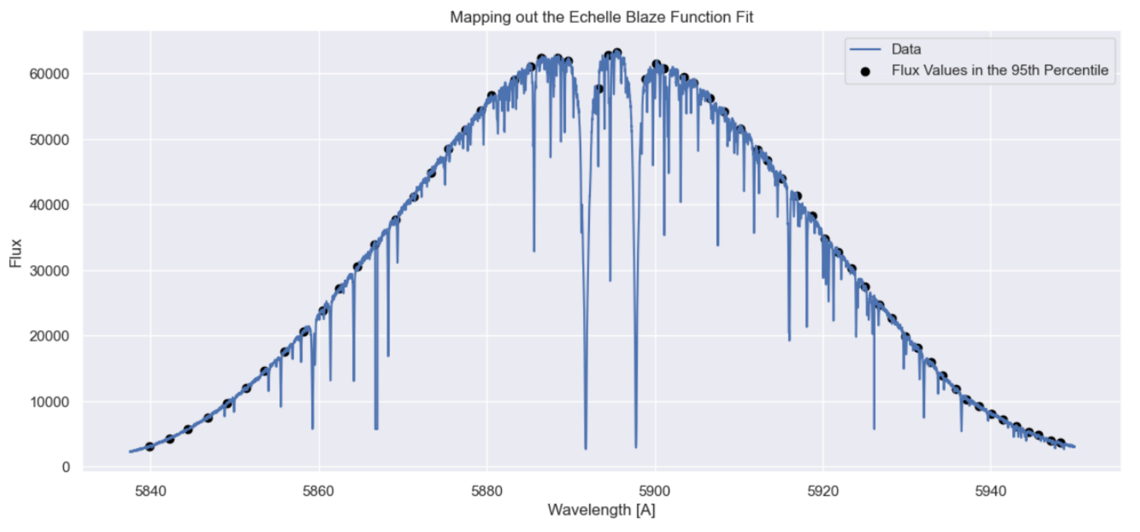

Figure 1. The Raw 1D spectrum of Tau Ceti for wavelength range 5830 to 5950 angstroms with Echelle Blaze values plotted as a scatter plot.

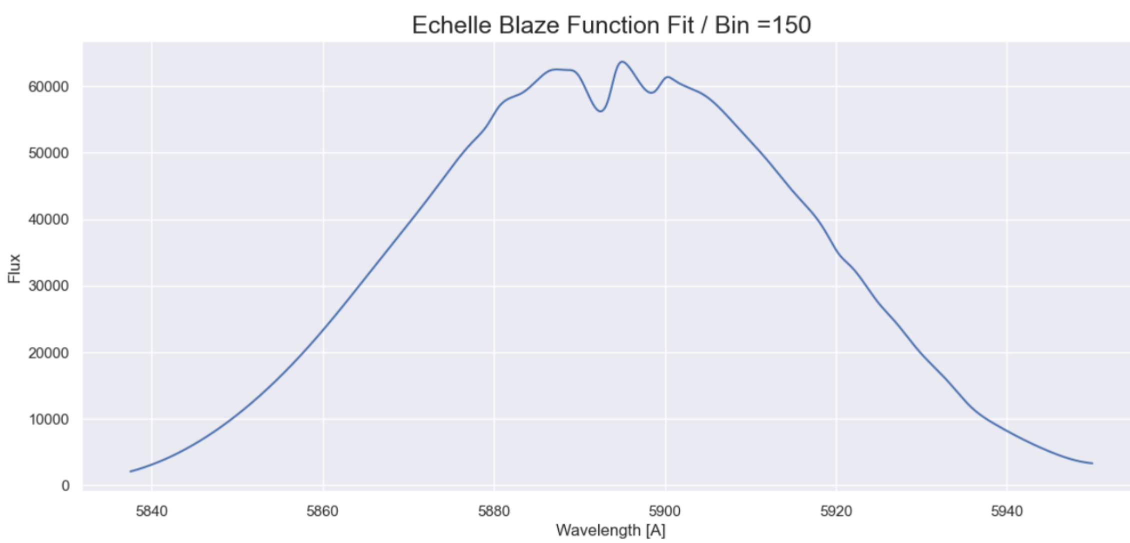

Figure 2. The curve fit of our Echelle Blaze values.

doppler shift is a function of velocity as change in wavelength. The change in wavelength is not perfectly proportional for all wavelength values, so velocity spacing accounts for those differences.

With our normalized data, we were able to create a model of the sun's spectrum and interpolate it to fit the NEID's wavelength range. We can use this still reference frame of zero radial velocity from us to calculate the radial velocity of our sun-like star with a similar normalized spectrum. This data is also shifted to be in constant RV Space. For determining the radial velocity of Tau Ceti, we used an algorithm that increases and decreases the doppler shift of our star and determines when it best lines up with the rest frame Sun spectrum through a Chi squared test. Where the chi is minimized is where Tau Ceti best lines up with our rest model.

Running a chi squared test on the difference between our NEID data modeled to be at different radial velocities compared to the sun's spectrum, as shown in figure 4 we can see where the chi squared value is minimized. The minimum chi value is our predicted radial velocity given the data from NEID in terms of the pixels of the data set. Our analysis showed that Tau Ceti has a radial velocity that causes the spectrum to be shifted 94 pixels to the left

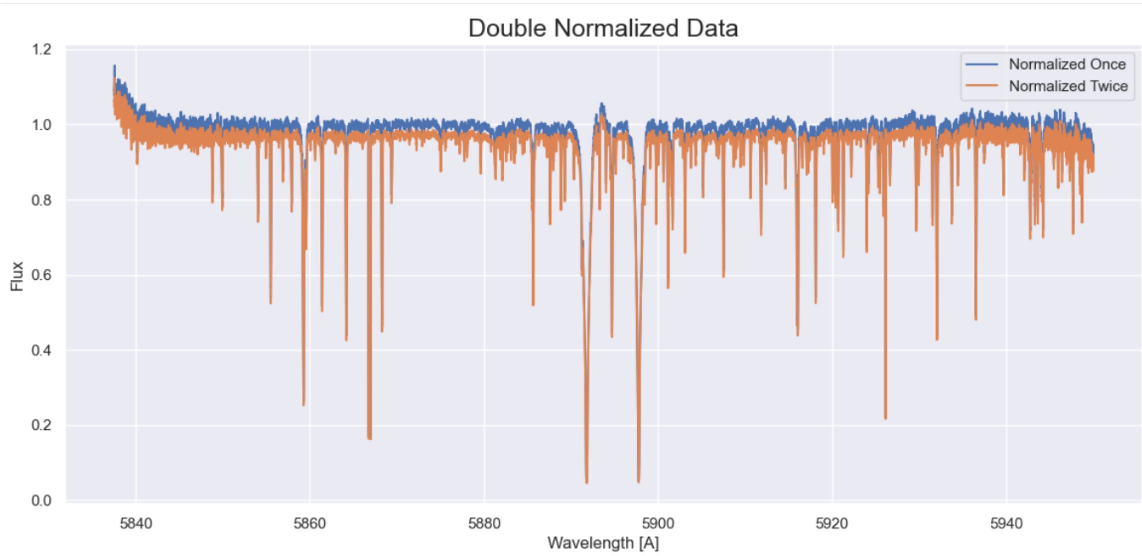

Figure 3. Secondly normalized flux with 98th percentile echelle blaze limit with first normalized flux plotted behind in blue.

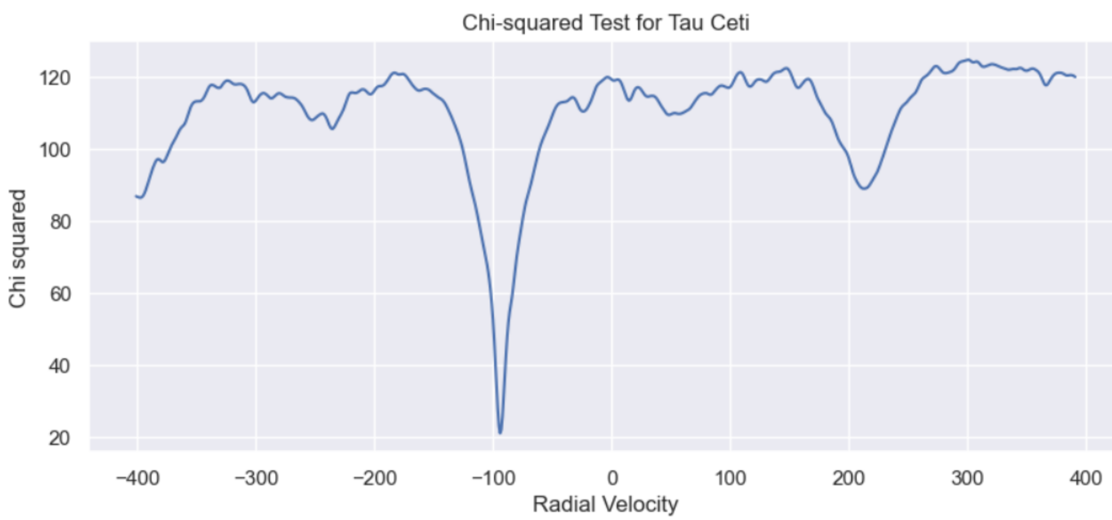

Figure 4. Chi Squared plot for different radial velocities.

to align with the rest frame. Shifting left indicates a negative value which shows that Tau Ceti is moving towards the Sun.

Performing the test again with our shifted spectrum of Tau Ceti and our rest frame solar spectrum, seen with Figure 5, the chi value is minimized for 0 pixels being shifted. This confirms that our shift of 94 pixels left is the most accurate rest frame model of Tau Ceti.

Now that Tau Ceti's normalized spectrum is successfully shifted into the rest frame, we can easily identify the deep absorption features as the Na D lines due to their placement lying exactly on the expected wavelength values as show with Figure 6 when we zoom in on the normalized plot around the predicted Fraunhofer Lines wavelength range.

3. POINT SPREAD FUNCTION

The Point Spread Function (PSF) is a mathematical representation of the blurring of a point source of light as it passes through an optical system such as a telescope. The PSF describes the way that the light from a point source is spread out or smeared in the resulting image due to various factors, such as diffraction, aberrations, and atmospheric

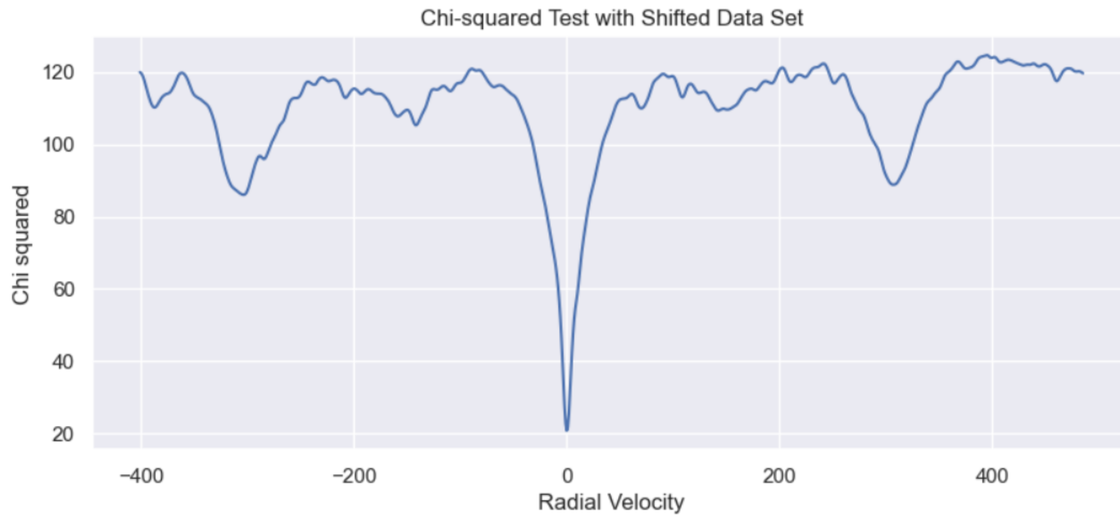

Figure 5. Chi Squared plot for shifted spectrum. The minimum is centered at 0, confirming a goodness of fit with our shifted model.

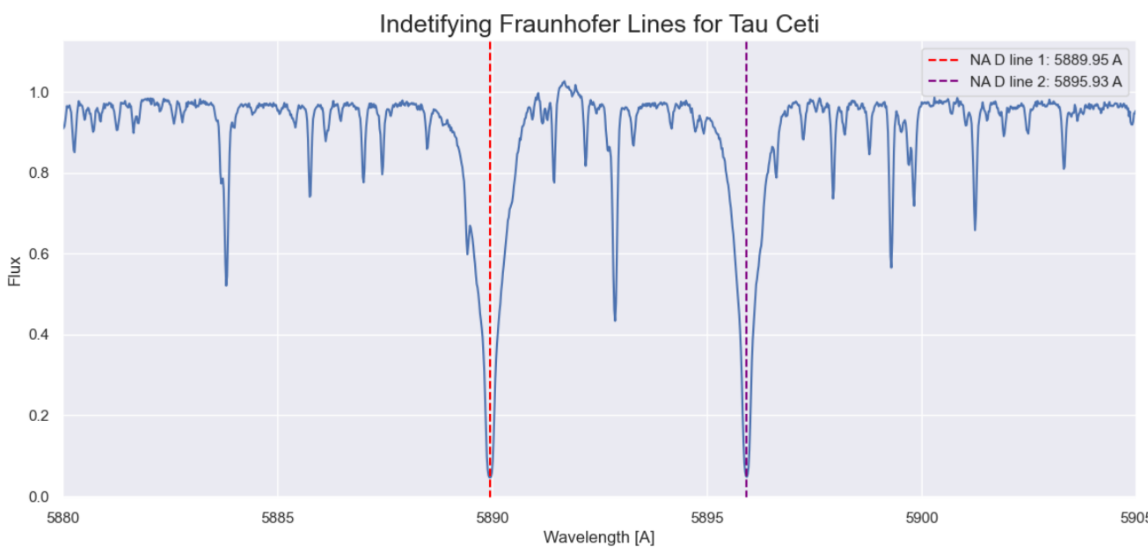

Figure 6.

effects. The PSF can be characterized by its shape and size, which depend on the properties of the telescope and the observing conditions.

In optical astronomy, the PSF is an important concept because it limits the resolution and fidelity of astronomical images. The PSF is used to describe the smallest scale on which features can be resolved in an image, and it is an important factor in determining the accuracy with which the properties of astronomical objects can be measured.

For our purposes, we determined the PSF value of our spectrum through finding the widths of many fitted gaussians to the thin spectral features of Tau Ceti. Through this fitting process, the widths were collected into a histogram, where the median value was selected as the PSF value. The median was selected as opposed to the mean due to the median being less affected by outliers as compared to the mean value.

Our PSF finder was created to fit gaussians order by order for the 1D arrays collected from the 2D format of the initial NEID data format. Doing so required generalizing our algorithm to apply to all wavelength values. This caused some issues in the shorter wavelength values less than 4000 angstroms. This is very close to the end of the visible spectrum (3800 angstroms), so it was more challenging to normalize and fit gaussians in this range as it is towards the limit of what is observable. To account for this and avoid unnecessary inaccuracies, we decided to disclude this data in favor of the higher wavelengths that were much more consistent in their recorded gaussian widths and more uniformly normalized. The lower wavelength normalized values stretched from ranges of 1 to 2000 in normalized flux values. This caused many complications as normalized flux is supposed to span from 0 to 1. For this reason, we decided that our limit for possible 1D arrays that would be put through our PSF finder algorithm would be arrays that fell in this 0 to 1 range for normalized flux. This left us with well over 2000 gaussian fits to determine our Tau Ceti PSF value.

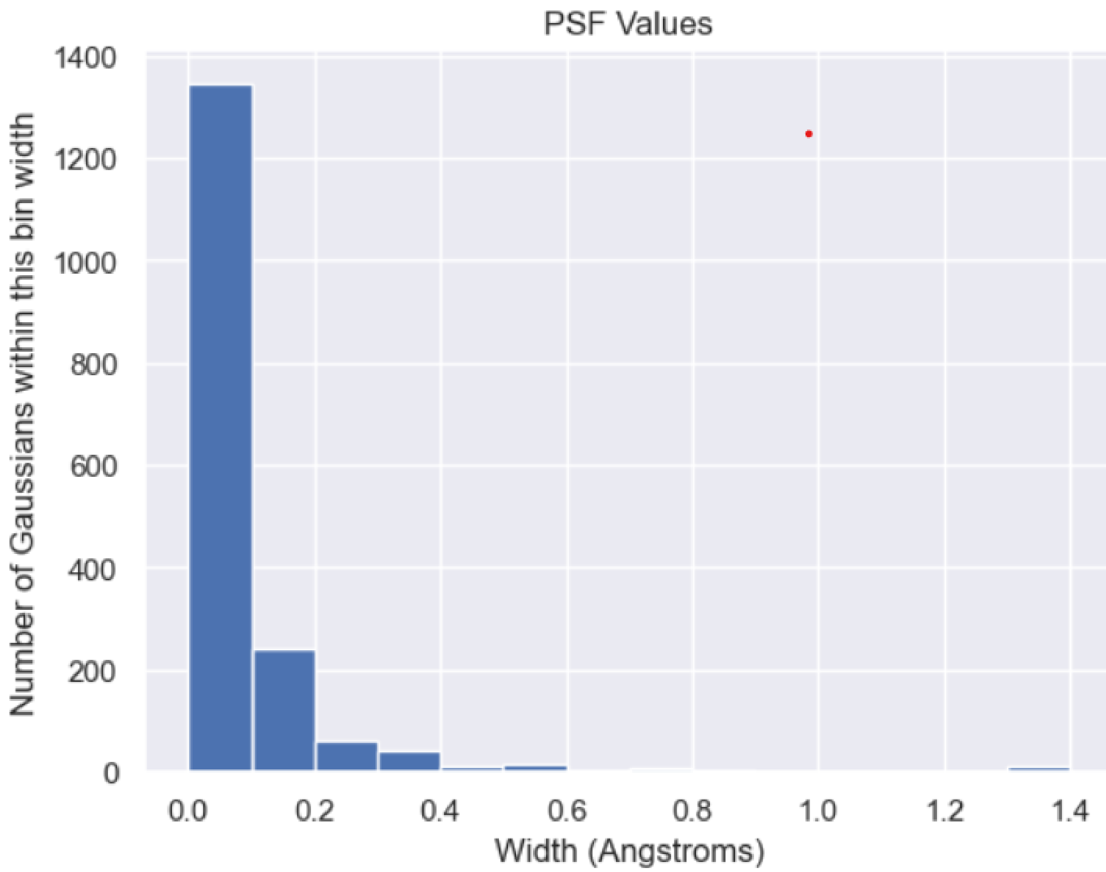

Figure 7. Histogram of measured gaussian widths to determine the PSF value of the Tau Ceti spectrum.

As shown in Figure 7 we see a histogram with the measured gaussian widths for our fits. These values are right skewed to be at very narrow widths with majority with a width of less than 0.2 angstroms. This in turn confirms that the median is a much better estimate of this minimum width value as there are very few widths that fall above 0.4, with an outlier of over 1.2 angstroms much to the right. The median width value is 0.05 angstroms and the mean is 0.10 angstroms.

4. LASER INJECTION AND RECOVERY

4.1. *Background*

The method of injection and recovery of laser lines in optical SETI involves the use of lasers to communicate with potential extraterrestrial civilizations. The basic idea is to inject a laser signal into the light received from a distant star and then recover the signal at a later time.

The process involves transmitting a laser signal that is of a specific wavelength and then searching for that same wavelength in the light received from a distant star. By comparing the laser wavelength with the star's spectral lines, any deviation from the expected frequency can be interpreted as a possible signal from an extraterrestrial civilization.

The injection and recovery of laser lines can be performed using a variety of different techniques, such as frequency modulation, pulsed laser transmissions, and direct detection of the laser signal. However, the primary challenge of this method is to distinguish between signals of extraterrestrial origin and signals that may be generated by natural sources or human-made interference.

4.2. *Methods*

For our purposes, our injections were created using an alogorithm that injects a laser emission feature placed at a random wavelength and intensity, but with a width of that of the median PSF value for NEID. This is to replicate what a recovered laser line would look like if recovered naturally.

4.3. *Results*

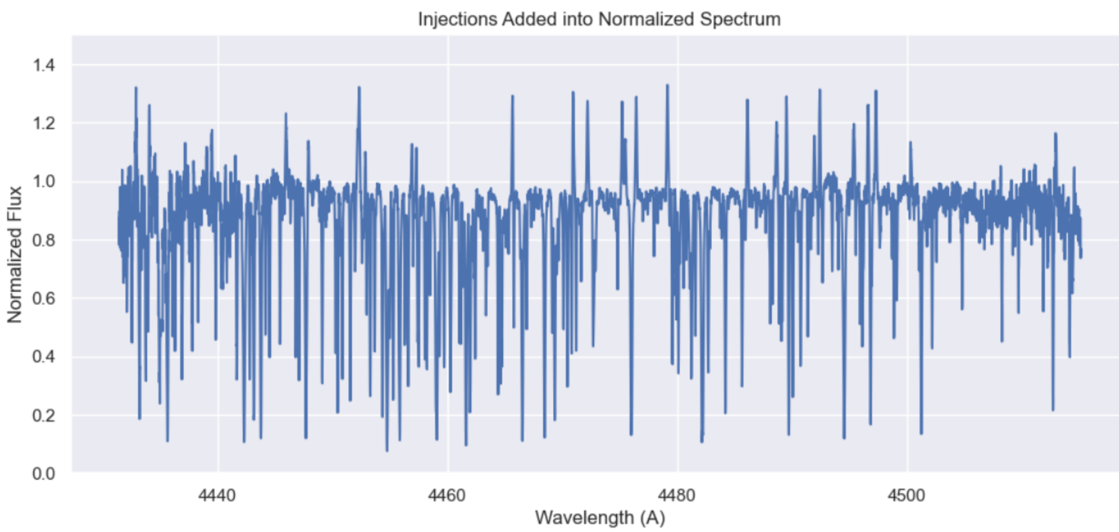

Figure 8. A sample of our injected laser emission lines for Tau Ceti

As shown with figure 8, our injected laser lines appeared as expected with reandom placement and falling randomly in height between 1 and 1.4, which we chose as a threshold for detection.

We were unable to begin recovery due to time constraints, but in future steps we would have begun collecting the emission lines idenitcally to how we recovered the absorption features. We would then begin identification of what was an injected feature, what is a feature of the spectrum, and what is due to outside influences such as cosmic rays due to the widths and amplitudes of the recovered features.

Through this project, we gained a deeper understanding of stellar spectrum and the methods that astronomers use to analyze stellar features.

5. CONCLUSION

In this project, we aimed to normalize a stellar spectrum, identify its point spread function, and inject and recover laser lines from the spectrum to simulate extraterrestrial intelligent laser emissions from distant star systems int eh search for extraterrestrial life. We successfully normalized and identified the PSF values, as well as injected laser lines, but were unable to begin recovery. However, our study creates a starting point for future projects to begin recovery of simulated laser lines and further the process of searching for intelligent life forms outside of our own solar system.

6. ACKNOWLEDGMENTS

We would like to express our sincere gratitude to the University of California, Berkeley, for providing the resources and support that made this research possible. Additionally, we would like to thank the team at Optical SETI, particularly Howard Isaacson, for their valuable guidance and insights throughout the course of this project. We are also grateful to our colleagues for their contributions and collaboration, which greatly enhanced the quality of our work. This research would not have been possible without the support and contributions of these individuals and . organizations, and we are truly appreciative of their efforts.

7. REFERENCES

Software: python, astropy, scipy, numpy, seaborn, matplotlib, pandas, pickle, chatGPT

REFERENCES

Collaboration, N. ????a, NEID Search Tool, https://neid.ipac.caltech.edu/search.php

—. ????b, What is NEID?, https://neid.psu.edu/what-is-neid/