Spectroscopy of HD 126053

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Spectroscopy is the study of the electromagnetic spectrum emitted by an object. For our project, we will be identifying the electromagnetic spectrum of a distant star. The Las Cumbres Observatory instruments have the capabilities to identify spectra at multiple observing locations through the Network of Robotic Echelle Spectrographs. This paper will discuss the spectroscopic data recorded of HD 126053 and its significance. The data will be analyzed to uncover stellar classifications of the star. We found the HD 126053 star to have effective temperature of 6 200K, traveling with radial velocity of -18.843 m/s with a partially metallic makeup, classifying it as a F8 type star.

I. INTRODUCTION

We owe much of our present day work of spectroscopies to Isaac Newton and Joseph Von Fraunhofer. Through their ingenious experiments, they largely explained the complexities of light and paved the way for our present day understanding the atomic composition of celestial objects. Spectroscopy has since emerged as a powerful astronomical tool, revolutionizing our exploration and understanding of the universe around us.

Beginning with Newton, his groundbreaking use of prisms to split white light into its array of colors marked the beginning of spectroscopy. Von Fraunhofer further advanced spectroscopic methods by observing the unique dark lines in the spectra emitted by stars when he provided various light sources through a diffraction grating or prism. He observed various dark lines when analyzing the spectra, and upon further study, noticed these spectral lines varied in position and intensity which were indicative of the composition of the source. Building upon these foundational discoveries, numerous physicists have since expanded our knowledge of spectroscopy, now being a valuable means of uncovering the atomic makeup of luminous structures.

Critical to the success of spectroscopy is an understanding of the quantum mechanics revolving the phenomena. Because energy levels are quantized, photon energy corresponds to a specific wavelength due to the relationship $E = \frac{hc}{\lambda}$. When a particle encounters a photon with just the right amount of energy to elevate it to a higher energy level, the photon is absorbed, resulting in the absence of a characteristic wavelength from the spectrum. Every element and their isotopes possess a unique arrangement of energy levels, dictated by its distinct properties. As a consequence, each element or isotope selectively absorbs or emits specific wavelengths, leaving behind a distinct pattern of absorption lines or emission spectra. By analyzing the light that arrives from these spectral features, we can uncover the isotopic composition of an object and gain insight into its atomic properties.

The aim of this paper is to delve into the applications of spectroscopy in astrophysics and apply the method towards a luminous object. For this spectroscopy, we chose to look into the spectral signature of HD 126053, a star in the Virgo constellation. Our choice was dictated by the data availability within the Las Cumbres Observatory Science Archive as well as its similarity to our own sun, being considered a solar analog- which we seek to compare for ourselves with the results of the spectroscopy. This makes it a particularly interesting target due to interest in solar systems that may exhibit similar characteristics to our own, like life outside of Earth. By examining the characteristic spectral signatures of elements and isotopes, we seek to provide a comprehensive understanding of spectroscopic methods and their pivotal role in advancing our knowledge of the universe.

II. METHODS

To set up our spectroscopy, there were multiple steps involving programming and data collection. In this section, we will explicitly go through the steps that led us to our final data acquisition. The Las Cumbres Observatory gives public access to many resources that were very helpful throughout these processes.

A. Las Cumbres Observatory Tools

The Las Cumbres Observatory (LCO) gives public access to all science data (raw and processed) produced from the observatory. Downloaded data comes packaged in a compressed format from the FPack library. Data can then be decompressed through NASA's CFITSIO, which will return FITS files that can be used for data analysis. FITS files are are condensed scientific data files that can be expanded through processing, which are useful to store large amounts of data without compromising quality. Although we do not have direct access to the spectrographs at LCO, there are an abundance of observations that can be used to process a spectroscopy of various stars. To complete a spectroscopy of a

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star, LCO developed the BANZAI-NRES data-reduction pipeline for high-resolution spectrographs. More specifically, BANZAI-NRES can process any LCO Network of Robotic Echelle Spectrographs to provide a finalized PDF containing the following information: wavelength calibrated spectra, stellar classification parameters, and radial velocity measurements. The LCO network can resolve a range of wavelengths from 3800-8600 Angstrom, which are included in the spectra, and are calibrated using the library xwavecal, that operates on 1D spectra for high precision radial velocity analysis by comparing observed spectra with a library of known wavelength calibration sources [2]. The returned spectra also contains the best fit from the PHOENIX library for stellar classification. PHOENIX is a large library containing models of various stellar atmospheres in order to compare spectra with the star's respective classification, which is used by LCO's processing methods [5].

BANZAI-NRES relies heavily on the BANZAI pipeline itself. BANZAI processes LCO images from the SBIG cameras on the 0.4 meter telescopes, the Sinistro cameras on the 1 meter telescopes, and Spectral cameras on the 2 meter telescopes. The NRES instrument is a high resolution spectrograph that is installed at these locations. The BANZAI python pipeline method follows from the 2014 Global Supernova Project team. It takes an input of raw bias, dark, and lampflat images and subsequently performs the following steps: bias subtraction - subtracting inherent detector noise; dark subtraction subtracting the thermal noise of the detector by using the same exposure time as the science data but with a closed shutter; flat field correction - compensating for pixel-topixel sensitivity within the detector for the science data; source extraction - locating and identifying astronomical bodies within the frame using various algorithms; and instrument calibration - aligning data with the specific orientation of the input to ensure accurate output. For full use of the spectrograph instrument, the installation needs light from two telescopes, four charge-coupled device (CCD) cameras for object orientation, and various stabilizing components for precision in measurement, which is why multiple different data files are needed to be reduced through the BANZAI-NRES pipeline. The BANZAI output is multi-extension containing the science data, bad pixel mask, error analysis, and a FITS binary table source catalog with information about the sources within the data [7]. The BANZAI-NRES pipeline is a similar process that uses the BANZAI output for the finalized spectral analysis. It takes the BANZAI input as well as the bad pixel mask, double images, and science files to complete full analysis. After running, the data is made available on the LCO science archive in three separate files: a one-dimensional calibrated wavelength spectra, a full two-dimensional un-analyzed image frame, and the summary PDF mentioned before. The one-dimensional spectra comes within a FITS binary table that describes the intensity of light as a function of wavelength for the given target. The two-dimensional



FIG. 1. This photo depicts the visibility of the target, HD126053, at all LCO sites during the day the observations were made. Note that all sites have visibility of the target, but the data acquired was taken from the LSC site at 12:23 AM due to the specific spectrograph instruments available for observation.

output provides an image that describes the spatial and wavelength information from the target, one axis being spatially on the detector and another describing its respective wavelength. It is also visually representative of the detected noise, which is processed in the summary PDF. The summary PDF is an overview of all of the received data. The two-dimensional can be used for more intensive analysis, but the entire spectra is displayed within the summary, which is what we use in this case. The PDF is a visual representation of the data alongside error analysis.

B. Data Acquisition

For our specific project, we used the star HD126053 for our spectroscopy. This star was chosen because the LCO observatory had recent observational data available for use within the BANZAI-NRES pipeline. This star is suitable for analysis especially because it is photometrically analogous to our sun [3]. After deciding our target, we downloaded and ran the BANZAI-NRES pipeline for its respective data on the LCO archive. Using Homebrew, a package manager for macOS, the GitHub repository was duplicated onto a group member's computer for data processing. This step allows us to interpret our own data taken from the LCO archive. To ensure correct processing, the test data available through the BANZAI-NRES documentation was checked for any problems. This preliminary step proved we were able to accurately and efficiently produce a spectroscopy for a given stellar source. After successful data processing, we moved to our official target and the HD126053 raw files were accumulated. The instruments that the raw data was taken from were the NRES unit 01 in Chile with the fa09 camera. The science data used for the input with the calibration files was dated to May 30th, 2023 at 00:23:10. At this time at the Chile (LSC - Cerro Tololo) observatory, the target was well within the visibility ranges with air mass of 1.4, below the maximum as seen in figure 1. This means that the acquired data at this time is viable for data process-



FIG. 2. This image shows the intermediate step to interpreting the spectra. The BANZAI-NRES pipeline interprets the light spots against the calibration lines to determine the peaks within the spectra. The spots are then contrasted against the standard points produced by the lampflat data to produce the finalized spectra.

ing. The raw data was then downloaded to a directory that served as the input for the pipeline. The processed files were exported and the summary PDF was then available for interpretation. In addition to the summary PDF, the one-dimensional and two-dimensional FITS files were also extracted. The Astropy library was used to interpret the one-dimensional FITS file of a binary table, however, the information within it was the same as represented in the summary PDF and did not provide any other context. Using Astroart 8, a commonly used software for astronomical image processing and analysis, the twodimensional output was also resolved as an image from the pipeline. The produced image, displayed in figure 2 shows the intermediate step for interpreting the spectra of HD 126053 as completed by the BANZAI-NRES pipeline.

III. RESULTS

Following our experimental methods, we were able to interpret the output data from the BANZAI-NRES pipeline. Since the spectra is large, ranging from 380-860 nanometers, it has been split up into multiple different sections for closer examination. Additionally, there is error analysis as well as identification of the radial velocity and surface gravity.

A. Main Spectra

As seen in figure 6, the observed spectra from HD126053 is compared to the PHOENIX library of spec-



FIG. 3. The calculated signal to noise ratio is a valuable identification of the reliability of data. Generally, a signal to noise ratio above 25 is preferred for radial velocity measurements.



FIG. 4. The CCF barycentric velocity graph is indicative of the radial velocity of the star [1]. This plot is valuable for the error analysis of the spectrum due to the Doppler effect on wavelengths.

tra from model atmospheres for the best fit of data. By comparing the two data, we can superficially observe that the best-fit is a good match for the star. Therefore, as shown in the summary data of figure 5, the effective temperature of the star is projected to be 6200K. This temperature allows us to classify the star as an F-type star, or more specifically, F8V from comparison to table 7 in [4]. F-type stars have effective temperature ranging from 6000K-7500K and are taken from the standard stars of [9]. Summary Information for file

Iscnrs01-fa09-20230529-0036-e92-1d.fits.fz Teff = 6200 K logg = 5.5 (cgs units) [Fe/H] = -0.5 [alpha/Fe] = 0

RV = -18.843 km/s RV error = 0.032 km/s Barycorr = -15.854 km/s BJD_TDB = 2460094.52679

SNR = 181/resolution element @ 5180 Angstroms Exposure time = 900 seconds

FIG. 5. This image displays the summary output of information for HD 126053, which includes valuable information such as radial velocity and effective temperature. This information is used within stellar classification as well as error analysis. This comes from the PHOENIX model fitting.

B. Wavelengths of Interest

Figure 7 displays various points of interest in a spectra, including the metallicity of the star. Given the top left plot showing the absorption line of Ca 2 H, its strong, deepening structure is a quality of many F type stars. Additionally, the H bands of F type stars become more prominent, as we can see with H beta and H alpha plots. Also worthy of noting are the three absorption lines of Magnesium. These three absorption lines are among the most prominent within the observed spectrum of HD 126053, which indicates a metallic environment within the stellar object. However, when observing the [Fe/H] ratio in figure 5, we see a slightly lower metal concentration in the star. This ratio is a representative measure comparing the metallicity of our star with the observed stellar structure, negative meaning a lower measurement than our sun. So, despite HD 126053 being a metallic environment, it is slightly less abundant in the atmosphere in comparison to our sun, which is to be expected with the F classified stars [6].

C. Error Analysis

With the BANZAI-NRES processing, plots give an error analysis for the star. Shown in figure 3, there is a negative barycentric velocity that corresponds to an error in measuring the wavelength due to the experienced Doppler effect. Since the star has a negative radial velocity relative to the observation, the corresponding measurements are slightly blue-shifted. This means the peak wavelengths are smaller corresponding to the correction. This is why in the plots of notable wavelengths mark the peak wavelength slightly offset from the data. Although the shift is minor, it is still noticeable in the observation and is taken into account when marking the absorption lines. Note in figure 5 the error in radial velocity being 0.032 km/s. This is not significant enough to change the representation of blue-shift in the wavelengths. Additionally, the small error in radial velocity is indicative of a bright object in accordance with the the BANZAI-NRES pipeline limitations statement, where accuracy within 10 m/s can be achieved with magnitude 6. Since HD 126053 is observed to be about 6.25 [3], the lower error in velocity is to be expected.

Additional to the radial velocity error in wavelength, there is also a source of error within the instrumentation itself. We can express this mathematically as $\frac{S}{N} = \frac{F \tau A_{\epsilon}}{\sqrt{N_R^2 + \tau N_T}}$, which is done within the pipeline for the error given by the CCD within the NRES instrument. The variables are as follows: F- total flux, τ - exposure time, A_{ϵ} - effective area, N_R - readout noise from dark frame subtraction, N_T - noise per unit of time Since we are observing an object many light-years away, there is intrinsic error if the source signal is not large enough. Although the instruments are calibrated and adjusted to get rid of as much error as possible, there is still going to be error due to environmental error such as atmospheric conditions (e.g., the measured air mass is not 1, it was about 1.4 at observation time according to figure 1). As we see in the calculated signal to noise ratio of figure, the lower end and higher end of the wavelength spectrum was more susceptible to the present noise than the middle range.

IV. DISCUSSION

This project was aimed at mastering the usage of the BANZAI-NRES pipeline to be able to perform a spectroscopy on a star of our choosing. Granted, our choices were limited in stars due to availability of data, we successfully used the pipeline for the stellar spectrum collection of HD 126053. In addition to the data that we received from the pipeline, we are able to make comparisons of this output to other public data and contrast sources of error or other reasons the conclusions may be different. To guide this discussion, I will be referring mainly to the summary information, which provides information about the classification of HD 126053

Following the SIMBAD database as well as the data from the NStars project, HD 126053 is considered to have a radial velocity of -19.214 km/s, a spectral type of G1.5V, surface gravity (in log g) of 4.57, temperature of 5700K, and metallicity [Fe/H] of -0.28 [8], [11]. Unfortunately, none of the data we have acquired precisely matches with these previous observations. Since the data we have received is following a well-established pipeline, the only attributions to data differences we can make are due to the science data input for the pipeline, or stellar evolution since the previous measurements in 2006. Both can make differences in measurement, however, since the stellar lifetimes of F type stars are very similar to that of



FIG. 6. Here is the spectra contrasted with the PHOENIX best fit. This plot shows the similarity between the target star and a modeled stellar atmosphere with effective Temperature $T_e = 6200K$, which we find to be largely a good representation of the received data due to the similarity in absorption lines.



FIG. 7. Here are six wavelength regions of interest of the spectra. The vertical blue lines represent the center wavelengths given radial velocity adjustment. From this, we see strong absorption bands in Ca 2 H type, which is indicative of F type stars.

our own, we can safely assume that no major temperature increase has happened within HD 126053. There is a possibility that the science data frames were contaminated in collection. There is also a possibility that the data collection methods of have become more accurate since the previous observation in 2006, and that our data we have had processed is a reflection of this advancement. Likely, it is a combination of both. Given that HD 126053 is not a commonly studied star, the variations between measurements may be large, especially with advancements in instrumentation, measurement, and comparison. One redeeming factor is that all measurements are on the same order.



FIG. 8. Further spectra of interest for the observed star. The vertical blue lines are two representative absorption lines for the Telluric A and B bands, which are often used for comparison to the sun's spectrum and used for error correction [10].

A. Further Steps

To further this project and its reliability, the best step forward would be to take science data over the various spectrograph locations of LCO multiple times and over different times of the year. This way, the data would be more accurate over any environmental interference factors as well as instrumental variances. Additionally, it would be worthwhile to take spectrographs of other stars considered to be similar and compare the results between stars. Given more time, it would also be informative to look further into the two-dimensional data output. This could lead to more in depth analysis of the spectrum of HD 126053 as well as more information about the raw data and errors (such as bad pixel mask) to identify more precisely where errors in output come from and if that were to significantly affect the results of the spectra of HD 126053.

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