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# Spectroscopic Observations of Stars from CTO

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## 1. BACKGROUND

Spectroscopy is a helpful tool used to find the properties of stars. Spectral features are used to classify stars by spectral type. The goal of this lab is to have hands-on experience with the Pepito spectrometer instrument at the Campus Teaching Observatory (CTO). We will become familiar with the process of taking spectroscopic data, from aquisition at the telescope to data reduction. We will observe the spectra of several different stars of various spectral types, as well as some bright solar system objects.

We also had to contend with two nights of observations, as we combined the data from two groups.

## 2. METHODOLOGY

At CTO, we set up the Pepito spectrometer to connect it to the telescope. We first took exposures of the twilight sky. These were not flats, but the spectrum of the Sun filtered through the Earth's atmosphere. Our goal was to observe stars of various spectral types. On our night to observe, the clouds started to roll in very quickly after sunset, so we observed Vega. After being clouded out, we took calibration spectra of Hydrogen, Mercury and Neon lamps. We then took darks, with the exposure time matching that of our observations. We took bias frames at the end of the nights. Finally, we took dome flats by lighting up the CTO roof with a projector and pointing the telescope at it.

For the other group, they took calibration data of Neon and Mercury. They then took dome flats, dark frames, and biases. They then took spectra of Vega, used the Moon to find the Sun's spectrum reflected off of it, Epsilon Peg, Jupiter, Albireo A, Deneb and Europa. The second component of Albireo was not observed due to the weather. There was some struggle with part of the telescope, which was then solved by replacing the paddle. They took darks at the end of the night, noting that the temperature of the CCD had increased to 14 C from the start of the night. The increase in temperature decreased the signal to noise of these observations.

The data reduction involved in this lab was similar to the other labs. I made two master bias frames by median combining the bias frames from the two nights separately. I then created master dark frames for both nights, making sure to subtract the master bias for each accordingly and making separate master dark frames for each exposure time. I then median combined the dome flats for each night and normalized them. We used a clear filter for spectroscopic observations, and did not expect the CCD to be lit up differently at any wavelength. I masked out everywhere on the CCD except where the spectra appeared on the exposures, median combined each. The spectrum of Vega that resulted is shown in Figure 1. I then made 1-D spectra by finding the median along the spatial axis.

The new data reduction step for this lab was to perform wavelength calibration. I used the observations of the Hydrogen, Mercury and Neon lamps from the first night of observations. I do not expect the range of wavelengths from the spectrometer to change between nights. I subtracted the master bias and dark from each exposure of the spectra, and then divided by the normalized master flat. I made a 1-D spectrum by masking out pixels outside of the spectrum and then finding the median along the spatial axis. The resulting spectra of the calibrators is shown in Figure 2.

$$\lambda = -0.207809 \times pixel + 565.381530 \quad (1)$$

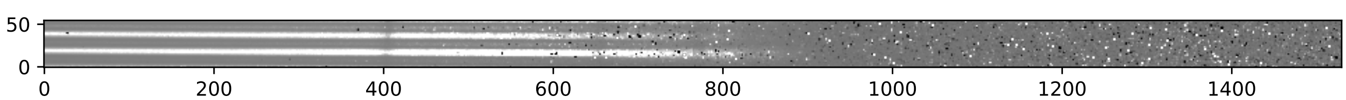


**Figure 1.** Calibrated spectrum of Vega. Note that the left of the image has the spectrum of Vega, with several dark absorption lines juxtaposed against the blackbody continuum radiation from the star. For Pepito, the wavelengths of light measured go from longer on the left to shorter on the right. Halfway through the spectrum, the CCD stops being sensitive to the light exposed to it.

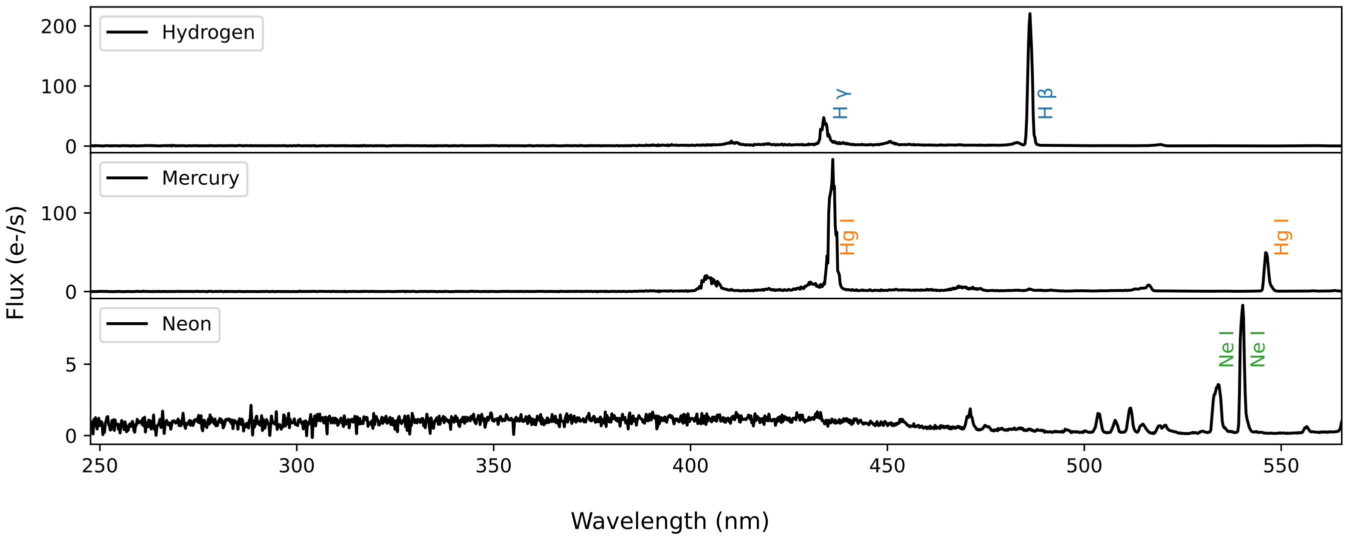


**Figure 2.** The spectra of the lamps used for finding the wavelength solution of the CCD. The top panel shows the spectrum of Hydrogen as detected by the CCD, with the spectral lines H$\beta$ and H$\gamma$ visible. The second panel has the spectrum of Mercury, with the most prominent spectral Hg I lines labeled. The third panel shows the spectrum of Neon, with just two spectral lines identified due to Neon having the majority of its optical lines at wavelengths not picked up by this CCD.

| Pixel pix | Wavelength nm | Element |
|---|---|---|
| 633.0 | 434.047 | Hydrogen |
| 382.0 | 486.133 | Hydrogen |
| 622.0 | 435.835 | Mercury |
| 93.0 | 546.074 | Mercury |
| 121.0 | 540.05616 | Neon |
| 151.0 | 534.10938 | Neon |

**Table 1.** Table of the pixel coordinates of the spectral lines detected in the spectra in Figure 2, along with the wavelengths of the lines and the elements that created them.

The calibrators in Figure 2 each show spectral lines which can be used to find the wavelength solution of the CCD. By finding where each familiar spectral line peaks in the spectra, I can find which pixel is associated with the wavelength of the spectral line. Table 2 shows the pixel value of the lines identified in Figure 2 and the wavelengths of the corresponding spectral line, identified with NIST. The Hydrogen $\beta$ and $\gamma$ lines are well known, and the wavelength of one of the Mercury lines lining up approximately with H$\gamma$ was able to show the orientation of the CCD. Pepito is an optical spectrometer, which means that ultraviolet wavelengths of the electromagnetic spectrum with wavelengths less than around 375 nm are not picked up by the CCD. I used a linear fit on the values in Table 2 to find the wavelength solution of the CCD, shown in Equation 1. The maximum wavelength picked up by the CCD was 565.4 nm. A longer CCD may have picked up even longer wavelengths from Pepito.

Comparing the orientation of the spectrum from the CCD in Figure 1 to that of the spectra with the wavelength solution solved in Figure 2, it is clear that the CCD was flipped so that shorter wavelengths appeared on the left of the CCD.

## 3. RESULTS

The spectra for the Sun, Vega, Deneb, Alberio A, Epsilon Peg, Jupiter and Europa are shown in Figure 3. The vertical lines are at the wavelengths of prominent Hydrogen Balmer line features and one Helium spectral feature. Although the wavelengths of the spectral features do not match up with the absorption lines in the spectra, it is important to remember that the spectra found in this lab have been redshifted away from the local standard of rest.

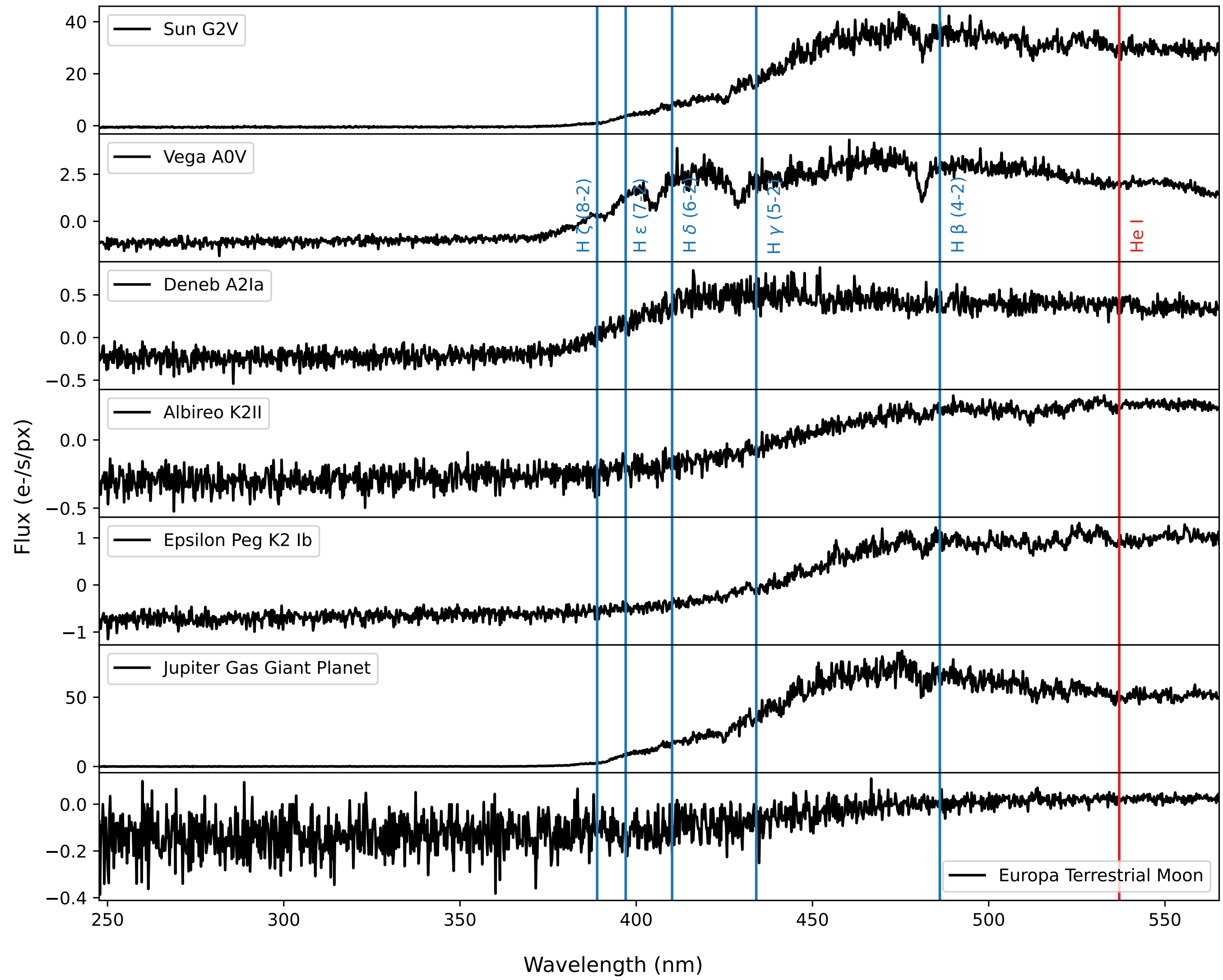


**Figure 3.** The resulting spectra of our observations. The top panel shows the spectrum of the Sun, with absorption lines from H$\beta$, H$\gamma$, and He I visible. The second panel shows the spectrum of Vega, with many absorption lines from the Balmer series visible. The third panel shows the spectrum of Deneb, which does not have many absorption lines resolved by the spectrometer. The fourth panel shows the spectrum of Albireo A, with absorption lines of H$\beta$ and He I visible. Epsilon Peg's spectrum is in the fifth panel, which again shows the absorption lines from H$\beta$ and He I. The sixth panel shows the spectrum of Jupiter, one of the gas giants of our solar system, which reflects the spectrum of the Sun. The spectrum of Europa is in the seventh panel, which is not very bright and does not show signs of absorption lines.

Astronomical bodies move in space with a velocity, including the Earth, so the wavelengths of the spectral features of each body in Figure 3 do not match up with the rest wavelengths.

The Sun is the nearest star to the Earth, and is so incredibly bright that we had to observe the Moon to find its spectrum. Most prominent in the Sun's spectrum on the first panel of Figure 3 are some of the Hydrogen Balmer lines, H$\beta$ and H$\gamma$. One spectral feature for Helium I is also visible. The Sun is a G2V type star. G2 is the Harvard stellar classification placing the temperature of the Sun on the warmer end of between 5200 K to 6000 K. The V is Yerkes luminosity class, which puts the Sun on the main sequence of stars. The Sun's temperature is 5772 K, with the peak of the continuum radiation from the Sun at 502.079 nm, which is on the spectrum in Figure 3. The offset between the apparent peak on the measured spectrum and the canonical wavelength of the peak of radiation from the Sun implies that the CCD does not respond to all wavelengths of visible light equally.

Vega is one of the brightest stars in the sky with a magnitude of 0 at all wavelengths. The only issue is that Vega is not a perfect blackbody at all, as shown by its spectrum in the second panel of Figure 3. Vega has the deep Balmer line features of an A0 type star, the strongest of its spectral type, with a temperature at around 10 000 K. It is also on the main sequence. Balmer lines of wavelengths all the way down to H$\zeta$ show up in the spectrum of Vega. Vega's temperature is 9602 K, placing the wavelength of the peak of its blackbody at 301.812 nm, which is beyond the sensitivity of the CCD.

Deneb is another A type star, with its stellar classification being A2Ia. Its spectrum is the third panel of Figure 3. The Ia for its luminosity class means that Deneb is an evolved star, a luminous supergiant. Deneb may have a high temperature, but it shows very few signs of spectral features. It is cooler due to being an A2 type star, with a temperature between 7500 K to 10 000 K. The temperature of Deneb is 8525 K, placing the peak wavelength of its blackbody at 339.941 nm, beyond the sensitivity of the CCD.

Albireo A is a K2II type star, the coolest so far. Its spectrum is the fourth panel of Figure 3. It is a bright giant by its luminosity class, with K2 meaning that its temperature is between 3700 K to 5200 K. Albireo is a double star system, which means that Albireo A has a companion, which is much hotter and bluer. The spectrum of Albireo B was not retrieved due to bad weather, and Albireo's companion was either not resolved by the telescope or outside of its view. The spectral features of H$\beta$ and the He I feature are just visible in Albireo A's spectrum. Albireo A's temperature is 4383 K, with the peak wavelength of its blackbody at 661.191 nm, a wavelength beyond the detection of the CCD. If the CCD was longer, maybe it would have been picked up.

Epsilon Peg is a K2 Ib-II star. The spectrum of Epsilon Peg is the fifth panel of Figure 3. Its K2 spectral classification places it at a similar temperature range to Albireo A, between 3700 K to 5200 K. Its Yerkes luminosity class sets it apart, placing it between a bright giant and less luminous supergiant. The spectral features of H$\beta$ and the He I feature are just visible in Albireo A's spectrum. Epsilon Peg is an evolved star, a supergiant with an envelope many times larger than the Sun. The temperature of Epsilon Peg is 3963 K, with the peak of its blackbody radiation at 731.264 nm, beyond the limit of the CCD.

Jupiter is a gas giant in the solar system. It is made of Hydrogen, much like the Sun and other stars, but it is much less massive and much cooler than a star. Its spectrum is the sixth panel of Figure 3. Some of the Balmer lines may be visible in its spectrum, due largely due to the planet reflecting the light from the Sun, however the planet itself is made of largely Hydrogen itself.

Europa is one of the many moons of Jupiter. It is made of ice and rocks, with barely any atmosphere. It is not very bright. Its spectrum is the seventh panel in Figure 3. It has no spectral features, as it does not have an atmosphere to create absorption lines. Its spectrum is that of a cold blackbody. Any reflected spectrum from Jupiter or the Sun is minimal.

## 4. CONCLUSION

We observed various astronomical objects with the Pepito spectrometer as a class. In the future, clearer nights for observing runs are necessary for effective observing. While it was unavoidable this time, ensuring that the CCD we are using keeps a stable, low temperature throughout observations is imperative. We were unable to observe the companion to Albireo A with Pepito, so returning to that target to find its spectrum would be necessary for measuring the pixel size relative to the angular resolution of Pepito. We did not observe any K type stars on the main sequence, B type or O type stars. Future observing strategies would include observing these stars.

The results of these observations are shown in Figure 3. We have observations of two main sequence stars, three evolved giant stars, a gas giant planet from our solar system, and a Galilean moon. Most of the targets show signs of spectral features from Hydrogen and Helium, with some unidentified absorption lines due to metals in the atmospheres of these stars. The absorption lines are shifted from the wavelengths of the spectral lines at rest due to the motion of the Earth around the Sun and the motion of the astronomical bodies through space causing the lines to shift in wavelength due to the Doppler effect.