Abstract:

This experiment explored the basic principles of spectroscopy and the error associated with technical capabilities of measurement. Spectra were taken of celestial and more common terrestrial sources. The nature of the spectra ranged from the characteristic atomic emission of neon and mercury, the emission spiked blackbody curves visible of stars, and the more ideal blackbody given off by an incandescent bulb. These spectra were used describe observational behavior of two different instruments: the USB 2000 Spectrometer and the SBIG Spectrometer. Wavelength solutions were found for both spectrometers, and the spectra were corrected using dark subtraction and elementary flat fielding. The terrestrial sources provided good references and allowed the honing of techniques like averaging the intensities, dark subtraction and pixel to wavelength conversion. These techniques were used to analyze the star spectra taken with the SBIG spectrometer to find source temperature, stellar type and absorption features.

Introduction:

Understanding and properly using equipment is crucial to any experimental undertaking. In the name of such understanding the characteristics of one of the most important astronomical instruments was investigated in this lab.

A spectrometer is a standard part of an astronomer’s toolbox. It is one of the best ways to gather information about stars, providing details about composition and temperature as well as the possible presence of other nearby celestial bodies. The spectrometers used in this lab disperse light into its component wavelengths via diffraction grating, and record it using charged coupled devices (CCD’s). The properties of this system introduce inherent error in the measurements – the extent and magnitude of these errors was the primary focus of the investigation.

Only after characterizing the spectrometer can meaningful results be drawn from it. Armed with a wavelength solution, read noise, dark noise and gain value, an astronomer might analyze the spectra by identifying the peak wavelength and emission or absorption features. This is precisely what took place in this lab, with Python doing most of the heavy lifting: fitting polynomials to the data, picking out molecular features, and providing corrected spectra.

\*\*diffraction grating and CCD

Observations

This experiment required the use of two spectrometers, one more complex than the other. Observations began with the simpler of the two devices, the USB 2000 spectrometer (referred to as the lab spectrometer).

The lab spectrometer was permanently attached to one of the laptops via USB cable. It was controlled through the SpectroSuite software installed on that machine. Settings like dark subtraction, pixel to wavelength conversion and time integration were available for modification. The data from the lab spectrometer displayed in this report was primarily recorded at 100 microsecond integration time, with the processing options turned off. Other integration times were experimented with, but the time is 100 microseconds unless otherwise stated.

The spectrometer itself was encased in a box, with only the USB cable and a fiber-optic cable protruding. At the end of this fiber-optic cable was the CCD, the pixels of which served as the detector. By experimentation, it was found that the sensitivity of this detector varies quite extremely when shifted only slightly. However, since there was no support provided for the detector, improvised stands were devised to ensure consistent measurements. In this fashion, a variety of sources were recorded (see Table~\ref{tab:datatable}). The group members present varied from day to day, but only the group member responsible for operating the software is listed.

The delicacy of the fiber-optic cable made these observations a bit challenging, and the slightest jostle of the detector would cause huge fluctuations in the signal recorded by the software. Taping the detector down provided the most consistent results. This approach was especially necessary for the data required to calculate the gain and read noise of the spectrometer.

The other primary mode of acquisition was the SBIG spectrometer attached to the 16 inch reflector telescope on the roof of the Burton Tower. This was a much more computerized process – and this proved detrimental on at least one occasion. The summary of telescope observations here will be mainly concerned with the second night’s viewing, since it was for this evening that the author was present.

The goal of the telescope observations was to take spectra of sources with different spectral types, to get a sense of the differences between them and eventually estimate their temperatures. However, the live display from the guiding CCD was mysteriously dark, even when pointed at a bright source such as Vega. It wasn’t until several hours later that it was discovered that the switch that toggled between the two diffraction gratings had been left midway between them. This was a relatively easy fix, and soon observations were taken of two stars (Table~\ref{tab:datatable}). A much wider variety of celestial sources were available from the first nights observing.

At both telescope session, and in the lab, dark spectra were taken, an attempt to measure the thermal noise in the system. The telescope observations also included ‘flat’ spectra, observations of uniformly illuminated sheet on the inside of the dome. This was later used to characterize pixel sensitivity and provide corrected spectra.

Data Reduction and Methods

The first line of defense against noisy data was to subtract dark counts, the false positive counts that come from thermal noise in the equipment. This wasn’t a significant feature in the lab spectrometer, both because it was relatively easy to shield the source from external contamination and because the sources were so bright that the thermal noise was insignificant in comparison. However in the telescope spectra, subtracting the darks improved the signal to noise ratio of the source.

The next step was to average several spectra together. Every spectrum exhibited wobbles in between both neighboring pixels and subsequent observations (see Figure~\ref{fig:pixels}). In the case of the lab spectrometer, the matter was simply to average together multiple scans taken in sequence. Though this had the effect of introducing more read noise (noise inherent to the process of reading data) where a single long scan would have much less, it was outweighed by the benefit of removing strange fluctuation within a pixel and resulting in a smooth curve.

The telescope spectrometer was a different matter. Where the lab spectrometer had 100$\mu$s scans, much longer integration times were required to see the celestial sources – anywhere from 30 seconds to two minutes. This being the case, it wasn’t reasonable to take multiple successive scans on the same source, especially with the additional problem fluctuations in the atmosphere. However, the telescope spectrometer’s spatial dimension alleviated the problem by allowing averages through space. This was less ideal than the time averages, since the signal would obviously grow fainter as one moved off source, but it produced a smoother curve, with fewer anomalous hot pixel spikes.

Once the spectrum had been improved in these relatively simple ways, the next matter was finding the wavelengths corresponding to the measured intensity. This was done for both spectrometers by taking a spectrum of known emission lines, and using these pixel to wavelength correlations to produce a polynomial fit (details explained in Section~\ref{sec:calc}). This fit was applied to other spectra to generate signal vs wavelength plots.

Analysis of the lab spectrometer went farther - the read noise and gain of the spectrometer were calculated by making a linear fit of a plot of mean value vs variance per pixel (see Figure~\ref{fig:gain}. The read noise (assumed to be a constant) was used to further reduce data, and gain used to convert the signal from Analogue to Digital Unit (ADU) to a count of electrons. With this information, and knowing the length of the scan, it was possible to produce a plot of source flux vs wavelength.

Calculations and Modelling

The most important step in the analysis of the data was to produce some meaningful wavelengths to correspond to pixel measurement. The naïve approach might be to take the range of the spectrometer and approximate a linear relation between wavelength and pixel based on that, but a better way to be certain was to use a source with emission lines at known wavelengths and fit a polynomial to the plot of wavelength vs pixel.

Neon was used for both spectroscopes (Figure~\ref{fig:labneon} and Figure~\ref{fig:telescopeneon}), and for the lab spectroscope, some of the mercury emission from the overhead lights was used as well (Figure\ref{fig:labneon}). For each of these spectra, the peaks were identified and compared with plots in which the peaks were labeled. Online resources were helpful for this, providing useful spectra of neon \citep{nelines} and a typical fluorescent lamp \citep{hglines}.

With this comparison, a set of pixel-wavelength points was found. Though initially fit with matrices constructed in Python, it became simpler to use the scipy.optimize,leastsq module to perform the least squares fitting. This method provides a fit for data points by modifying the parameters used in a function of the users choice so as to minimize the \chi^2 value, where:

\begin{equation}

\chi^2= {\sum\_{i=1}^{N}{\frac{y\_exp-y\_{fit}}{\sigma^2\_y}}}

\end{equation}

The other parameters are familiar: N is the number of data points, the y\_{i}’s are the measured data, the y\_{fit}’s are the predicted values and \sigma^2\_y is the variance in y.

A linear fit proved to be adequate for the telescope, but a more complicated fit was necessary for the lab spectrometer (Figure~\ref{fig:solution}). The final polynomial solution had the form of Equation~\ref{eqn:wavesolution}, and a comparison of the calculated values and those supplied by the manufacturer can be found in Table~\ref{tab:polytable}.

Discussion

This discussion shall be in two parts: the first concerned solely with characterizing lab spectrometers, the second with the analysis of acquired spectra.

The former was, in some senses, the simpler of the two components. Clear instructions were given on the methods of characterizing the spectrometer, it was simply a matter of following them. In the case of the wavelength solution, results correlated remarkably well with expectations. A linear fit to the telescope data, though not pictured here, was very appropriate, and was only to be expected. It was easy to assume that the spectrometer used on the campus telescope would be of a higher quality than the one in the lab, and a linear fit makes sense. As the pixel number goes up, so does the wavelength. The lab spectrometer required more work; a polynomial solution was needed. However, this was anticipated by the manufacturers, and the fit values found were all of the same order (Table~\ref{tab:polytable}). The higher order terms are very small, 10\e{-5} and 10\e{-10} times less than the linear term.

It is possible that the telescope wavelength solution might also have more polynomial characteristics, but the only available emission lines for comparison were those of neon, and they were shifted to the redder end of the spectrum. With more emission lines (like those of the overhead lights used for the lab spectrometer), the fit would have been different, and might have been a better description of the pixel to wavelength relationship at low pixel numbers.

In any case, it was a simple matter to apply this wavelength solution to the raw data and take some initial steps towards spectral analysis. After its application, further properties of the spectrometer could be investigated. Saturation level was another concern, as it limited the intensity of the data recorded. Saturation occurred when the CCD well was full of electrons. Since the CCD pixels record by accepting electrons and transforming them into counts, it is bounded by an upper limit called full well capacity: the maximum number of electrons it can accept. The telescope spectrometer simply resets the pixel count to zero when it reaches this maximum, no longer allowing that pixel to accept photoelectrons. However, the lab spectrometer simply stops collecting, and remains at that constant, maximum value.

This value was easy to measure. Slightly more challenging was characterizing the break down in expected CCD behavior as that value is approached. In Figure ~\ref{fig:gain}, the mean and variance per pixel follow the expected linear relation until around 40000 ADU, when the curve suddenly turns over, following an almost quadratic curve back down to lower variances. Consider the trend prior to this point. The mean is increasing, and as it does, variance increases with it linearly. This is the hallmark of Poisson statistics. However, at high enough means, the standard deviation is limited by the saturation level. Pixel ADU fluctuates over the course of the successive scans and may find itself trapped against this ceiling on a few of them. This has the effect of lower the value. If one were to perfectly saturate the detector, so that pixels were all receiving much more than 65536 ADU, one would expect zero variance, since all fluctuations would occur above the saturation level.

At low means, Figure ~\ref{fig:gain} exhibits nonlinear behavior again, but for a different reason. As the mean ADU decreases, it approaches a lower limit in the form of the noise floor \citep{ccd}. This limit is the read noise, and comes from the fact that counts are added to the data by the process of reading them in. Rather than follow its linear behavior all the way to zero, the curve flattens against this lower limit, with the effect of increasing the variance. It was for this reason that two fits were used on the curve: one to measure the linear behavior, the other to find this lower limit. In this case, it presented as a read noise of 34.52 ADU. This is on order with typical read noise values \citep{telescopes}. The linear fit gave the gain as the inverse of the slope, equal to 0.83307. Since the gain is the number of electrons needed to produce 1 ADU, this doesn’t seem to be correct. One would expect an average of one or more electrons needed to produce one count.

It is highly likely that even though a small and relatively steady interval was selected from the set of exposure used to make this plot, some overall trend produced distortions in the data. The fit also might have been improved by having more points in the region of means less than 40000 ADU. However, five separate trials and various selections from each failed to remove this effect. The detector sensitivity simply allows for high value of fluctuation.

The read noise was subtracted from the lab data to remove the noise floor, and the gain (electrons per ADU) was used to convert from ADU to electrons. From there, it was a matter of assuming that each electron at a particular wavelength $\lambda$ represented a photon with energy $E=frac{hc}{\lambda}$ to find the total energy at each wavelength. This value was converted to power by dividing by the exposure time, to create plots like Figure ~\ref{fig:labspec}.

The data from the telescope was also processed according to the method outlined in Section~\ref{sec:calc}, changing a two dimensional spectrum like Figure~\ref{fig:vega} to a more comprehensible spectrum like Figure~\ref{fig:processed}. Similar steps were taken with the other stellar sources to produce Figure~\ref{fig:bin}.

Applying Wien’s Law to the processed stellar spectra produced strange results (see Table~\ref{tab:sources}, not at all matching expecations. It can only be assumed that something went wrong during the processing step, though it is not clear what exactly that was. The only thing that matches well is the sun temperature, which was measured with the lab spectrometer

The precise nature of the problem is not immediately evident, as the processing step was followed exactly, using the same exposure times and a temperature derived from the lamp spectrum itself. If the lamp spectrum were a perfect blackbody, the process would do nothing at all, since it would simply divide and multiply by the blackbody function. It is the lamp’s imperfections that are taken to be characteristic of pixel sensitivity, but they clearly do not characterize appropriately. The Vega spectrum, with both before and after images (Figure~\ref{fig:processed}) provides an example. Here, the processing step has blue-shifted the peak, as would be expected. However, the shift is not as far as anticipated. It is not clear why this should be.

The sun spectrum obviously shows the best correlation because the sun is so bright, and there are no significant effects due to the atmosphere or noise from other celestial sources. The background noise and telluric absorption in the visible band can play havoc with the signals received to the telescope from the other fainter sources. However, that would simply make the spectrum noisier, not shift it to the extremes noted in Table~\ref{tab:sources}.

In addition to determining spectral type, emission and absorption features were investigated. For the sun spectrum, it is easy to see characteristic absorption features: two Ca^+ ion features near 400nm, an Fe absorption line around 450nm, Na around 600nm and an O\_2 feature around 700nm. H$\alpha$ and H$\beta$ lines are also visible.

Hydrogen lines can also be seen in the Vega and Albireo 2 spectra, though in this case far more of them are obvious: H$\beta$ through H$\delta$ as well as the Balmer jump, which presents as a series of dips at low wavelengths. The H$\alpha$ feature appears in Vega and Enif.

The characteristics of these hydrogen lines were investigating quantitatively in the Vega spectrum, and it was found that the location of the lines are redshifted from the expected values by about 7nm \citep{hlines}. This doesn’t necessarily say anything to inaccuracy of the wavelength solution. It may, in fact, be a result of Vega’s movement with respect to the earth (a red shift would imply it is receding).

Vega displays the O\_2 feature as well, and it also appears in the Albireo 2 and Enif spectra.

The Albireo 1 spectrum’s features mostly appear as emission spikes, mostly located around the H$\alpha$, H$\beta$ and H$\gamma$ wavelengths.

Though these absorption features make sense, the temperature characterization does not. Stars are expected to be reasonably good blackbodies. Though the exhibit spiky emission and absorption lines, they have an overall smooth curve, the peak of which occurs at a wavelength that determines the temperature according to Wien’s law. This was not found to be the case, and so further investigation is needed.

Conclusion:

Although the results of this lab were at times unexpected, the theory needed to access them will doubtless prove useful in future astronomical endeavors. The nature of the processing steps used on the telescope spectra bear further investigation, as some step in that procedure produced unexpected results.