Astronomical Spectroscopy at the Cal Poly Observatory

A Senior Project

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Christopher James Almich

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Abstract

Embarking on the first ever astronomical spectroscopy project at the Cal Poly Observatory, I have tested the capabilities of our equipment. Our spectrograph, in conjunction with a telescope and CCD camera, is capable of making fairly precise measurements of absorption and emission lines with sub-nanometer precision. In my research I obtained a spectrum of Jupiter and was able to confidently identify a number of Fraunhofer solar absorption lines.

1. Introduction

Astronomy is a fascinating field of study. To me, the distance scales and sizes of astronomical objects are incredibly humbling and awe inspiring at the same time. The cosmos has grand examples of both harmony and destructive chaos, each beautiful in their own way. Space has an alluring mystique; the dark, emptiness is as beautiful as it is terrifying. The raw power of a supernova or the inescapable gravitational pull of a black hole seem to make trivial human problems seem insignificant.

I have always been intrigued by astronomy. It started most likely when I was young, went to Disneyland, and embarked on the ride Space Mountain for the very first time. I had never been on a roller coaster and was apprehensive to board the ride. However, after zipping around the galactic-themed set, whizzing by a huge black hole (it looked real at the time), I had to be pried off of the seat, begging to go again. Soon after, I had my first telescope.

When I started at Cal Poly, I had no real intentions of pursuing an astronomical education. However, my interest could not be contained and I started doing independent research and added on an astronomy minor.

My research projects included measuring variable star timings, the period of an eclipsing binary, extrasolar planet detection, and astrometric measurements of a visual double star. The latter two projects were significantly more noteworthy. Over the summer in 2010, Josh Thompson and I were the first to detect exoplanets using the Cal Poly Observatory. In the year prior to that, I worked with Dr. Russ Genet at Cuesta College where we taught astrometry to local high school students and went on to publish a paper in the Journal of Double Star Observations. Though not all of my work was done at the Cal Poly Observatory, I was very familiar with the equipment, thus choosing an astronomy-related senior project was obvious.

Having previously done mostly differential photometry projects, comparing a variable light intensity source with one that is constant to observe the change, I was ready for a new challenge. Spectroscopy is fundamentally different from standard imaging astronomy. Having no experience with obtaining or analyzing astronomical spectra, I figured that this would provide the most useful learning experience.

Since I would be the first to attempt this project at Cal Poly, I didn't know what to expect. I went in with predictions of success, but as with any project, much of the learning is obtained through troubleshooting problems. Without knowing the limitations of what we could observe with our spectrograph, I had no specific targets in mind. Rather, my project was to be an exploration of the capabilities of our spectrograph so that students to follow could choose research projects within the scopes of our equipment.

2. Spectroscopy

To better understand the applications of astronomical spectroscopy it is advantageous to have a solid understanding of spectroscopy as a whole. Spectroscopy is the study of spectral light and spectral lines. Tremendous amounts of information can be carefully extracted from subtleties in this spectral data.

Properties of Light

Light is an extremely complex phenomenon but it is modeled quite accurately as a transverse wave, propagating through space at the familiar speed of light, c. The energy of one photon of light (a light *particle*) corresponds to its associated wavelength, where shorter wavelengths correspond to higher energies, as seen in Figure 2.1. The entire range of wavelengths of electromagnetic radiation is known as the electromagnetic spectrum.

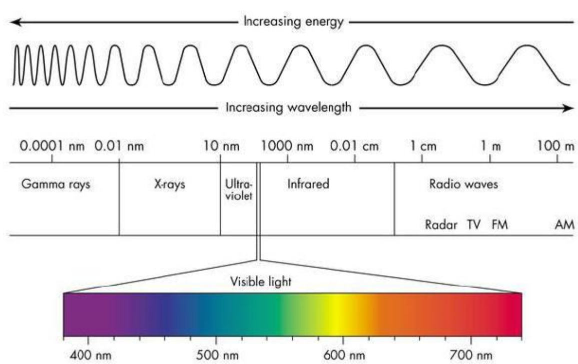

Figure 2.1 The electromagnetic spectrum. Higher energy photons will appear bluer while lower energy photons will be red.

When an object emits light, it does it for a reason. Heat causes an object to radiate thermal energy in the form of photons (humans, for example, emit infrared light). This type of radiation is known as black body radiation, which all dense objects that exist above absolute zero undergo. The energy of the photons emitted by a black body is dependent on the temperature of the object.

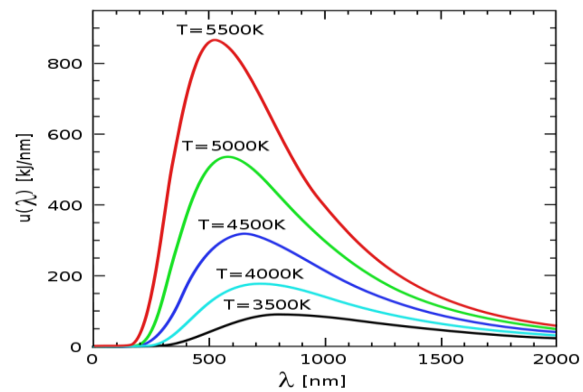

Figure 2.2 Here, several black body emission curves are plotted as a function of the wavelength of light. Hotter objects have shorter peak wavelengths. For comparison, the temperature of the sun is roughly 5,800K, making the peak wavelength that it emits in the visible range.

In astronomy, stars are approximated as black bodies, so understanding black body radiation will be crucial to our success; however, there are additional processes of producing photons. At the atomic level, electron energy transitions, governed by the quantum mechanical selection rules, either absorb or emit a photon that corresponds to the energy of the transition. These transition energies are well known for different atoms and molecules, and provide us with an atomic fingerprint to look for when we observe unknown sources.

Emission Spectra

Figure 2.3 This is an emission spectrum of hydrogen. Each line corresponds to a specific electron energy transition.

Figure 2.3 shows an emission spectrum of hydrogen gas. As you can see, the distinct lines are easily identifiable. Quantum mechanically the lines correspond to the difference in energy

from an excited state of the wave function to a lower state. Furthermore, the energy transition is unique to each atom and molecule. As the atoms or molecules become more complex, more and more transitions become possible, thus we get more lines. Figure 2.4 shows spectra of some other common atoms.

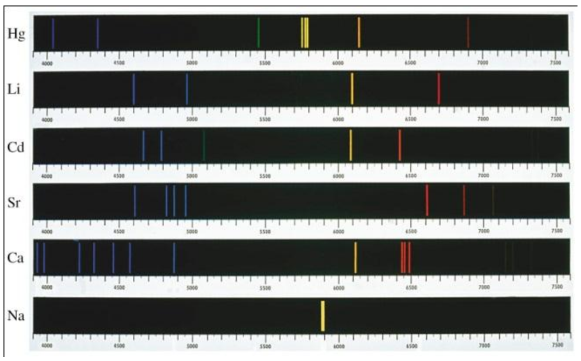

Figure 2.4 Each atom has a distinct spectrum, making them "easily" identifiable.

Absorption Spectra

An absorption spectrum works on the same principle as an emission spectrum, but in reverse. Instead of looking at lines where an atom was excited and lowered its energy level, we observe where atoms in low states absorb photons and promote electrons. To do this, we need to observe a continuum and place a sample between us and the source.

Figure 2.5 This is an example of an absorption spectrum; where distinct spectral lines have been absorbed from a continuum.

In astronomy, since we treat stars as black bodies, we mainly deal with absorption spectra. By looking at a star and seeing what lines are *not* there, we can infer the composition of the star's atmosphere, a gas cloud between us and the star, or even the composition of the Earth's atmosphere. We will be using emission spectra to calibrate our spectrograph in the lab setting which will provide us with a relative way of measuring the other lines that we observe.

Doppler Shift

When an object is moving at high velocity, the light it emits changes wavelength. The wave is compressed in the direction of travel and elongated in the opposite direction. This elongation lengthens the wavelength, thus making it appear redder as it moves away from you. Since spectral lines of atoms are so well known, we can make very accurate measurements of small changes in wavelength, therefore allowing us to calculate the radial velocity of the object in question.

Measuring the redshift of astronomical objects has helped modern astronomy solve many problems. By measuring Doppler shifts of galaxies and noticing, strangely, that they all move away from us, we were able to infer that the universe is expanding. By measuring the slight wobble of a nearby star in our own galaxy we were able to find planets in a solar system other than our own. Quasars were found to have massive redshifts which implied that they were very far away and most likely galaxies in the process of formation, emitting tremendous amounts of energy from the supermassive black hole core.

Astronomical spectroscopy is a much broader field than *just* the study of atmospheres and gas clouds. Planets, galaxies, nebulae, asteroids, and quasars are just a handful of interesting objects that have information waiting to be unlocked with spectroscopy.

3. My Project

Undertaking this project, I would be a pioneer in astronomical spectroscopy at the Cal Poly Observatory. The spectrograph was unused and not yet calibrated, thus the scope of my project was hard to gauge at first. I intended to push the spectrograph to its absolute limit; however, a multitude of technical problems surfaced. As each new issue arose, it was clear that in such a short time we could not reasonably expect to push the spectrograph to

its limit. Rather, it would be more useful if I tackled each issue individually to lay the groundwork for future research.

Equipment

Grating spectrographs are comprised of a rather small amount of optics. Light passes through an entrance slit and then is diverted towards a collimating mirror. This mirror redirects the light onto the diffraction grating which spreads the light into a spectrum. This light then hits a focusing mirror, and is finally sent out to the detector. By rotating the diffraction grating you can effectively scan through the dispersed spectrum. The amount of the spreading of the light is determined by the groove spacing on the diffraction grating, and the range of wavelengths that are dispersed is called the spectral range. (Pedrotti[3] 1987)

The spectrograph at the Cal Poly Observatory is a Santa Barbara Instrument Group (SBIG) Self Guided Spectrograph. It has a wavelength range from 3800 to 7500 Angstroms. The two diffraction gratings with which it comes equipped offer a spectral coverage of 750 Angstroms in high resolution mode, or 3200 Angstroms in low resolution mode, and has a resolution of 2.2 Angstroms Full Width at Half Maximum (FWHM) and 8 Angstroms FWHM in the respective modes. Uses for a spectrograph of this caliber are: stellar classification, analysis of nebular lines, identification of spectroscopic binaries, measurement of stellar proper motions, measurement of emission nebula proper motions, measurement of bright quasars, measurement of galactic redshift, and of course, for analyzing spectra of laboratory sources. Physically, the spectrograph is contained in a 4 x 5 x 8 inch box, weighing just over 5 pounds.

The SGS is coupled to our CCD camera, a SBIG ST-10XE. The function of the CCD is to convert photons of light into electrons via the photoelectric effect, which are read out and exported to the computer, producing tangible data. Although the operations of CCDs are extremely complex and interesting, for the scope of this project it can be thought of as a digital camera, with the exception that the CCD does not distinguish between different colors of light. The CCD does not need the spectrograph to operate and can be used for direct imaging for a variety of other projects including differential photometry. On the other hand, the SGS is merely a box of optics and is useless without the CCD to record the spectra at the back end.

Our CCD actually has two chips. The main chip is used for imaging, but there is also a much smaller chip located above the main chip which is used for autoguiding. Autoguiding is a method used to ensure that your target doesn't move around in the chip; such motion is caused by imperfect telescope tracking. It does this by quickly reading out the smaller chip, where you have positioned a "tracking" star (often a chore in and of itself), and it verifies that the star remains on the same pixels. If there is any motion, it makes a small adjustment to the telescope pointing.

The autoguiding chip plays a different role when the spectrograph is installed. It images our target while the actual spectrum is recorded on the main CCD. The advantage of this is that the main CCD is much bigger, so we can see a broad range of wavelengths; however, the drawback is that finding our target and positioning it on the slit is now done on the much smaller autoguider chip. This causes severe headaches when looking for an object when the telescope is out of focus!

When in high resolution mode, the dispersed spectrum is spread out so much that only a small portion of it actually fits on the main CCD chip. To scan through the spectrum you adjust the micrometer on the spectrograph which rotates the diffraction grating.

Optics

It is useful to understand exactly how the light makes its way through the spectrograph, especially if you need to make calibration adjustments.

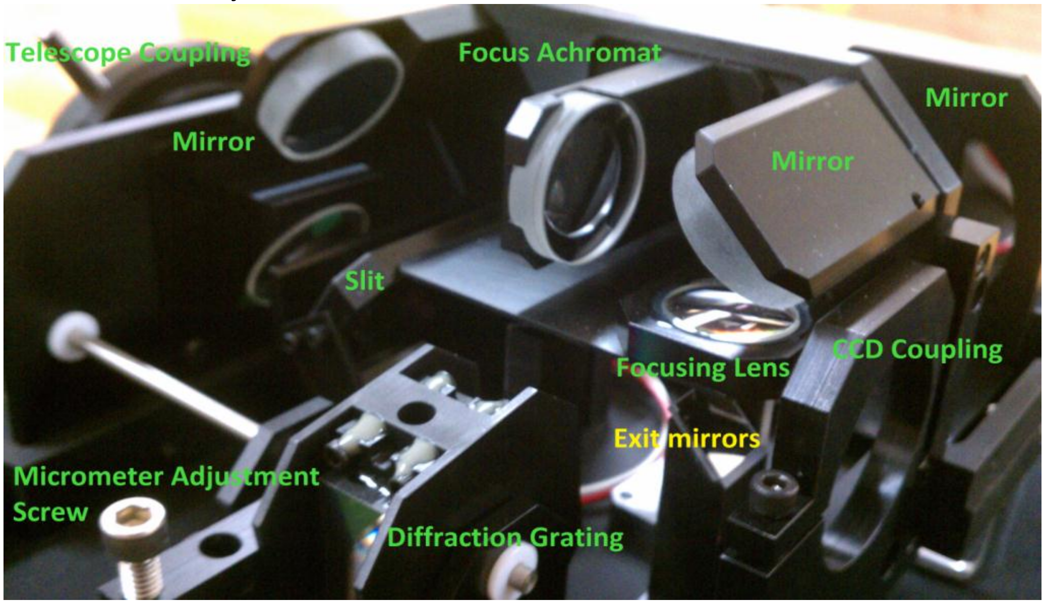

Figure 3.1 From this angle, all of the important optics are shown and labeled.

In figure 3.1 above, most of the main optics can be seen, but a few things are hidden from view. Underneath the focus achromat there is a mirror that directs light that makes it through the slit to the large mirror in the back.

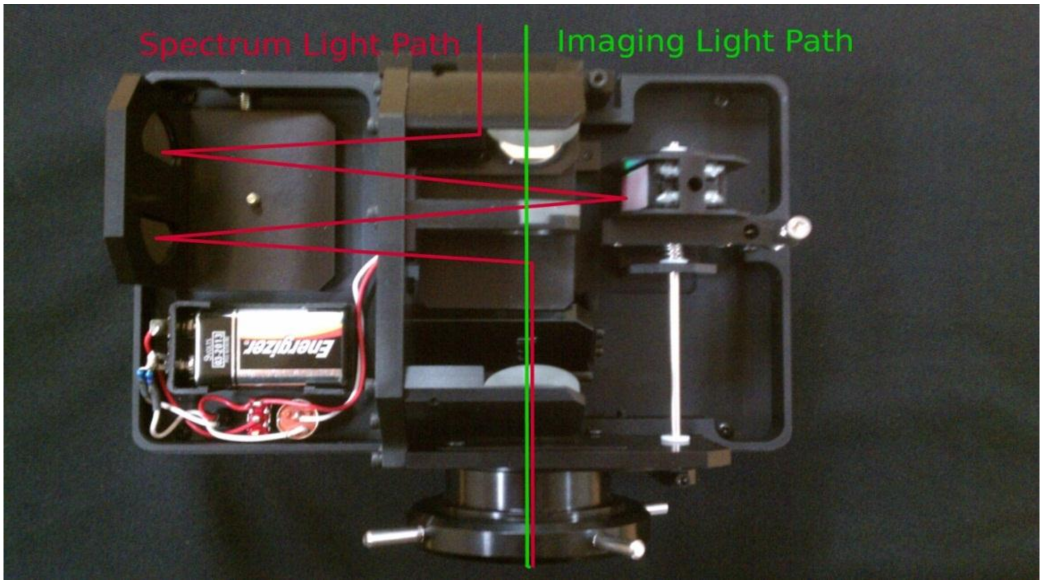

Figure 3.2 A view from the top with the two separate light paths labeled. They are displaced upon entrance for clarity. This view shows the intricacies of the spectrum light path; however most of the optics that it involves are blocked from view. The 9V battery is wired to a small LED that you can turn on to light up the slit. This is useful for verifying that your target object is indeed on the slit.

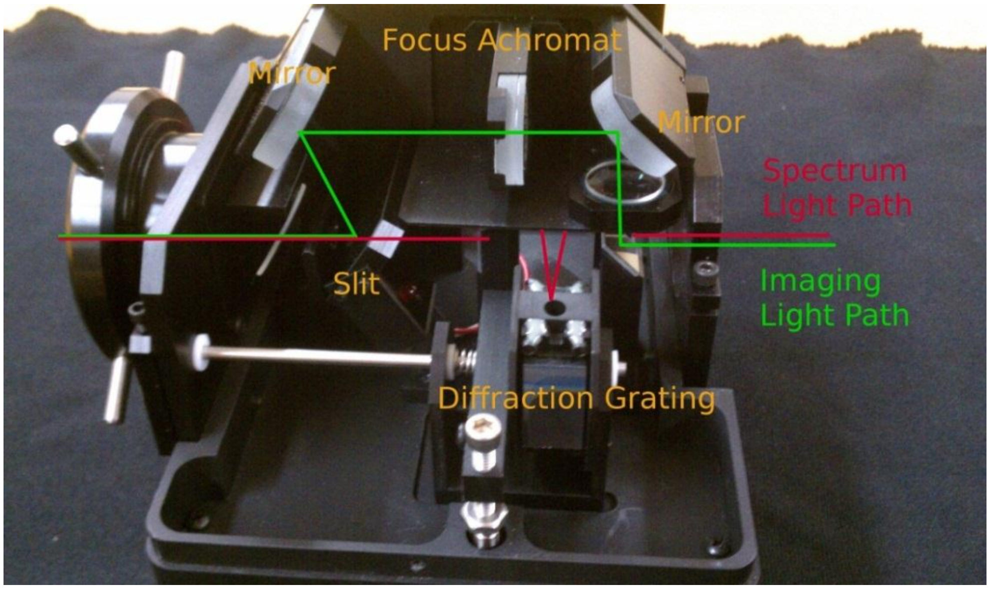

Figure 3.3 This view from the side shows exactly how you get your imaging light. The key thing to note here is that the slit itself is cut out of a reflective surface that acts as a mirror. Thus, all light that doesn't make it through the slit is reflected upward and through the achromat and other focusing optics.

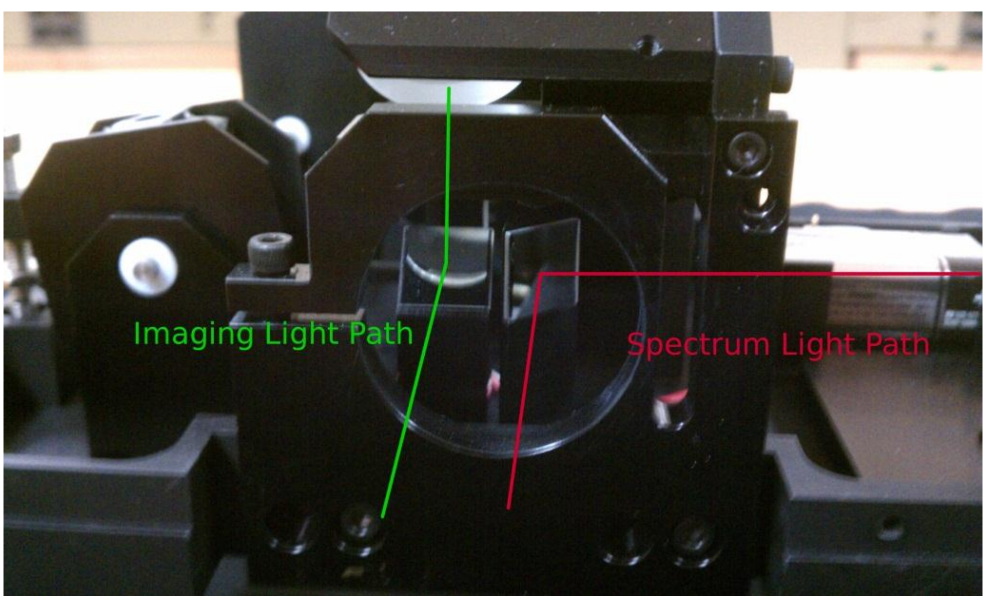

Figure 3.4 This last angle shows the two exit mirrors in action. The two light paths will hit the two independent CCD chips inside our CCD camera.

The figures above clearly show the two independent light paths. In words, the light is collected in the telescope and it moves into the spectrograph via the telescope coupling. This light is focused onto the slit where most of it is reflected upwards (this is now the imaging light) and the rest makes it through the slit (spectrum light). The imaging light simply reflects off of a mirror which sends it through the achromat followed by being focused and reflected into the CCD. The spectrum light is initially diverted to the far mirror where it is focused onto the diffraction grating. This light disperses and hits the opposite end of the far mirror from which it came, focusing it again (but now it's a spectrum) and diverting it through the CCD coupling and onto the main CCD chip, parallel to the imaging light. This spectrograph is elegant and simple, and the optical setup is relatively straightforward. All of the components are adjustable using a hex wrench, making the manipulation of the optics feel much like working on a small scale optics bench.

Calibration

The calibration procedure was slightly crude and tremendously tedious. The first step is to adjust the slit focus which is accomplished by adjusting the focus achromat, which is merely a basic focusing lens that aims to deal with and correct spherical and chromatic aberration. The adjustments needed were only possible by merely loosening the bolts on the focus achromat, giving it a slight wiggle, and retightening. This slight change was usually too extreme, thus, this step is accomplished, more or less, by trial and error. Once the slit has a tight focus, the next step is to center it. Again, this step is accomplished via a minute change in the position of the second fold mirror.

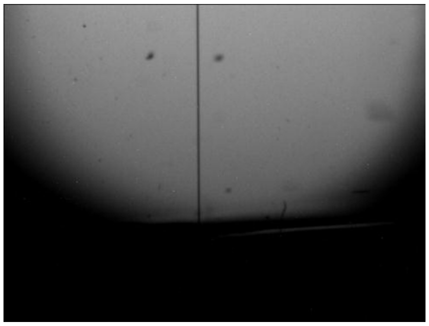

Figure 3.5 This is the image of the focused slit on the autoguider chip.

After the slit is focused and centered, you repeat the procedure for the spectral lines – adjusting different optics, of course, but in the same way as before. The spectral lines are obtained by looking at an emission lamp on the table in the observatory with the spectrograph. To calibrate the micrometer, I used a mercury emission tube with well-known wavelengths, and positioned the 5461 Angstrom line in the center while the micrometer was set to roughly 5.45 mm. This way you can easily set the micrometer to the wavelength you want to see with a simple mental conversion.

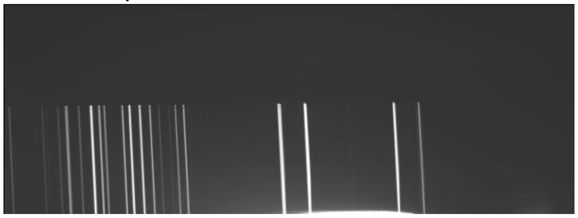

Figure 3.6 Here is an example of a mercury spectrum. By finding some of the easily identifiable spectral lines, you can determine the wavelength of light as a function of the pixel position on the CCD.

Calibration Errors and Other Difficulties

When I first calibrated the spectrograph, I followed the instructions so carefully that I overlooked a problem that, at first, I didn't know was a problem. Although I had the slit carefully focused and centered *horizontally* on the CCD, the light was not entirely illuminating

the autoguiding CCD. There was no mention of this in the user manual, nor was there an example image, so I worked for some time on the assumption that the spectrograph was calibrated when it really was not. The spectra that I obtained were not influenced by this misalignment; however, positioning targets onto the slit was nearly impossible since the already small autoguiding CCD was limited to half of its capability.

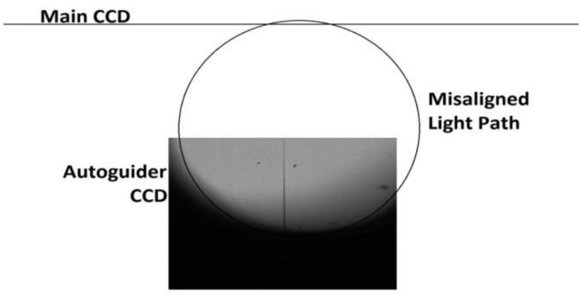

Figure 3.7 This figure shows the nature of the misalignment. Less than half of the imaging light is actually making it to the proper CCD.

In my troubleshooting attempts, I tried to determine if my troubles with placing an object on the slit were due to telescope pointing errors. To test this I had to take the spectrograph off of the telescope and look through a standard eyepiece. I would then visually center the star as best as I could and put the spectrograph back on. This way, if I put the spectrograph back on gently (so as to not disturb the telescope pointing), and fast enough (so that the telescope tracking imperfections wouldn't be significant), the star should still be roughly in the center of the frame. However, the difference in the focusing lengths of the eyepiece and spectrograph was so large, I was unable to conclude whether I was not pointing at the star, or if the star was so out of focus that the light was spread out too much to be distinguishable as a star. After dozens of trials using this method, I was confident that the telescope pointing or focus was not the issue, and that the problem must have been improper calibration.

The number one obstacle and hindrance of progress, however, was not human error or spectrograph misalignment; it was the fog. San Luis Obispo is notoriously foggy at night during the summer, even on the clearest of *days*. Like clockwork, a thick fog layer would roll in on a nightly basis at around 10:00 PM, and would linger for hours, if not the whole night. Like salt in the wounds, most of my observing nights were scrapped due to weather. This, unfortunately, is the reality of doing astronomy at the Cal Poly Observatory in the spring and summer months. In previous years when working on exoplanet detection, I encountered this problem and hoped I would have better luck, but, alas, nobody can control the weather.

Refined Project Goals

It was clear within a few months of working on this project that measuring galactic redshift was probably not going to happen. A more useful approach to this project was to use it as groundwork for future astronomy at Cal Poly. Students in future years may wish to do any number of projects involving astronomical spectroscopy, and they would likely encounter all the same problems I did. Thus, by taking careful methodical steps towards perfecting the techniques of spectrograph usage, it is my hope that this project can be used by future students to springboard their research – clearing up all of the ambiguities and unknowns that I was faced with. So, instead of galactic redshift, I set my sights on identifying absorption lines in planets and stars. Vega and Jupiter, outshone by few in the night sky, were my new targets.

4. Theoretical Data Reduction and Analysis

Once the telescope time has been put in and you have tangible data, the next step is to reduce and analyze it. This is quite an intensive process, and thankfully, there is computer software to help you crank through this procedure. One such piece of software is known as IRAF (Image Reduction and Analysis Facility).

IRAF is a fickle beast (after a while you **will** develop a love-hate relationship with IRAF), but it is enormously powerful, and can handle massive amounts of data reductions in a few short steps. However, before we jump into the specifics of reducing and analyzing spectral data, it is useful to understand data reductions as they apply to astronomical data in general.

Data Reduction

With any data that you collect using a telescope and CCD, there are inherent sources of noise that you will want to get rid of. For example, dust on the telescope lens or mirror, or thermal activity inside of the CCD that registers counts. These bits of noise can be dealt with by taking careful calibration images that are specifically designed to do just this. The three standard calibration images for data reduction are flat field, dark, and bias frames.

Darks and biases deal with the thermal noise of the CCD. While the CCD is on, the electronics inside will produce some noise on the chip – setting off pixels that were not hit by photons that came from your target. Darks are exposures that have the aperture closed, allowing no light in, and are taken for the same length of time as the object observation images. This accounts for the bulk of the thermal noise that you get while taking any image. Bias images are similar, except they have no exposure time at all. This effectively gets rid of the offset (or bias) that you get with any image.

The final calibration image is a flat field. Flat fields are designed to account for the telescope and optical path imperfections. A flat field is obtained by taking an image of something that is evenly illuminated; in most cases it is merely a picture of the sky after sunset and before it gets completely dark. Without any optical path issues this image should look evenly illuminated. Instead, what you see is a relatively evenly lit background with dark areas – usually donut shaped rings that correspond to dust or dirt on some of the primary optics. Since the dust will remain in place throughout the night, the dim spots they produce shouldn't move and the whole flat field can be subtracted out of the image. The goal of these calibration procedures is to eliminate any pixel counts that are not directly caused by photons from your target hitting the CCD. After removing the darks, biases, and flats the background counts should be close to zero.

For spectroscopic observations, darks and biases remain the same; however, flat fielding requires an entirely different technique. Since you are no longer imaging the object, the flat field looks instead for wavelength dependent variations on brightness. Because of this, the twilight sky is no longer an adequate source, and you are forced to take an image of an evenly illuminated object that emits a wide range of wavelengths. This is accomplished by placing a large evenly illuminated screen inside of the dome. The color temperature of the flat field lamp can be adjusted to match the temperatures of the stars you are observing. Dome flats are advantageous since they can be taken at any time during the day or night.

Spectral Analysis

To more easily discuss the procedures of spectral data analysis, I will be using sample data that comes pre-loaded in IRAF[1]. These data are comprised of the spectrum of a single star on the slit as well as a flat field and emission lamp spectrum for comparison.

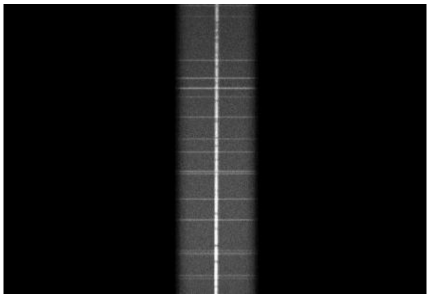

Figure 4.1 This is an example of an ordinary stellar spectrum, preloaded into iraf, with a vertical dispersion axis.

[1] A tutorial of how to run the doslit package with this preloaded data can be found at http://iraf.noao.edu/tutorials/doslit/doslit.html

Flat Field

Darks and biases are subtracted from the spectrum just as they would be for any CCD image; however, the flat field is not simply divided out like normal. IRAF uses an algorithm to model the shape of the flat field and then normalize it.

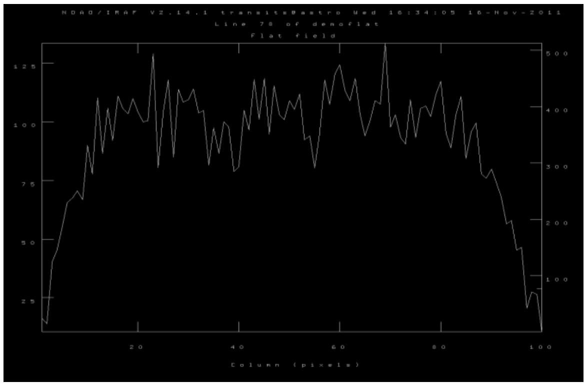

Figure 4.2 This is a counts versus column plot of our flat field shown at a particular row of our CCD array (a cut along the length of the slit, perpendicular to the dispersion axis). Counts on the ends of the aperture are diminished. We will deal with this by cropping these sections out of our image.

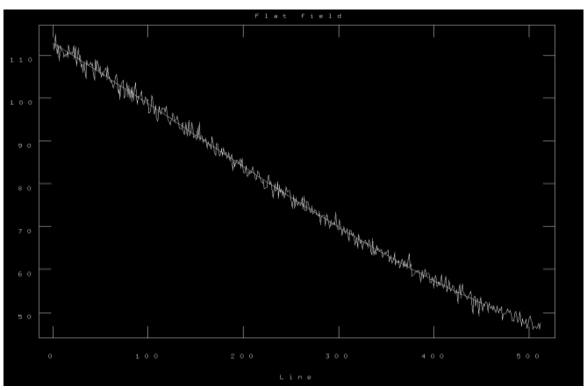

Figure 4.3 Here is the overall shape of our flat field with the fitted function overlaid.

Apertures

The first step is to have IRAF recognize the spectrum. Since the spectrum has some finite width, IRAF again takes cuts along the rows (or columns if your spectrum is horizontal) and finds the peak. Often times the dispersion axis is tilted with respect to the CCD array, howver, IRAF calculates the tilt and defines the dispersion axis. After taking several lines and averaging them, IRAF defines an aperture and background regions.

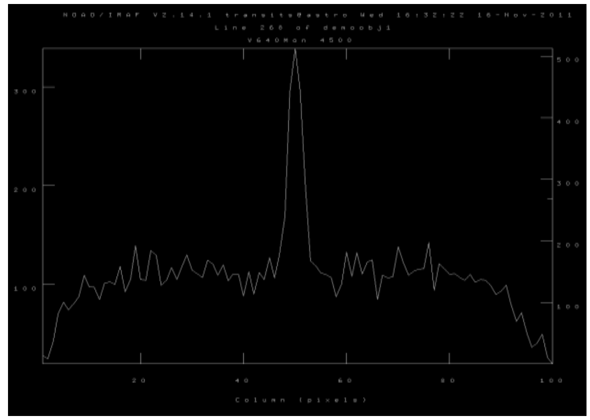

Figure 4.4 This is a plot of one of the horizontal cuts. The left vertical axis represents photon counts and the horizontal axis is the pixel column. The right vertical axis indicates which row this is a cut of.

IRAF's algorithm for detecting the aperture works fairly well; however with more complicated spectra, some user interaction is required to visually verify its accuracy. This process is repeated, of course, for each image.

Wavelength Dispersion Calibration

Extracting the spectrum is obviously a very important step in our analysis procedure, but it would be in vain if you had no spectra to compare it to. For example, if you are trying to detect Doppler shift, every wavelength is shifted equally, thus there is no way to detect any change with only one image. One requires a spectrum with identifiable and well-known wavelengths to establish a wavelength scale – a function to relate pixel position to wavelength. This comparison spectrum is obtained using an emission lamp.

After feeding IRAF your emission spectrum it will again take a cut along the dispersion axis. Since you know the element which produced the lines, it is your task to identify two or more of the lines by hand. This can be done rather easily with well-known spectra. Once a few lines have been identified by the user, IRAF finds and labels the remainder of the lines as well as giving us our wavelength scale.

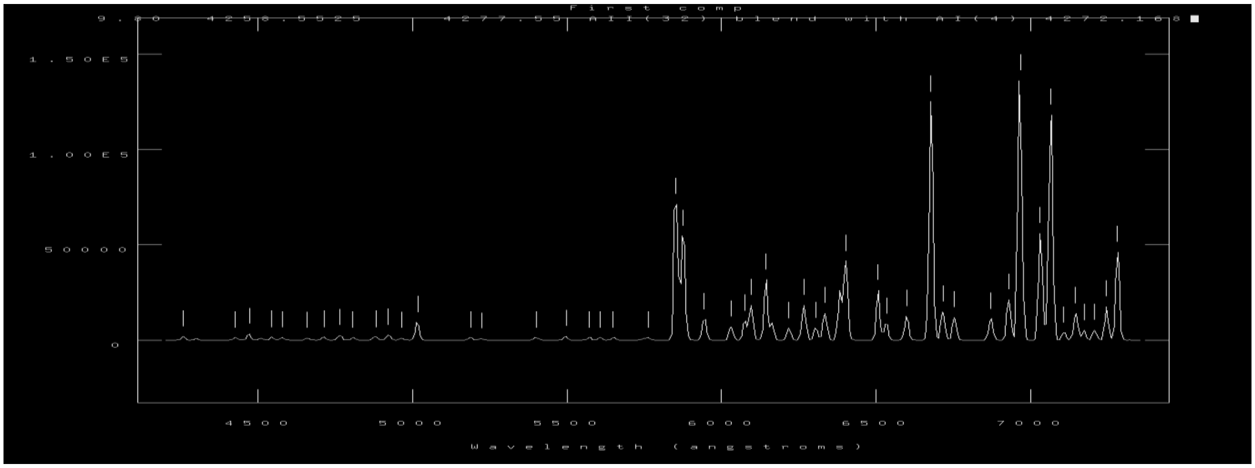

Figure 4.5 This is a typical emission lamp spectrum. The vertical lines above the centroid of the peaks represent the emission lines that IRAF has recognized.

Spectral Extraction

Now that the aperture is defined and we have our wavelength-calibrated scale we can go ahead and extract the spectra. However, at this point, there will still be a blackbody shape. If you are only interested in equivalent widths or other relative measurements, you can fit a function to the continuum and divide it out. This effectively flattens your absorption spectra into a line with a series of dips corresponding to the absorption lines. By doing this, however, you lose information regarding the absolute flux of the object.

Flux calibration compares your object to a known standard star so that your final spectrum can have units of flux. There are many ways to flux calibrate; one for a simple case is to generate a blackbody spectrum at an appropriate temperature and scale it to fit your data. Taking the data from the standard star and dividing it by the generated blackbody spectrum yields a sensitivity function which is the value of the flux at any particular wavelength needed to produce one count per second.

This has an inherent problem in that your comparison star is not a perfect blackbody and has some absorption lines, which should stand out on the sensitivity plot. Flux calibration is a difficult process, and it requires very carefully taken data as the position of the different stars on the slit must be similar. Although it unlocks more information, it is not always necessary depending on what exactly you are looking for. For many projects, it can be ignored.

5. Obtainment and Analysis of a Spectrum of Jupiter

Even though the spectrograph calibration was not perfect, I was still able to obtain and analyze a spectrum of Jupiter. To better prepare future observers, in this section I will highlight the nuances specific to Cal Poly Observatory as well as discussing my data.

Observing with the Spectrograph

Finding objects with the spectrograph is reasonably difficult if you are transitioning from eyepiece or normal CCD observing since the focus will be terrible at first. If this is the case, I found that it is easiest to point the telescope at a very bright star, using the finder scope mounted on the side for rough alignment. Once the pointing is close, an autoguider image should be illuminated. Often times, it is not, and very small adjustments can be made on the fly with the telescope hand controller slew set to “center”. Once there is light on the autoguider, set a series of quick exposures and

begin to adjust the primary mirror focus until your star is a manageable size. The fine focus adjustments can be made with the normal focuser.
Once the star is focused, you must place it on the slit to get a spectrum. Again, I found this easiest to do by using the hand controller for the telescope and making very small adjustments. The star will remain on the lower half of the chip and minor adjustments may need to be made between images.

Raw Data

After placing Jupiter on the slit, I took several images with the spectrograph set to high resolution mode. I had, however, set the diffraction grating micrometer such that I could easily find mercury emission lines that I was going to use for wavelength dispersion calibration by checking the emission lamp spectrum first. This meant that I would see a smaller spectral range from Jupiter; however, my ultimate goal was to see if I could accurately identify *any* solar absorption lines so a very broad spectrum wasn't required. Moreover, I wanted to see just how good our resolution was.
After subtracting out biases and darks (I did not take flats because, at the time, all we had for dome flats was a poster board and an incandescent light, and I was afraid they would do more harm than good in terms of data reduction) I proceeded to extract and analyze the spectra with IRAF. I gave an overview of this procedure in section 4 but the reality is that the majority of the work goes into setting up your data so that IRAF recognizes what to do with it.

Running the doslit task in IRAF

The data analysis procedure is almost completely handled by a single IRAF task called doslit. This task uses many subroutines to achieve its goal, however many of these remain fairly hidden to the user. Indeed, you could use more specific IRAF functions to complete each step of doslit individually; however it wouldn't save you any time or hassle.

Doslit will take an object spectrum and compare it to your arc lamp to give you the wavelength calibrated spectrum which you can then continuum normalize. For this to work, you must manually edit your file headers to define which images are object spectra and which are calibration spectra. Furthermore, IRAF expects four additional parameters in the header file that are not there by default: gain, rdnoise, jd, ljd. Gain and rdnoise (read noise) should be known values that you can enter in. Jd (Julian date) and ljd are used for sorting. If you are not interested in sorting by date, for example, when you have a small data set, you can enter any numerical value for jd, however be sure to use the same value for both the object and arc lamp. Once these parameters have been added to the header file, IRAF should be able to recognize your data.
The first steps, again, are to interactively find the aperture (usually IRAF finds it fairly well by itself) and to identify the arc lamp lines.

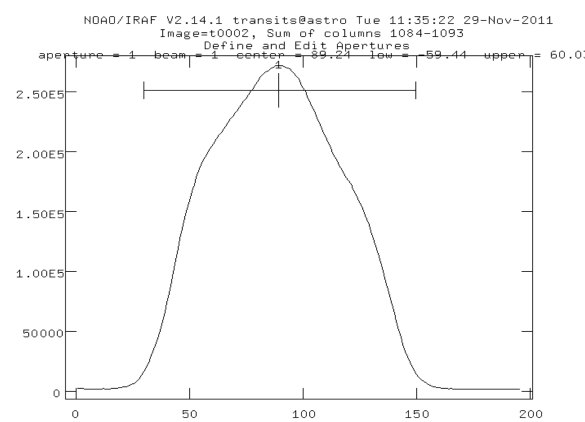

Figure 5.1 IRAF correctly identifies the aperture. The width is much larger, as you would expect, due to the size of Jupiter.

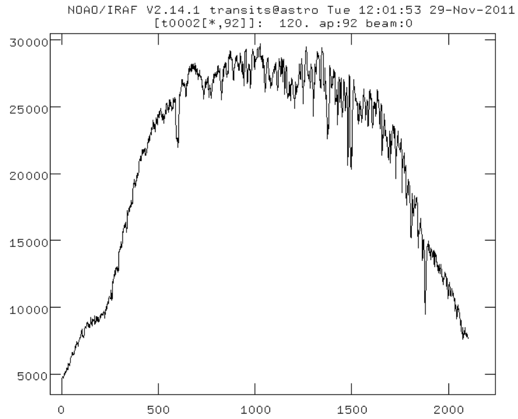

Figure 5.2 This is a plot of the raw extracted spectrum. There is a lot of noise throughout the spectrum, however, many deep prominent absorption lines are clearly seen.

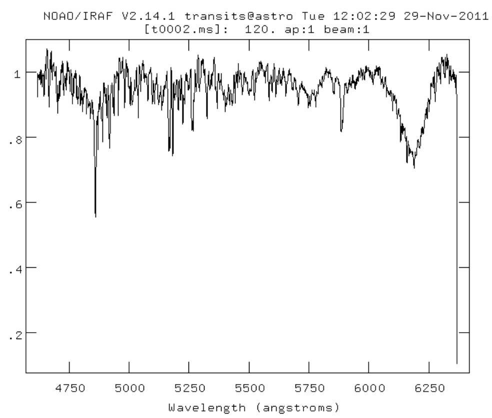

Figure 5.3 Shown here is the spectrum from figure 5.2 which has been continuum normalized and wavelength calibrated.

IRAF will then use splot, an interactive plotting task that allows you to find centroid and equivalent widths of absorption lines. Splot is also able to fit a function to the data, which you can use to continuum normalize. The default fit is a low order spline that does not resemble a continuum very well, and parameters (such as function order and the high/low data rejection values) within splot need to be modified to produce a reasonable fit to the continuum.

Identifying Spectral Lines

After fitting the continuum and dividing it out of my spectrum, I began to locate the prominent lines using splot. Specifically I was looking for Fraunhofer lines, which are a set of solar absorption lines produced by the gasses in the outer regions of the Sun's atmosphere (Jenkins, 1981). These lines are very well known and guaranteed to be in the spectrum, so they were the obvious reference to verify the accuracy of the spectrograph.

Observed Line (Å)	Fraunhofer Line (Å)	Element	Δλ (Å)
4858	4861	H_β	3
5166	5167	Mg	1
5180	5183	Mg	3
5264	5270	Fe	6
5886	5889	Na	3
5891	5895	Na	4

Figure 5.4 A table comparing the observed wavelengths of solar absorption lines found in a Jupiter spectrum to the known Fraunhofer Lines we expect to see.

Figure 5.4 shows that using our current spectrograph setup we can observe known spectral lines with sub-nanometer accuracy. The discrepancies between the observed and expected lines most likely are accounted for by imperfect wavelength calibration, rather than natural phenomenon such as Doppler shift. The Doppler shift we expect from Jupiter in the most extreme case due to its rotational velocity is found using the equation

$$\Delta\lambda = \lambda_0(^v/_c) \tag{1}$$

where λ_0 is the expected wavelength and $\Delta\lambda$ is the wavelength shift. The maximum Doppler shift produced by this rotation is roughly 0.2Å.

Galaxies, on the other hand, move relative to us at much higher velocities. For example, Andromeda moves towards us at around 100 km/s and NGC4151 moves away from us at roughly 1000 km/s. The latter would yield an expected Doppler shift of about 1.6 nm, which is well within the limits of our spectrograph.

6. Conclusions

In my research, I found that the capabilities of the spectrograph as listed by the manufacturer are accurate. Galactic redshift measurements are attainable with our spectrograph; however the functionality is greatly diminished due to the difficulty in attaining the data. The good news is that the inherent miscalibration can be remedied by making adjustments to mirror positioning. I made several attempts at this; however, due to the delicacy of working near the diffraction grating, which is dangerously close to the exit mirrors in question, I recommend contacting the manufacturer for further assistance.

The spectrograph itself has the capability to be a very accurate tool for the Cal Poly Observatory; however, our results could be greatly improved with the addition of supplemental equipment. A proper dome flat setup is going to be required for any precision data to be taken. Also, the installation of a simple flip mirror will make the location of objects significantly easier. Once improvements pertaining to data acquisition and reduction have been made, students may wish to try more complex projects, such as determining the absolute fluxes of stars via flux calibration.

Detection of the Fraunhofer lines in the Jupiter spectrum was a very rewarding experience. Since, at the outset of the project, I had no idea what our observatory was capable of, I was happy to get tangible, accurate results.

7. References

Birney, D.S., Gonzales, G., Oesper, D., 2006, in *Observational Astronomy*, p. 215

Grevesse, N, Sauval, A.J., 1998, Space Science Reviews, v. 85 Issue ½, p.161-174

Jenkins, F. A., White, H. E., 1981, in *Fundamentals of Optics* (4th ed.). McGraw-Hill. p. 18.

Pedrotti, F.L., Pedrotti, L.S., Pedrotti, L.M., 1987, in *Optics* (3rd Edition), p. 292