Improving and Characterizing a High Resolution Spectrograph For Use in Measuring the Zeeman Effect in Mercury Gas Emission Lines

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Abstract

We have built and calibrated a high resolution spectrograph capable of resolving $0.024259 \pm 3.24x10^{-6}$ Angstroms per pixel. With several improvements to the instrument as well as extensive focusing, we have greatly increased the resolution of the spectrograph to $0.008782 \pm 3.24x10^{-6}$ Angstroms per pixel. The spectrograph displays a slight asymmetry in the emission lines, yet through careful data analysis we have determined several possible sources for line asymmetry. We have also made attempts to correct this asymmetry and make suggestions for further improvement. We further propose that the spectrograph is capable of resolving the Zeeman line splitting effect caused by a magnetic field introduced to the emission source if the field is greater than or equal to 631 gauss.

1 Introduction

1.1 Spectroscopy

A spectrograph is an instrument used for facilitating the chromatic decomposition of light, meaning that it collects light and splits that light into its individual wavelength components. In a typical grating spectrograph, light is focused onto a very thin slit. The light is then directed into a parallel beam by a device called a collimator. The parallel light beam hits a reflection grating which is a flat mirror with grooves etched into it. Typically, there are several hundred to several thousand grooves per millimeter on a grating. Since light diffracts at different angles based on the wavelength of the light, we see a different wavelength of light based on our position relative to the grating. This effect is seen in rainbows. A telescope is strategically positioned to receive light from the grating. The spectral lines are imaged via a sensitive CCD camera which is attached to the eyepiece of the telescope.

1.2 Spectrograph Components and Specifications

We have built a high resolution spectrograph on an optics table. The spectrograph consists of a 37 millimeter lens, a 10 micron slit, two 90 millimeter aperture (focal length 1250 millimeters) Meade ETX 90 Maksutov-Cassegrain telescopes (one which performs as a collimator), and a reflection grating with 1800 groves per millimeter. An SBIG ST-8E CCD camera is used to take images of spectral lines.See Figure 1 for a diagram of the basic spectrograph setup.

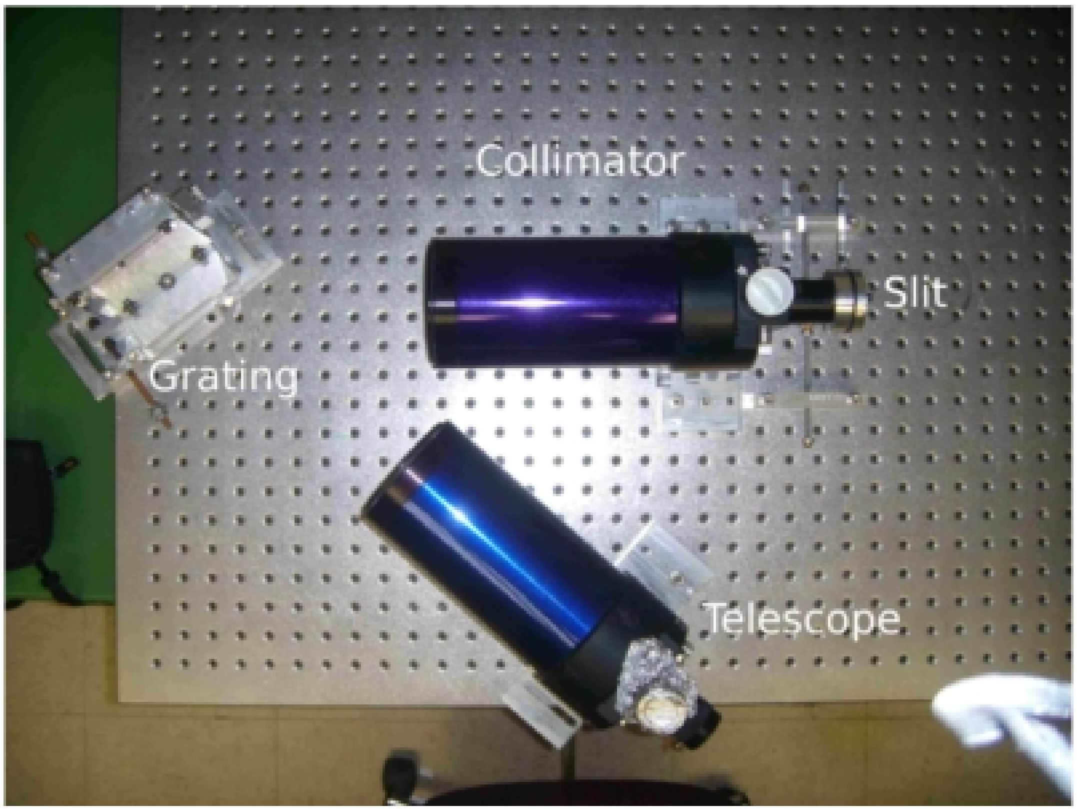

Figure 1: Basic grating spectrograph setup with a slit, a collimator, a reflection grating, and a telescope

Initial calibration of the instrument was performed by a previous student [4]. Calibration is done by taking an image of two lines of known wavelength and determining the ratio of the difference in wavelength between the lines. This is done by imaging two or more spectral lines simulatneously. A function (a gaussian for the peak, and a lorentzian for each side) is fitted for each spectral line in order to determine the positions of each peak. The difference in the wavelength of each line is compared to the difference in position of each line. Each pixel is then given a set increment of wavelength. This gives the calibration ratio in photons per pixel [4, p. 6, 14].

2 Improvements to Spectrograph

2.1 Improvement in Resolution

To improve the resolution, we have placed a 2.8x Barlow lens between the telescope and the camera. This has increased the resolution dramatically from $0.024259 \pm 3.24x10^{-6}$ Angstroms per pixel to $0.008782 \pm 3.24x10^{-6}$ Angstroms per pixel. With the spectrograph's new resolution and the CCD camera's pixel array of 1530x1020 pixels, the field of view has been reduced to only 13.4 pixels, making calibration with an emission source like Mercury difficult or impossible. It is recommended that further calibration be carried out using an incandescent light bulb as the emission source. See Figures 2 and 3 for a comparison of a focused Hg 5460.74 (green) [3] line without a Barlow lens and the same line with a 2.8x Barlow lens. As seen in the images, the Barlow line shows a slight asymmetry which the line without the Barlow lens did not fully resolve.

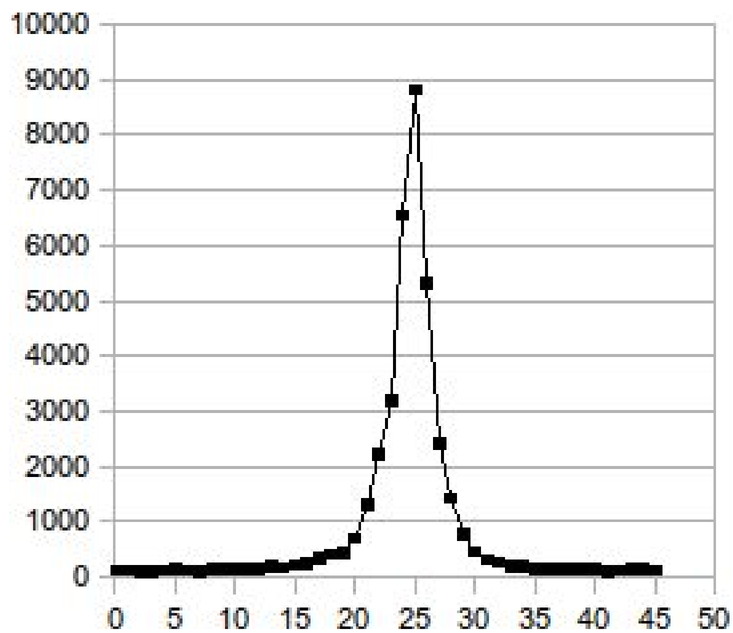

Figure 2: Hg 5460.74 without a Barlow lens, 100 second exposure

2.2 Focusing the Spectrograph

After adding the Barlow, we focused the spectrograph. There are several components in the spectrograph which need to be in the correct position in order to achieve maximum focus. The position between the gas tube and the lens, the lens and the slit, the slit and collimator, the collimator and the grating, the grating and the telescope, and finally the telescope and the camera. The process of focusing requires us to adjust these components

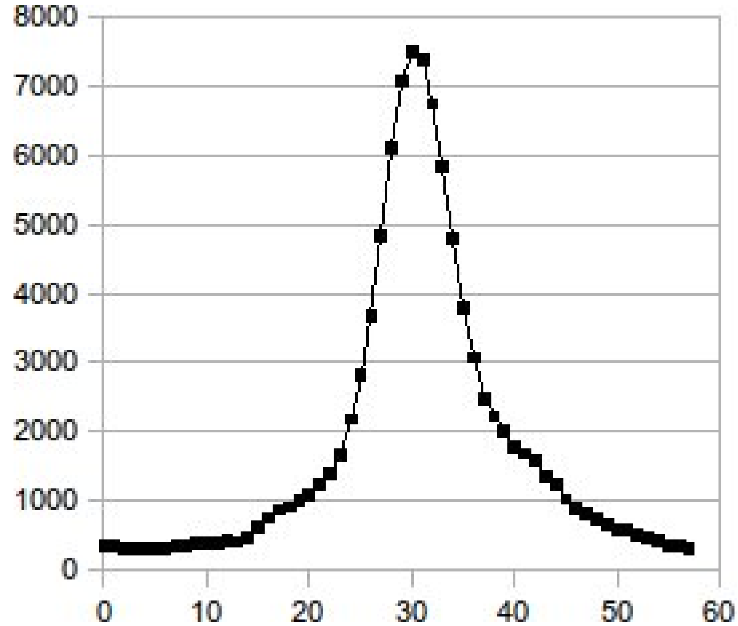

Figure 3: Hg 5460.74 with a 2.8 Barlow lens, 100 second exposure

one at a time. After a component is adjusted, a short exposure of 1 to 30 seconds (based on the line intensity) is taken. The image is opened in MaximDL where a line profile slice is taken and exported into graphical format showing photon count per pixel. Based on the line profile and the half-width of the peak (smaller is better), we determine if the line is better focused or worse focused than the previous image. The component is continually adjusted in this manner until we observe the best possible focus. We then begin to focus each component one at a time until all components are observed to give the best possible focus.

The primary components to focus are the telescope and the collimator. Each time the grating is moved, either to reposition it or to look at a new line, the telescope and the collimator must be refocused separately. So while in use and with all other components positioned correctly, the operator needs only to readjust the telescope and the collimator to focus each line he images. When the spectrograph is at maximum focus with the Barlow lens installed, the half-width of the line is typically about 5 pixels for the Hg 5460.74 line. This corresponds to a half-width of about 0.04 Angstroms.

2.3 Correcting Asymmetry

As seen in Figure 3 there is a slight asymmetry to the right. Focus does not change or improve this asymmetry except to accentuate the asymmetry when the line is "fat" (half-width is large). There are several other possible sources of the asymmetry. A light shield was created to eliminate faint vertical lines to the left as seen as a slight bumpy left asymmetry in Figure 4. The left asymmetry is not visible after the light shield is put in place Figure 5.

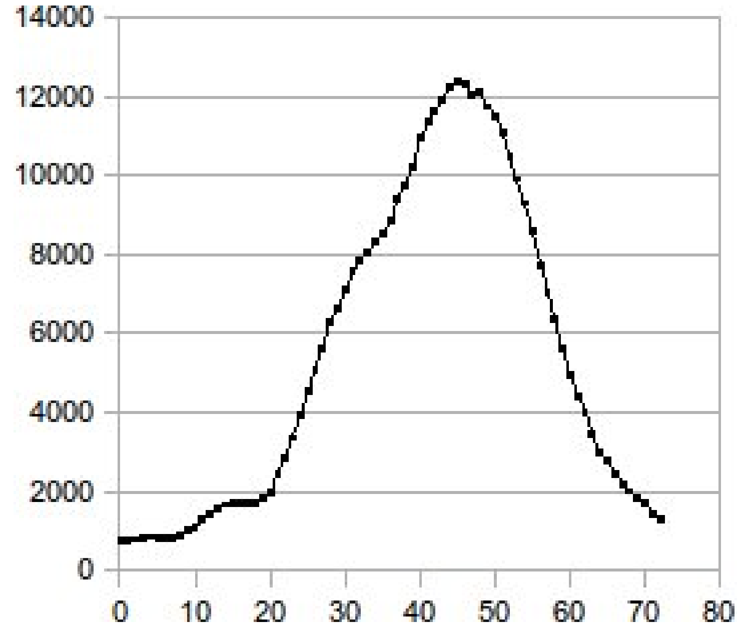

Figure 4: Hg 5460.74 with left asymmetry due to ambient light scatter, 100 second exposure

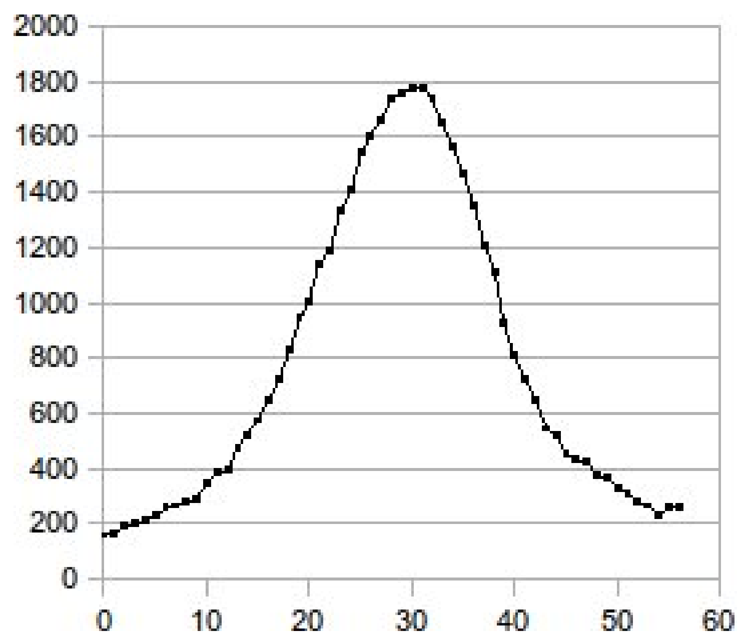

Figure 5: Hg 5460.74 with no left asymmetry after light shield is installed, 15 second exposure

Another possible source of asymmetry is the position of the grating. The center of the grating needs to be aligned with the center of the collimator and the center of the telescope. As we move the grating right of center or left of center, a small part of the asymmetry shifts from one side of the line to the other as can be see in Figures 6 and 7. An attempt to position the grating at center was made by hand.

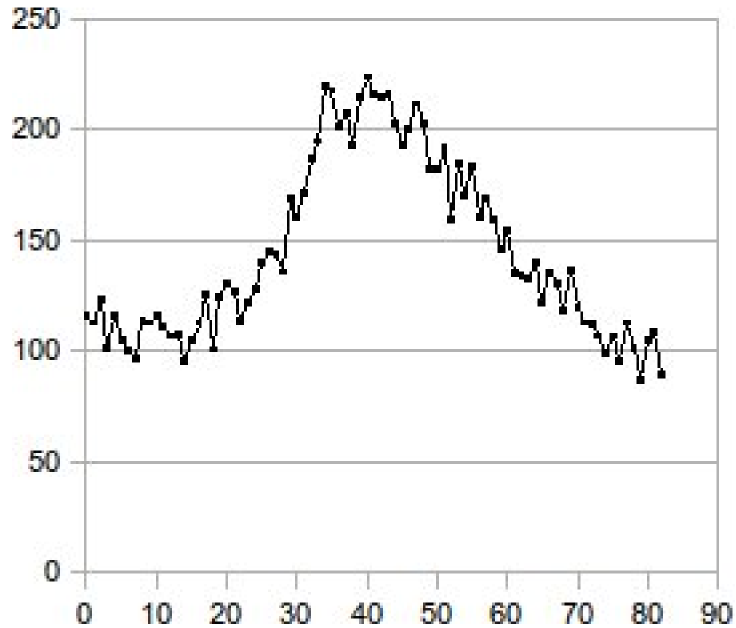

Figure 6: Hg 5460.74 with the grating positioned right of center, 1 second exposure

We also found that the slit position has an effect on asymmetry. The orientation of the slit with respect to the grating has a great effect on the spectral lines. When the slit is not lined up parallel with the etched lines in the grating, the resulting spectral line is asymmetric. The resulting line also displays a very flat top (see Figure 9) or in the case of longer exposures (10 to 15 minutes), the line appears to have two peaks as seen in Figure 10. This is especially apparent when the slit is positioned to the left of center. In Figure 10 the shorter of the two peaks is on the right which is where the slight persistent asymmetry shows up in the other images. As seen in Figures 8 and 9 the changes in asymmetry due to the orientation of the slit with respect to the grating are clearly apparent.

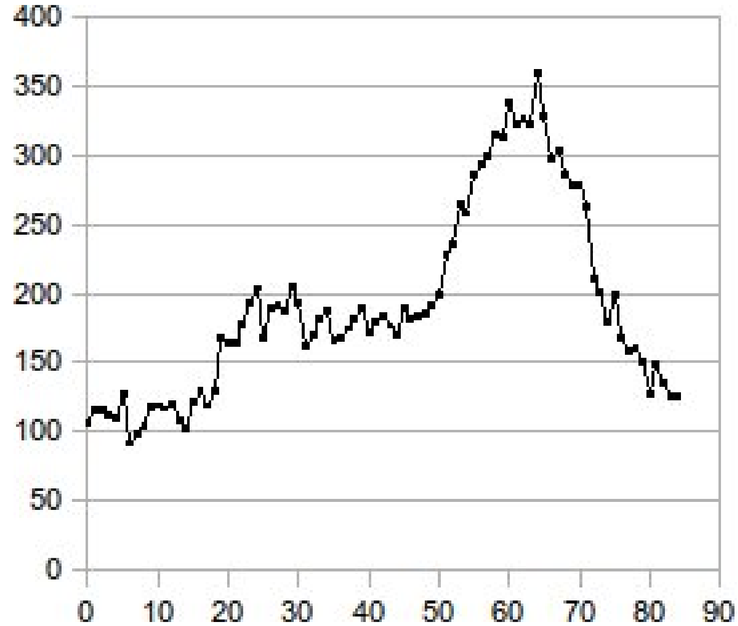

Figure 7: Hg 5460.74 with the grating positioned left of center, 1 second exposure

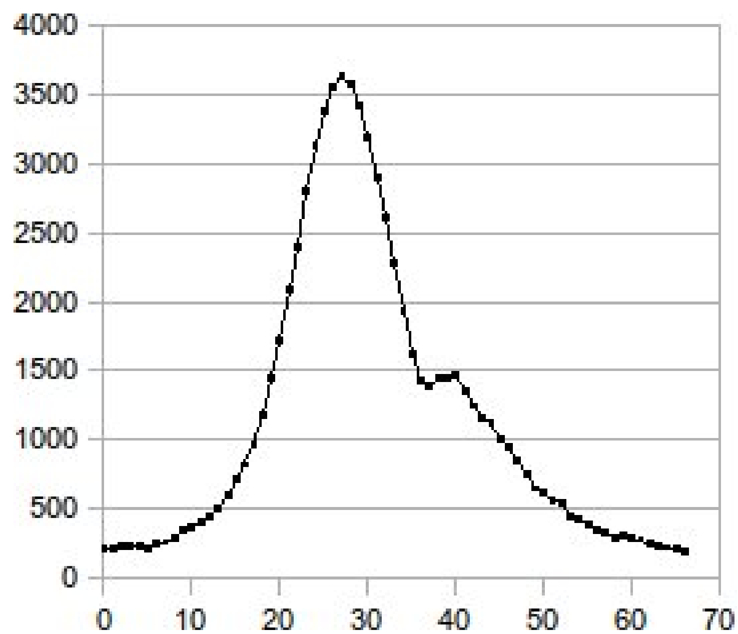

Figure 8: Hg 5460.74 with the slit positioned right of center, 60 second exposure

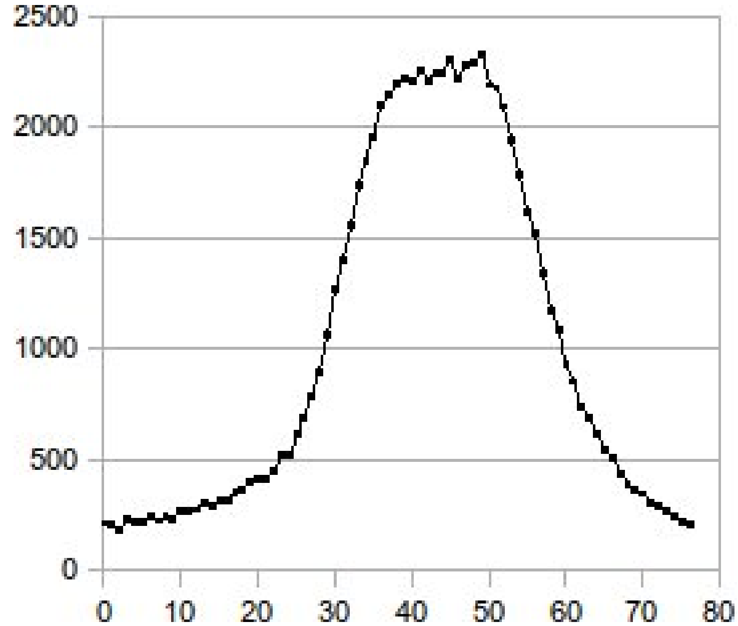

Figure 9: Hg 5460.74 with the slit positioned left of center. Notice the flat top of the peak and the bigger half-width, 60 second exposure

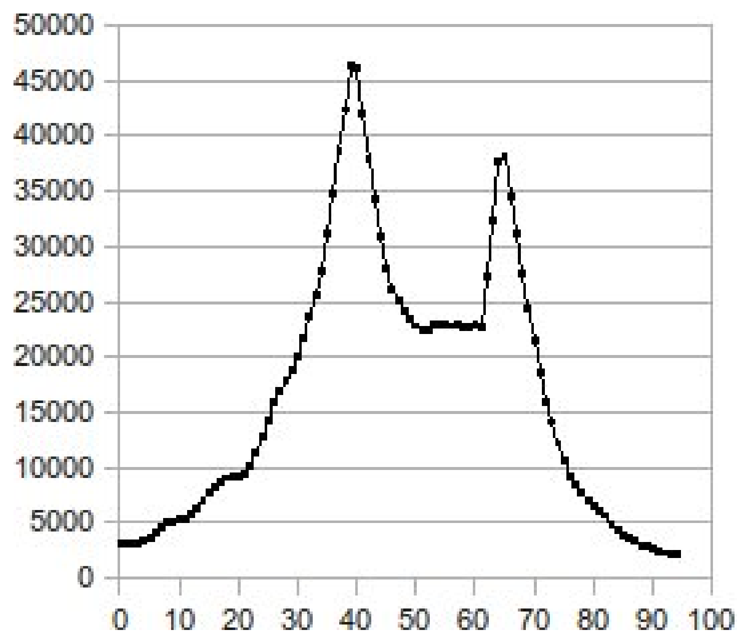

Figure 10: Hg 5460.74 with the slit positioned right of center, 15 minute exposure

3 Zeeman Effect History and Detection

3.1 Zeeman's Effect

In 1897, Dutch physicist Pieter Zeeman discovered that the spectral lines of a heated, light emitting substance were tripled in the presence of a magnetic field [5]. At the time, Zeeman did not have a reasonable hypothesis for why this effect occurred. He did, however, propose that the magnetic field affects the electrons (which he called "ions" at the time) in some unknown way. The magnetic field did not affect the thermodynamic properties of the heated substance. Some other effect was taking place.

3.2 Important Developments

H. A. Lorentz later used classical physics to describe what was then called the "Normal Zeeman Effect." With the birth of quantum theory, physicists were finally able to come up with a hypothesis for the cause of the Zeeman Effect. In 1924, physicist Wolfgang Pauli published the Pauli Exclusion Principle in which he assigned the electron two intrinsic degrees of freedom (representing two directions of momentum), thus allowing up to two electrons to occupy the same state. Shortly after, a young PhD student named Ralph Kronig was inspired by the Pauli Exclusion Principle and proposed electron spin; however, Kronig was discouraged by Pauli from publishing his idea. Months later, physicists George Uhlenbeck and Samuel Goudsmit published their proposal for electron spin. Years later in 1927, Wolfgang Pauli would finally work out the math for the complexities of spin. Physicist Alfred Lande developed a more complete explanation of the Zeeman Effect, including the g-factor in the equations.

As discovered by Kronig, Uhlenbeck, and Goudsmit, electron spin is an angular momentum different from the electron's orbital angular momentum; however, this angular momentum is an intrinsic degree of freedom and not a physical spin about the axis as they had originally thought. An electron has two possible states corresponding to two possible spin momenta: spin up and spin down. Each spin has a magnetic dipole moment associated with it. Because of this, the presence of an external magnetic field will cause the magnetic moment to align itself antiparallel, in the case of spin down, or parallel, in the case of spin up, with the external magnetic field. This will in turn, change the transition energy of the electron. As the electron makes a transition from one energy level to the next and emits or absorbs a photon, the photon will have a slightly different wavelength (higher or lower depending on the electron being parallel/spin up or antiparallel/spin down) than it would if the electron were not in the presence of an external magnetic field. Thus, an observer would see two spectral lines with wavelengths slightly higher and lower than the rest wavelength, because electrons have two possible spin states.

3.3 Significance of Zeeman Effect

The Zeeman Effect was originally important as a verification of electron spin; however, this effect has been used in many fields to increase knowledge and better lives. Astrophysicist George Ellery Hale used the Zeeman effect to calculate the magnetic field strength of sunspots. With his invention of the spectroheliograph, Hale was able to make measurements of the magnetic fields and activity of sunspots which led to the important development of the 22 year solar Hale cycle [1]. Since our sun and other stars are too far away to physically measure magnetic field strengths, astrophysicists rely on knowledge of the Zeeman effect in order to measure the magnitude of these fields [2].

The Zeeman Effect is also important in chemistry and medicine. Electron Magnetic Resonance (EMR) technology uses microwaves and other electromagnetic waves to 'flip' the electron. EMR is used in MRI machines, chemical analysis machines (Nuclear Magnetic Resonance (NMR), Electron Spin Resonance (ESR), and Electron Paramagnetic Resonance (EPR)), and other medical and anthropological machinery. All of these machines take advantage of electron spin and calculations of the Zeeman Effect in order to produce data used to identify chemicals, create photos of the interior of a living animal, identify bone and tissue densities, and analyze the activity of a brain.

3.4 Resolving the Zeeman Effect

We have determined that this spectrograph is capable of resolving a change in wavelength caused by the Zeeman Effect. As calculated previously, the smallest resolvable shift in wavelength is $0.008782 \pm 3.24x10^6$ Angstroms. So, any change in wavelength greater than about 0.009 Angstroms should be resolvable by the spectrograph. The change in wavelength due to an external magnetic field is given by:

$$\Delta\lambda = \pm\lambda_0 \left[\frac{\lambda_0}{hc} |\mu \cdot B|\right]$$

where $\Delta\lambda$ = the change in wavelength, λ_0 = the original line, hc = Planck's constant times the speed of light, μ = the magnetic moment of an electron, and B = the external magnetic field.

Once we know the accurate value for the change in wavelength for a given line due to the Zeeman Effect, we can predict the new wavelengths of the split spectral line. Finding the new wavelength is a simple matter of calculating the change in energy of the line:

$$E = \frac{hc}{\lambda}$$

where E = the energy of the new line and λ = the wavelength of the new line. Then we can substitute in for energy and solve for the new wavelength:

$$\lambda = \lambda_0 \pm \lambda_0 \left[\frac{\lambda_0}{hc} |\mu \cdot B|\right]$$

This relation will allow us to determine the wavelength values of the two new lines.

Using the equation for change in wavelength, we determined the change in wavelength of the Hg 5460.74 line with a 325 gauss (0.0325 tesla) permanent magnet to be: $\Delta\lambda = \pm 4.234$ Angstroms which corresponds to the new lines: $\lambda = 5464.97$ A and $\lambda = 5456.51$. Due to an error in calculation however, we incorrectly determined the 0.0325T permanent magnet to be sufficient enough to produce this resolvable change in wavelength. Upon recalculation, we find that the necessary field strength required to produce resolvable line splitting is 631 Gauss (0.06309 Tesla) with the 2.8x Barlow lens and 1800 gauss (0.1767 tesla) without the Barlow lens.

4 Discussion

4.1 Recommendations for Further Improvement

In order to make the spectrograph worthy of use in an astrophysics or other fine resolution application, several improvements must be made. We recommend that the camera, grating, collimator, and telescope be fitted with micrometer mounts which would allow the user to adjust these components by very small amounts. Since focusing and eliminating asymmetry depend on making very minute adjustments to these components, a fix like this would prove an invaluable time saver to the instrument operators. It will also be necessary to build a full light shield around the entire instrument. This alone will eliminate one source of left asymmetry.

To eliminate a major source of asymmetry, we propose that the slit be aligned perfectly with respect to the reflection grating. Though this removes most of the asymmetry, there is still a slight right asymmetry as seen in Figure 11. We believe that this not due to fine structure effects in the Mercury gas and that the asymmetry could be eliminated with proper slit alignment; however, due to the inaccuracy of the slit rotation mount, we are currently unable to prove this. For that reason, we also recommend a more precise slit rotation mount and method.

In the future it will be necessary to calibrate the instrument using multiple lines. We recommend that the operator use an incandescent light bulb for calibration as the field size of the spectrograph with the 2.8x Barlow lens and the CCD camera is very small (about 13.4 Angstroms side to side) and unable to resolve multiple Mercury emission lines simulaneously. Calibration in this manner will give a more precise resolution which will allow the operator to use the spectrograph in several multi-line spectral analysis applications such as astrophysics and Zeeman Effect measurements.

Even without all of these improvements, the spectral lines have a impressively small half-widths of around 4 pixels. A half-width of 4 pixels corresponds to a half-width of only 0.035

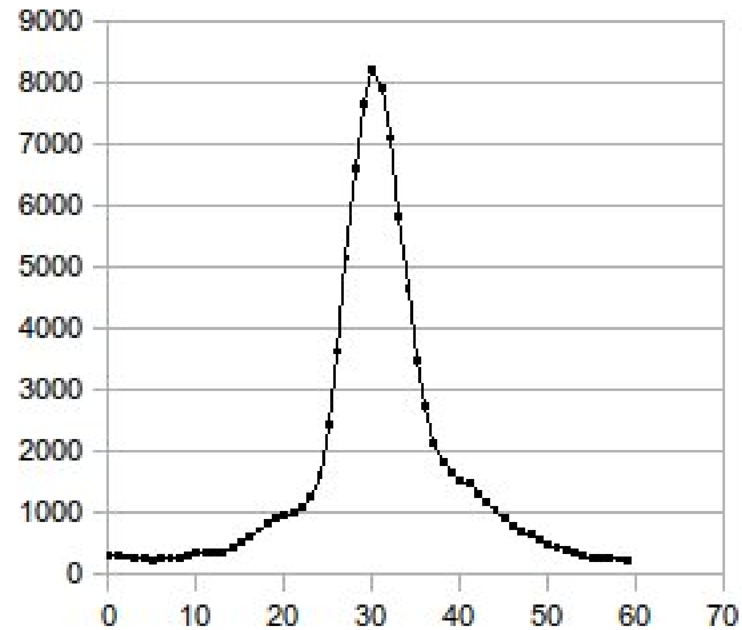

Figure 11: Final focused image of Hg 5460.74. Notice the asymmetry that remains on the right, half-width of 4 pixels, 100 second exposure

Angstroms which may be acceptable under certain conditions if the operator wishes to make Zeeman line splitting measurements.

4.2 Use in Zeeman Measurements

With the improvements to focus, resolution, and asymmetry made, we are able to use this instrument to conduct measurements of Zeeman line splitting. Once a suitable magnet is found, that is one which has a magnetic field strength of 631 gauss (0.06309 tesla) or more, we may take several long exposures of the Hg 5460.74 line in the presence of this field. Using MaximDL, we may take line profile slices of the spectral line images and use the graphical photon count data produced to determine if splitting is visible. Upon detecting Zeeman line splitting (visible as two new peaks in the line profile slices), we can determine the change in wavelength from the data and calculate the magnetic field using the equation relating change in wavelength to the magnetic field. A comparison of the calculated magnetic field to the actual magnetic field can then be made.

References

[1] Babcock, H.W. "Zeeman Effect in Stellar Spectra." American Astronomical Society (1947).

[2] Carroll, Bradley W. An Introduction to Modern Astrophysics. 2nd ed. San Francisco, CA: Addison Wesley, 2007.

[3] Weast, Robert C. et al, "CRC Handbook of Chemistry and Physics, 65th Edition." The Chemical Rubber Publishing Company, 1974.

[4] Lyons, Dan J. "The Design, Fabrication, and Calibration Of a High Resolution Spectrometer." Carthage College (2004).

[5] Zeeman, Pieter. "The Effect of Magnetisation on the Nature of Light Emitted by a Substance." Nature 55 (1897).