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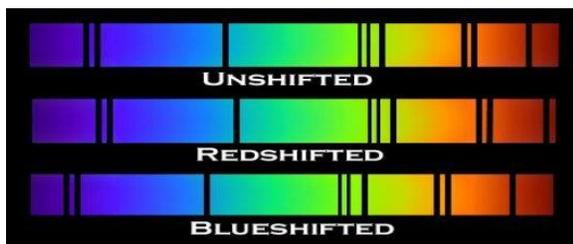
# Calculating Redshift via Astronomical Spectroscopy

By Joshua Glatt

The Doppler effect is a well-known physical phenomenon which results in a change of a wave's frequency or wavelength due to the motion of its source. Celestial objects in space (stars, galaxies, etc.) also experience a Doppler effect on their emitted electromagnetic radiation called redshift. In this study, redshifts were observed in the spectrographic observations of various celestial objects. This was done using a high-resolution near ultraviolet spectrometer in conjunction with a 14-inch Celestron Schmidt-Cassegrain telescope. The spectrometer was used to measure the absorption spectrum of the bodies and then these absorption spectrums were compared against the Hydrogen emission spectrum. By calculating the difference in wavelength between the body's absorption spectrum and Hydrogen's emission spectrum, a redshift value,  $z$ , was determined. The redshift values for these celestial bodies were then used to infer additional information about them, such as velocity relative to Earth and distance from Earth.

## Introduction

In 1666, Sir Isaac Newton discovered how to use a glass prism to split visible light into the rainbow of the visible portion of the electromagnetic spectrum [1]. Since then, the electromagnetic spectrum's properties have been heavily used and studied and form the foundations of almost every branch of modern physics. The purpose of this experiment was to obtain high resolution spectra for various astronomical objects. In this type of spectroscopy, both emission and absorption lines are studied, which correspond to specific elements and molecules. These absorption lines, however, are subject to a shift in wavelength due to the doppler effect [3]. As a result, objects moving towards the Earth will experience a wavelength shift towards the blue end of the electromagnetic spectrum and objects moving away from Earth will experience a wavelength shift towards the red end of the electromagnetic spectrum (figure 1).



*Figure 1: Types of experienced doppler shifts*

These shifted absorption lines can be

compared with the non-shifted emission lines from elemental source lamps on Earth and a measure of how much the light has been shifted by is determined, denoted by the letter  $z$ . Redshift observations can be used to determine a multitude of information about a celestial body, such as velocity relative to and distance from Earth.

## Theory

Although Isaac Newton is often credited for discovering the electromagnetic spectrum through his prism light-splitting experiments, it took just under 150 years for any sort of advancements to come in the understanding of the electromagnetic spectrum. Beginning in 1802, physicist Johannes Fraunhofer discovered the presence of dark gaps/lines when looking at spectra under a magnifying glass. By 1814, Fraunhofer had published his results, documenting a total of 576 dark lines [2]. These dark lines were unable to be explained by Fraunhofer, however, and it wasn't until 1859 that Gustav Kirchhoff and Robert Bunsen discovered that each element on the periodic table emits and absorbs photons at specific, unique wavelengths by observing the spectra of various salt lamps with a spectrometer [1]. Then, in 1896, physicist

Henry Rowland used his own advancements in diffraction gratings to become the first person to photographically document shifts within the sun's spectrum in great number [4]. It was then discovered that these shifts were due to the doppler effect on the observed spectra. From these shifts, a  $z$  value can be obtained as a measure of the magnitude of the celestial body's redshift by using the following equation:

$$1 + z = \frac{\lambda_{observed}}{\lambda_{emitted}} \quad (1)$$

After a value for  $z$  has been determined, a negative value corresponds to a blueshift while a positive value corresponds to a redshift of the spectrum. The  $z$  value can then be used in the following simple relation to determine the velocity,  $v$ , of the object:

$$z \approx \frac{v}{c} \quad (2)$$

Where  $c$ , denotes the speed of light. The above relation, however, does not account for the effects of special relativity by assuming a Lorentz factor of 1.

Accounting for special relativity yields the following equation:

$$1 + z = \left(1 + \frac{v}{c}\right) \gamma \quad (3)$$

Where  $\gamma$  is the Lorentz factor, defined by the relation:

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (4)$$

The velocity of the object can then be used further through Hubble's law. Hubble's law allows one to determine how far away an astronomical object is from us [5]:

$$v = H_0 \times D \quad (5)$$

Where  $v$  is the velocity of the astronomical object relative to earth (km/s),  $H_0$  is Hubble's constant ( $73.45 \pm 1.66$  (km/s)/Mpc), and  $D$  is the distance from the astronomical object to earth (km) [6].

### Procedure

There were only a few equipment pieces used in the data collection for this project: a 14" Celestron Schmidt-Cassegrain telescope (figure 2), an Ocean Optics HR4000 spectrometer with collimating lens and fiber optic cable (figure 3), a laptop to run necessary software and save data, and lastly, a Hydrogen discharge tube.



**Figure 2: Celestron telescope used for data collection**

Before any data collection, there were 2 primary steps that needed to be taken: aligning the telescope and initializing the HR4000 spectrometer. To align the telescope, it was first powered on and the “Two-Star Alignment” option is selected within the settings menu on the remote. The two-star alignment method has the user manually point the telescope at two different stars from its database. It uses the positions of these two stars in conjunction with the telescope’s physical location (latitude/longitude) to properly calculate its alignment, so the user can simply select what astronomical object they want to view and hit the enter button to point the telescope towards it. To initialize the spectrometer, the HR4000 was connected to the computer with its USB cable, and its supplementary software, OceanView, was launched. Within the OceanView software, the user can adjust the spectrometer’s settings such as the integration time and number of scans to average. The integration time varies depending on the astronomical object being observed, with longer integration times for dimmer objects and shorter integration times for brighter objects. The number of scans to average can

be increased as much as desired, with more accurate data resulting from more averages. A dark count is also taken in the OceanView software. A dark count is simply a spectrum of pure darkness, which is subtracted from any future taken spectra. This reduces the amount of digital noise produced by the HR4000 spectrometer’s CCD sensor.



**Figure 3: Ocean Optics HR4000 spectrometer with fiber optic cable and collimating lens**

After the spectrometer and the telescope were properly aligned and initialized, data could then be captured. The desired celestial body was then selected from the telescope’s onboard computer. Fine adjustments were made to the telescopes alignment using the remote’s adjustment D-pad to ensure the object was perfectly centered in view. After the object was centered, the eyepiece for the telescope was then replaced with the collimating lens

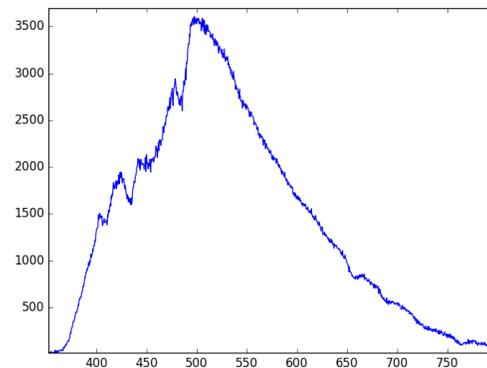
of the spectrometer and a spectrum was obtained within the OceanView software.

A second type of spectrum was also gathered with the HR4000 spectrometer using a Hydrogen discharge tube. The spectrum of this tube contains the well-defined emission peaks for Hydrogen which are commonly known as the Balmer series and occur at 656.3 nm, 486.1 nm, 434.0 nm, and 410.2 nm. These emission peaks from the Hydrogen discharge tube are not subject to any sort of doppler shift and are thus compared with the Hydrogen absorption lines from the collected astronomical spectra in the OceanView software package. The  $z$  value corresponding to these shifts was then calculated using the above referenced formulae.

### Results

Data collection using the HR4000 spectrometer proved much more difficult than anticipated. In a previous project, a lower resolution Ocean Optics USB4000 spectrometer was used to determine the elemental composition of various astronomical objects. The newer, higher-resolution HR4000, however, was not producing any usable data when connected to the telescope. A spectrum of the star

Sirius from the USB4000 is shown in figure 4. The vertical axis corresponds to the intensity of the light and the horizontal axis corresponds to the light's wavelength in nanometers.



**Figure 4: USB4000 spectrum for Sirius**

In the USB4000's spectrum for Sirius, noticeable dips occur at the known wavelengths of the Balmer series. However, the USB4000 is too low of a resolution to detect any doppler shift in wavelength. The HR4000 spectrometer had a detection range between 400nm and 500nm to view the Balmer series' lines at 486.1 nm, 434.0 nm, and 410.2 nm in high resolution and detect the doppler shift of the star. When the HR4000 was connected and a spectrum was taken, only a flat line with an intensity of zero was output from the spectrometer. This made it appear as if no source signal was being detected at all by the spectrometer,

despite having it centered in the view of the telescope's eyepiece. Interestingly, the HR4000 was, however, able to get a very clear spectrum for the Hydrogen discharge tube, and it had well-defined peaks for Balmer series' lines 486.1 nm, 434.0 nm, and 410.2 nm.

### **Discussion and Conclusions**

Failing to get any spectral data for astronomical objects from the HR4000 was disappointing, considering the many hours spent attempting to solve the problem. After the first failed attempt at obtaining a spectrum, it was thought that the integration time for the spectrometer was too low. This is because the entrance slit for the HR4000 is only 5  $\mu\text{m}$ , multiple times smaller than the slit on the USB4000 used previously. A smaller entrance slit corresponds to less light entering the spectrometer, so the integration times were drastically increased incrementally starting at a few microseconds and gradually increasing them to over 2 minutes. With the USB4000, integration times longer than  $\approx 10$  seconds were never used, and it was decided that integration times longer than 2 minutes would have ample time to absorb enough

light to have a visible spectrum in the OceanView software.

After trying the various integration times on multiple stars, there still were no successful spectra observations. This led to the second attempt at fixing the problem: the telescope was not properly in focus to the spectrometer's collimating lens. The eyepiece of the telescope has a focal length of 32mm and the collimating lens for the HR4000 has a 30mm focal length. Therefore, no extra focusing was done initially since they were so close. After failing to get data a second time, however, a systematic approach to the focusing was attempted similar to the attempts with the integration time adjustments. The telescope's focusing knob was turned as far left as possible and the integration time was held at 45 seconds. Every time a spectrum was taken, the focusing knob was turned slightly to the right and another spectrum was taken. This process was repeated until spectra were taken for every possible focusing step the telescope could focus to.

Unfortunately, the attempts at adjusting the telescope's focus were also unsuccessful. This has led to the conclusion that the issues must be arising within the

alignment of the telescope itself. When a DSLR camera was attached to the telescope and a picture was taken with shutter a speed of a few seconds, the star would be seen streaking across the frame, rather than staying centered within it. This would only be possible if the telescope's alignment were off. Even though the celestial objects were manually centered within view during the alignment process, any slight deviations would result in the tracking to have slight deviations as well. The longer the integration time on the spectrometer, the more pronounced these deviations will be, which is not beneficial since the new HR4000 requires longer integration times than the USB4000.

Therefore, it was considered whether the USU observatory's 0.5m PlaneWave telescope would yield actual spectra. This is because the tracking system used by the USU observatory is much more precise and is always set, as opposed to realigning the Celestron telescope each time it was used. Having the more accurate tracking system of the 0.5m PlaneWave telescope would allow for much longer integration times than those able to be used with the Celestron telescope. The USU

Observatory's PlaneWave telescope, however, has not yet been tried due to time constraints, and remains an area for further study.

### **Acknowledgements and References**

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