SOFTWARE AND HARDWARE DESIGN FOR A SMALL ASTRONOMICAL SPECTROPHOTOMETER

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ABSTRACT

I propose the construction of a UVEX spectrograph for use with $\lesssim$0.5 m-class astronomical telescopes. I will also develop custom software to interface with and analyze collected spectral information. The completed product will be portable and telescope-independent, and the software will be feature-rich, generalizable, and open-source. This project will involve and require skill in optical design, fabrication, instrument calibration, and software algorithm/GUI development.

1 MOTIVATION

Stars and other astrophysical objects emit light across a wide range of wavelengths, with some sources producing low-energy, long wavelength radio emission up to extremely high-energy gamma rays. The relative intensities of photons across the range of energies of electromagnetic radiation that a source produces is its *spectrum*. Until fairly recently, light from astrophysical objects was essentially the only way that scientists on Earth were able to study them, making spectra a particularly important tool in the astronomer's toolbox.

An early demonstration of the power of spectral analysis was the discovery of Helium for the first time in 1868. Its lines were observed in the Sun's spectrum and its existence was thus inferred before it was ever detected on Earth. In a similar but opposite fashion, emission lines from planetary nebulae were analyzed to discern their nature as rarefied gas, and the 'forbidden lines' they displayed provided insight into a new physical phenomenon as well (Kwok, 2001).

It is not unreasonable to expect that I will be able to replicate some of these kinds of observations using this instrument. The merits of this project are thus three-fold: not only will this project constitute a valuable learning experience for me, but once complete, the spectrograph will also be both a powerful outreach/educational tool for the Physics Department and an instrument with real scientific potential.

2 PROJECT OVERVIEW

For this project, I intend to follow the UVEX (**U**ltra**V**iolet **EX**plorer) framework. UVEX is a build-it-yourself spectrograph design with plans, parts lists, and schematics available online for free, and is intended to be used with small, amateur-class telescopes, as well as functioning as a free-standing instrument (Buil et al., 2020).

2.1 OPTOMECHANICAL DESIGN

UVEX uses a Czerny-Turner optical design which consists of an entry slit that sits at the focal plane of the telescope, two spherical mirrors, a reflective diffraction grating, and a cylindrical lens to correct astigmatism. Figure 1 shows the physical setup of these components as well as ray traces for each of the primary spectral colors.

Because the primary optics involved are mirrors, there is no chromatic aberration. To preserve this, it is best to use a reflecting telescope that does not require a focal reducer or field flattener (which are refractive optics that can introduce chromatic aberration). To this end, I intend to use this instrument on the Department's Meade SCT.

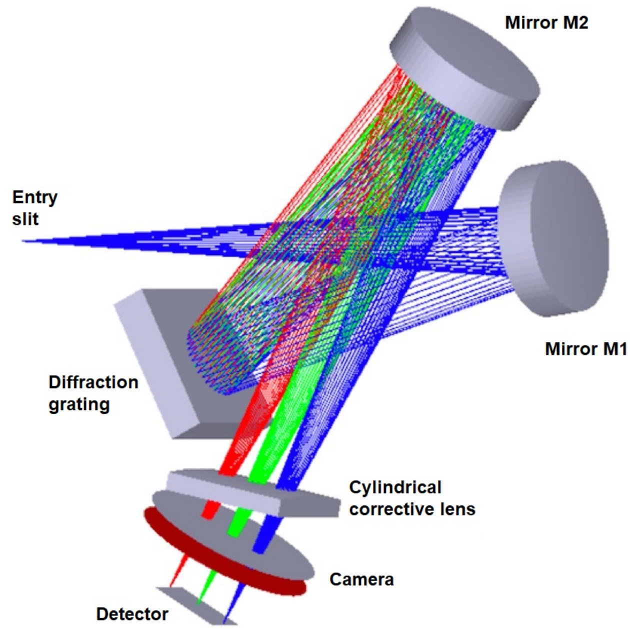

Figure 1: Schematic view of the physical configuration of the UVEX spectrograph.

The overall optical efficiency at $\lambda = 550$ nm of the instrument itself is approximately 35%, which is very good for a spectrometer.

The case that houses all of these components is designed to be 3D-printed, and CAD files are provided by the UVEX project.

2.2 Calibration/tuning

The superior optical efficiency and simplicity of the design come at the cost of complexity in calibration. One must focus the detector, orient the spectrum relative to it, adjust the angle of the M1 mirror so as to minimize vignetting on either the red or blue end of the spectrum, adjust the angle of the M2 mirror to minimize the 'width' of point-source spectra.

In the end, the entire optical path must be tuned such that the slit image, a guide image of the star and the spectrum of the star are sharp all at once. This process will require bench testing using known line emitters (i.e. lasers, neon lamps) as well as field testing on stars.

3 Hardware

One major draw of the UVEX framework is the relatively low cost. The optical components discussed in Section 2.1 that make up the actual spectrographic elements are listed in the table below.

Item name	Thorlabs part #	Unit price	Quantity	Total
Diffraction Grating, 300/mm	GR25-0305	\$116.86	1	\$116.86
1" Aluminum-Coated Concave Mirror	CM254-100-G01	\$60.34	2	\$120.68
1" Mirror Mount	FMP1/M	\$17.10	2	\$34.20
N-BK7 Cylindrical Lens	LJ1934L1-A	\$96.31	1	\$96.31

Table 1: Essential optical components list. Subtotal: \$368.05

Additionally, a camera will need to be selected and purchased, if it is decided that a DSLR (e.g. Nikon) is not appropriate or optimal. Some combination of other parts, such as hardware/fasteners ($\lesssim$\$20), calibration equipment ($\lesssim$\$30), and adapters ($\lesssim$\$50) will likely be necessary as well. Due to the lack of detailed information about these requirements as of yet, financing for these items will be requested and proposed as they come up over the course of the project.

4 SOFTWARE

Spectrographs that use regular cameras as detectors end up producing images that look something like Figure 2 (minus the annotations). The final problem then, is to transform this color image into numerical spectral data along a wavelength or frequency axis.

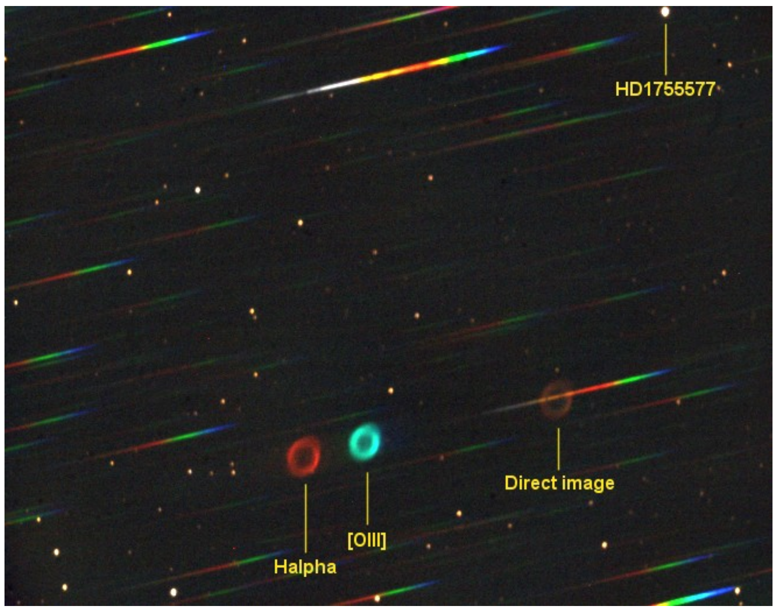

Figure 2: Example spectrographic image of the region around M57, the Ring Nebula.

4.1 IMAGE ACQUISITION

A number of camera and telescope control softwares exist already, and some are even open source. In the beginning it may be better to use one of these, as they can also handle pointing and tracking, which will simplify locating sources in the sky.

In the interest of fulling automating the spectral analysis pipeline, however, I may eventually write my own interface with the camera to capture images.

4.2 SOURCE SPECTRUM SELECTION

Once an image like Fig. 2 is captured, the spectrum of the particular star or object of interest will need to be selected (likely manually). I have developed code already to select the endpoints of a spectrum trace, take the pixels along the line between the two points, rotate them onto the horizontal, and map their intensities into a pseudo-spectrum.

4.3 TRANSLATING RGB-SPACE TO λ-SPACE

There is no absolute mapping of a red/green/blue color triplet to a single, spectrally pure wavelength. As such, one needs to either calibrate certain pixel indices to certain wavelengths and assume some progression (i.e., linear) between them, or attempt to use color theory algorithms and white points with calibrated responses on a given camera detector to compute dominant wavelengths for various

RGB pixel values. Either way, the intensities of each pixel value along the axis are then plotted to form a spectrum.

5 Conclusion

I will consider this project a success if I am able to make substantial progress toward having a working spectrometer by the end of the semester. I imagine it is perfectly feasible to expect to be able to complete the physical assembly and have at least a functioning software prototype. Due to personal interest in this project, I am also prepared to continue working on tasks such as calibration and adjustments in the Innovation Lab during next semester as well.

This project has a high return for its budget in terms of both scientific and educational merit and I hope to be able to proceed.

References

C. Buil, P. Dubreuil, S. Ubaud, J.-L. Martin, A. Lopez, and P. Thierry. The UVEX project. Technical report, Astronomical Ring for Access to Spectroscopy, October 2020. URL http://www.astrosurf.com/buil/UVEX_project_us/.

S. Kwok. The origin and evolution of planetary nebulae. *Cambridge University Press, New York*, 2001.