ASTRUN3646: Observational Astronomy
Integrating a Fiber Optic Cable into a 3D-Printed Spectrograph

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I. INTRODUCTION

A spectrograph is a device that separates electromagnetic radiation into its individual wavelengths and measures the intensity at each one, effectively capturing the spectral content of light. Any object that absorbs or emits light can be studied with a spectrograph [1]. This is accomplished by dispersing the incoming light into its component wavelengths, which are then recorded and analyzed.

In this setup, a diffraction grating is used as the dispersive element. Spectrographs are essential tools in fields such as astronomy and chemistry, where they enable researchers to identify the composition, temperature, and motion of distant objects based on their spectral signatures. Spectrographs are essential tools in fields such as astronomy and chemistry, where they enable researchers to identify the composition, temperature, and motion of distant objects based on their spectral signatures.

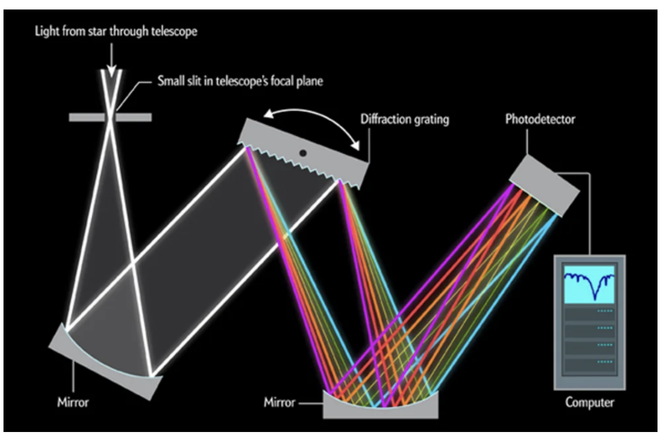

FIG. 1. A diagram of a simple spectrograph

Light entering the spectrograph first passes through a narrow slit before striking a collimating mirror, which aligns the light rays to travel parallel (see Figure 1). These rays then reach the diffraction grating, a finely ruled glass surface, which disperses the light by bending each wavelength at a slightly different angle depending on its color. This separation creates a continuous spectrum, spreading red, orange, yellow, and other wavelengths across a detector. By rotating the grating, specific wavelength ranges can be selected and directed toward a focusing mirror, which concentrates the light onto a photon detector such as a charge-coupled device (CCD). The detector then converts the incoming photons into electronic signals that are interpreted by software to measure the intensity across the spectrum.

In Spring 2024, Tina Liu, Ranger Kuang, and Mike Yang developed a lightweight and compact 3D-printed spectrograph using polylactic acid (PLA) based on the *Sol'Ex* design (see Figure 2). This project aims to improve and expand their spectrograph by integrating a fiber optic cable into the slit and connecting a guider camera in conjunction with a telescope mount to precisely track and correct for any drift in the telescope's field of view, ensuring the target remains centered during long-exposure observations.

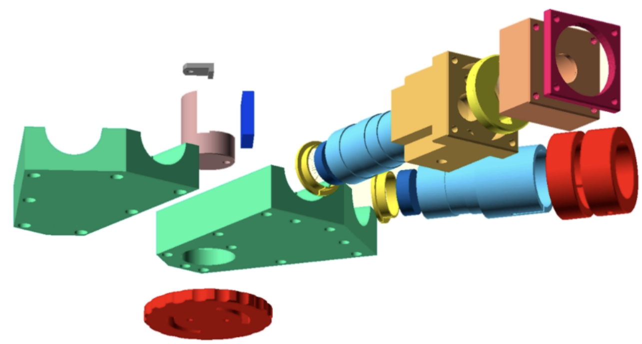

FIG. 2. The spectrograph CAD model showing individual components and their spatial configuration made by *Sol'Ex* [2]

In this continuation, the spectrograph will be adapted for observational use by integrating it with the telescope at at Rutherfurd Observatory in Pupin Hall with a Celestron 14" optical tube, enabling the collection of high-resolution spectra from astronomical sources.

II. CONCEPT DESIGN AND PROTOTYPING

Beam-Splitting Design

To accommodate both the spectrograph and the guider camera, the new optical design required splitting and redirecting the incoming light from the telescope to each device. Three beam-splitting designs were explored to achieve this, all using a fiber optic cable as the conduit for the telescope's light (i.e., the light observed from a celestial object).

Each of the three proposed designs directs light from the fiber optic cable into a tube, where it encounters a mirror that splits the beam between the spectrograph and the guider camera. The configurations differ in the method used to achieve this split.

Design 1: Dual Mirror Reflection

In the first design, two mirrors were positioned at the end of the tube to reflect the incoming light in two distinct directions: one towards the spectrograph and the other towards the guider camera (see Figure 3).

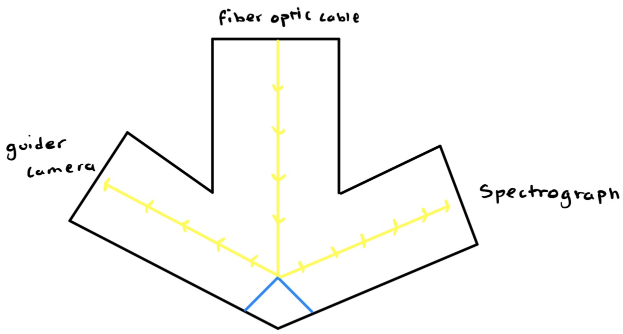

FIG. 3. The dual mirror for the first design

The proposed optical design shown in the sketch may not function effectively as a beam splitter due to several issues. The mirror positioned at the intersection is angled in a way that may entirely reflect the incoming light rather than evenly splitting it between the spectrograph and the guider camera. Unlike standard beam splitters, which use partially reflective coatings to simultaneously transmit and reflect light, the depicted configuration could result in one device receiving the majority of the light while the other receives little to none.

Additionally, the unequal optical path lengths from the intersection to the two devices may introduce phase differences, compromising the system's efficiency. Light loss may also occur if standard mirrors are used instead of specially coated beam-splitting optics. The alignment and stability of the mirror are crucial, as even a slight misalignment can prevent light from properly reaching one of the devices.

Design 2: Angled Mirror with Pinhole

A single angled mirror with a central pinhole allows a portion of the incoming light to pass through to one device (e.g., the spectrograph), while the reflected component is directed to the second device, the guider camera (see Figure 4).

The optical design shown in Figure 4 would not work effectively as a beam-splitting mechanism. The angled mirror with a central pinhole was intended to allow part of the incoming light from the fiber optic cable to pass through to the spectrograph while reflecting a portion towards the guider camera. However, in practice, the pinhole itself would limit the amount of light that reaches the spectrograph, as only a small fraction of the light passing through the fiber optic cable would make it through the narrow aperture. The reflected light directed to the guider camera may also not be properly collimated or focused due to the mirror's position and angle, leading to poor light transmission.

Therefore, the pinhole may cause diffraction effects, further degrading the quality of the transmitted light and making Figure 4 unsuitable for observing the spectra of celestial objects.

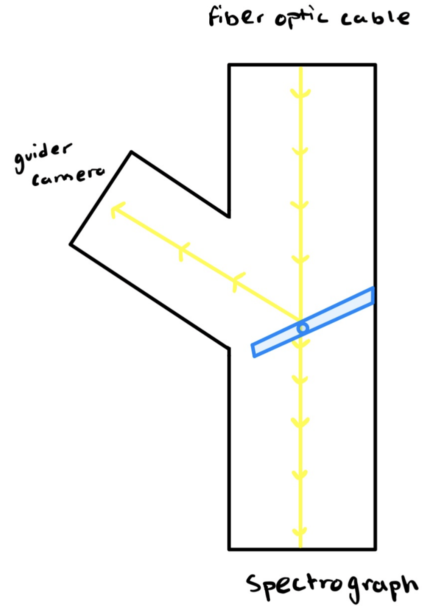

FIG. 4. The angled mirror with pinhole for the second design

Design 3: Angled Mirror with Slit

Similar to the previous design, the pinhole was replaced with a slit, effectively creating two beam paths. Part of the light passes through the slit, while the remainder is reflected at an angle (see Figure 5).

Design 3 was selected for its greater tolerance to misalignment and improved light transmission efficiency. In this design, the pinhole from the previous design was replaced with a slit, which effectively creates two beam paths: one that passes directly through the slit to the spectrograph and another that reflects at an angle toward the guider camera. The slit design offers more flexibility in beam placement compared to the narrow pinhole used in design 2. This reduces the risk of complete light loss due to minor alignment errors, as the wider slit can accommodate slight deviations without significantly diminishing the transmitted light intensity. The slit reduces diffraction effects that are more prominent with a single pinhole, thereby allowing a greater portion of the incoming light to reach the spectrograph.

Therefore, compared to design 1, which requires precise alignment of two separate mirrors to split the beam effectively, design 3 only needs one reflection angle to be correctly positioned. This simplification minimizes cumulative alignment errors and reduces the time required for calibration. As a result, design 3 provides a more practical and efficient optical setup for integrating both the spectrograph and the guider camera.

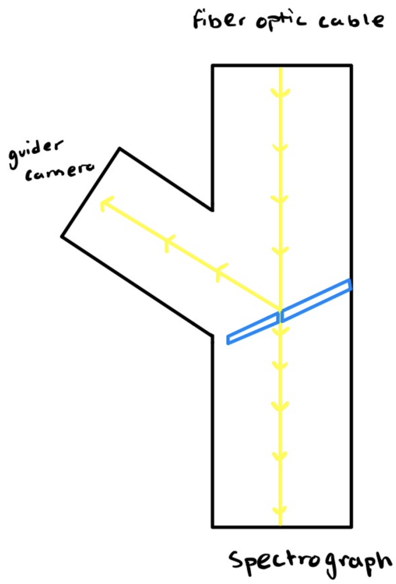

FIG. 5. The angled mirror with slit for the third design

Prototype and Component Integration

Following the selection of the beam-splitting method (design 3), an enclosure was initially designed to connect the spectrograph, guider camera, telescope, and fiber optic cable into a stable unit.

Prototype Design Progress

In the first iteration, the fiber optic cable was directly connected to the telescope lens and routed into a 3 × 3 × 9 inch rectangular prism (see Figure 6). Inside the rectangular prism, a 4.24" × 3" slit mirror was installed at a 45° angle. Light from the fiber optic cable was split: part of it passed through the slit into the spectrograph, while the reflected portion was directed through a cylindrical tube with a 0.65" radius into the guider camera. The tube was chosen to match the guider camera's lens mount.

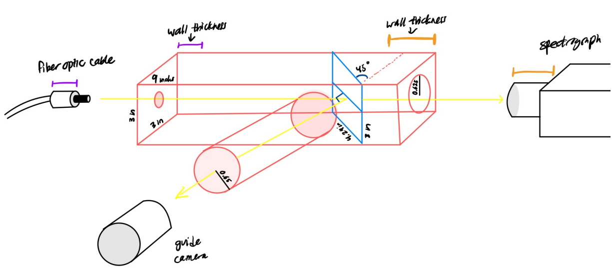

FIG. 6. The first design of the prototype

However, the new integrated design ideally directed light from the telescope into two separate devices: the spectrograph and the guider camera. Initially, it included a beam splitter enclosed within an additional rectangular prism of same size. One end of the optical fiber cable is connected to it, while two mirrors (3 in × 4.24 in), positioned at 45° angles and oriented perpendicular to the guider camera box, are mounted at the center (see Figure 7). The opposite end of the rectangular prism was designed to connect directly to the telescope.

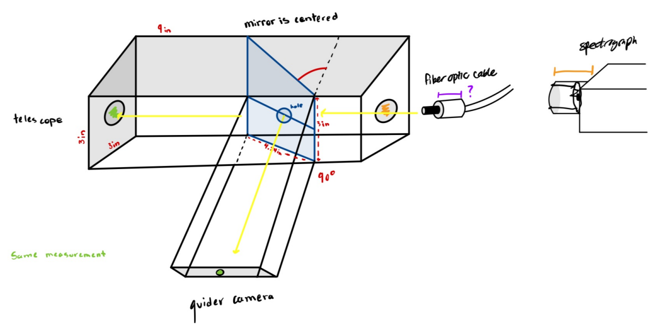

FIG. 7. The improved design of the initial prototype

While improving the initial prototype, the enclosure was modified to enable direct connection with the telescope and spectrograph. In this new design, the fiber optic cable was positioned after the mirror within the pinhole at a 45° angle, connecting to the spectrograph's slit and collimating lens. The spectrograph itself was connected to the telescope along with the guider camera.

To improve structural stability, the enclosure was redesigned to allow the telescope to connect directly to the housing. In this setup, light from the telescope enters the housing, strikes the 45° slit mirror, and splits: the transmitted light is funneled into the fiber optic cable (leading to the spectrograph), while the reflected light is directed to the guider camera. Additionally, the cylindrical tube was replaced with a rectangular prism to better interface with available guider camera mounts.

The initial prototype consisted of a 3 mm thick plywood enclosure created using a laser cutter (see Figure 8). The components were assembled using a hot glue gun and a simple wooden piece was used to simulate mirror placement. Although functional, this prototype served primarily as a proof of concept rather than a final implementation.

Subsequently, access to a *Thorlabs* beam-splitter cube and additional optical components enabled significant stabilization of the system. The updated design reduced the contraption's previous dimensions approximately to a 60 mm cage, retrofitted by mounting an acrylic mirror onto a standard optic mount (see Figure 9).

This assembly is enclosed between two `LCP01` 60 mm cage plates (each with SM2 threads and 0.5 in thickness). One cage plate interfaces with the telescope, while the opposite plate connects to the guider camera, enabling

FIG. 8. A prototype of the revised design

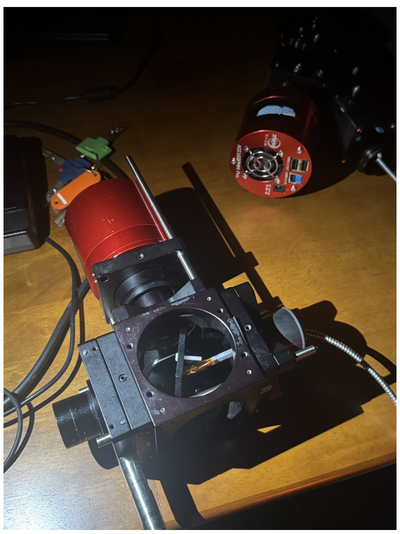

FIG. 9. *Thorlabs* beam-splitter cube with the cage plates, guider camera, and fiber optic cable

modular integration with both components. To fine-tune the optical path, the acrylic mirror was slotted to allow the fiber optic cable to enter at the appropriate angle for a straight beam path to the guider camera.

The 3D-printed spectrograph consists of four essential components commonly found in standard spectrographs (see Figure 10). Unlike traditional designs that use mirrors, the *Sol'Ex* uses a collimating lens and an objective lens, allowing for a more compact and lightweight instrument. Additionally, Figure 10 highlights the top of the grating chassis, which securely holds the diffraction grating (not visible in the image). Notably, the chassis is rotatable, enabling adjustment of the grating angle. This feature and its applications are discussed further in the following section.

Light enters from the top left side of the instrument

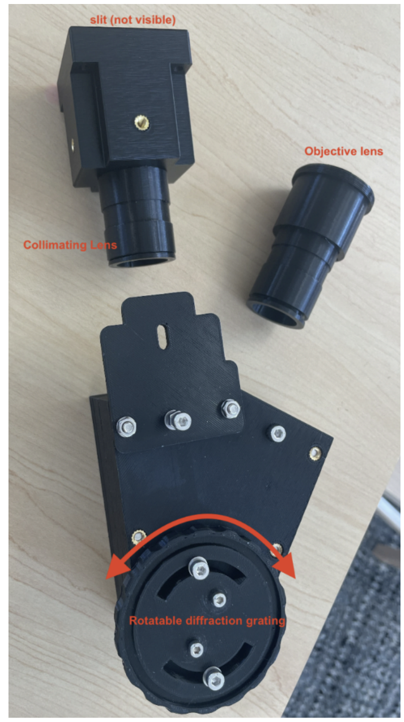

FIG. 10. 3D-printed spectrograph model showing individual components and their spatial configuration made by *Sol'Ex* [2], respectively

through a slit (not visible in the figure) with the fiber optic cable attached, then passes through the collimating lens. It is subsequently reflected by the internal diffraction grating and finally exits the main chamber on the right side through the objective lens.

The final prototype included the beamsplitter cube, which was connected to the 3D-printed spectrograph via the fiber optic cable (see Figure 11). The diffraction grating was rotated as needed to obtain the desired spectra during observations with the 3D-printed spectrograph.

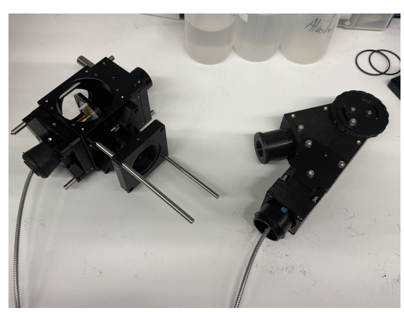

FIG. 11. Left: Finalized prototype with the appropriate components. Right: the 3D-printed spectrograph connected with the fiber optic cable

III. TESTING AND ANALYSIS

Analyzing Spectra

The prototype was tested at Rutherfurd Observatory in Pupin Hall with a Celestron 14” optical tube (see Figure 12).

FIG. 12. The prototype mounted on the Celestron 14” optical tube at Rutherfurd Observatory in Pupin Hall

The telescope was aimed to collect spectral data using the fiber optic attachment to the spectrograph from sunlight reflected off the lunar surface. Raw image data was collected with a ZWO ASI2600MC Pro camera, which produced an encoded RGGB Bayer filter array (a pattern of red, green, and blue filters on the camera sensor). This data was then algorithmically debayered into an RGB image of the spectral data using a module from the OpenCV Python package (see Figure 13).

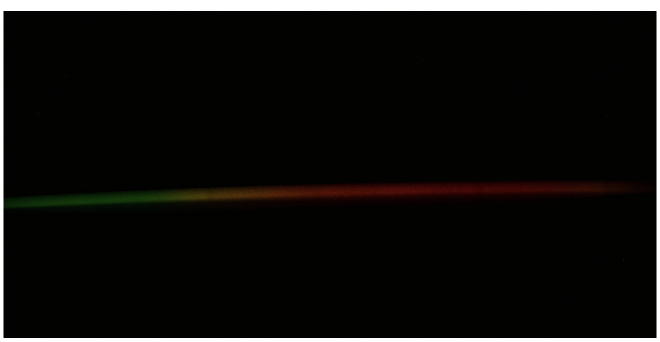

FIG. 13. Raw image data converted from a Bayer filter array into a full-color (debayered) solar spectrum.

Once processed, dark absorption lines in the solar spectrum became visible in the RGB image, closely matching the spectral locations of key Fraunhofer lines. Each absorption line is caused by the transition of an electron between energy levels in an atom, with each element exhibiting a distinct pattern of absorption lines (see Figure 14). Joseph von Fraunhofer’s catalog of dark absorption lines in the solar spectrum has proven to be a valuable tool for gauging the wavelength range and accuracy of the spectrograph attachment.

The solar spectrum displayed identifiable D (neutral sodium, Na I)), C (hydrogen, Hα)), and B (terrestrial oxygen) lines at wavelengths of 5896 Å - 5890 Å, 6563 Å, and 6867 Å, respectively. Visually, these lines matched the dark absorption markers in the processed RGB spectrum.

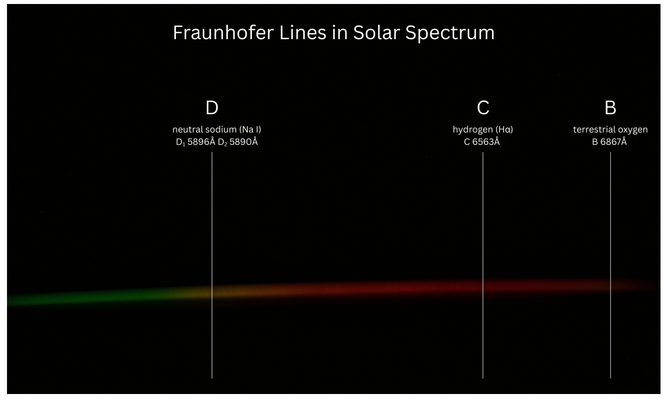

FIG. 14. Dark absorption lines in the solar spectra (Fraunhofer lines) in Angstroms as reflected off the lunar surface.

An issue we struggled with while testing was properly aligning the guide camera on the prototype attached to the telescope. Although we were able to see our target, coma aberrations were present in the image. This typically happens when light enters the optic at an oblique angle and distorts off-axis points of light, causing them to appear coma-shaped or trailing blurs.

FIG. 15. Coma abberated image of the moon due to improper angular alignment of the mirror.

The coma abberations present in Figure 15 were most likely due to the angular alignment of the mirror. While we had intended for the mirror to be set at an exact 45°angle, the best we could get was an approximation due to the emphasis on properly aligning the fiber optic cable to be in the focus of the telescope.

IV. CONCLUSION

Although none of the group members come from an engineering or instrumentation background, building a physical product from scratch gave us valuable insights into the complexity and rigor of the design process. We were surprised by the level of iteration and planning required, not only to create a functional prototype but also to ensure that each step of the design was clearly communicated, understood, and executable by all team members.

This project marked our first experience using CAD software to model components to precise specifications. Even small elements, such as the mirror, required numerous prototypes and laser-cut iterations to achieve the correct dimensions and fit within the optical mount. Translating our ideas from 2D diagrams to 3D CAD models and then into physical prototypes revealed the often underestimated challenges of aligning theoretical designs with practical constraints like material strength, spatial tolerance, and structural stability.

One unexpected issue we encountered was that laser-cutting the acrylic mirrors caused burn marks and surface smudges, which could interfere with optical clarity and degrade light reflection. This highlighted the importance of material handling and post-processing in optical systems, where even minor imperfections can affect performance.

At several points, the realities of fabrication, such as the fragility of components or space limitations, forced us to revise our initial plans, often opting for more compact and robust solutions. For example, we chose to reduce the size of the enclosure from $3 \times 3 \times 9$ inch to the 60 x 60 mm *Thorlabs* beam-splitter cube to improve rigidity and ease of use. Ultimately, this experience taught us how to bridge the gap between conceptual design and real-world implementation, balancing idealized models with hands-on feasibility.

CONTRIBUTIONS

M. Maldonado Gutierrez contributed to the writing, testing, and partial construction of the prototype; E. Cullen contributed to the assembly of the optics, testing the prototype and analyzing the collected prototype data; F. Tanvir was responsible for building and testing the prototype; and L. Chen contributed to the writing and developed the design configurations under the guidance of Professor David Schiminovich.

[1] ESO (2024). *Spectrograph and Spectroscopy*. Retrieved from https://esawebb.org/wordbank/spectrograph-spectroscopy/#:~:text=Spectrographs%20are%20instruments%20that%20are,and%20the%20atmospheres%20of%20planets.

[2] Bull, Christian (2024). *Sol'Ex slit GEN2*. Retrieved from https://esawebb.org/wordbank/spectrograph-spectroscopy/#:~:text=Spectrographs%20are%20instruments%20that%20are,and%20the%20atmospheres%20of%20planets.