A Compact Grism Spectrometer for Small Optical Telescopes

Dominic A. Ludovici* and Robert L. Mutel†

Department of Physics and Astronomy,
University of Iowa, Iowa City IA 52242

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Abstract

We describe a low-cost compact grism spectrometer for use with small astronomical telescopes. The system can be used with existing CCD cameras and filter wheels. The optical design consists of two prisms, a transmission grating, a collimating lens, a focusing lens, all enclosed in a 3-d printed housing. The system can be placed inline, typically in an unused filter wheel slot. Unlike conventional spectrometers, it does not require the target to be precisely positioned on a narrow slit. The mean spectral resolution \( R \approx 300 \) is sufficient to resolve the spectral lines of many astronomical objects discussed in undergraduate astronomy labs, such as stellar absorption lines along the main-sequence, emission lines of early-type hot stars and galactic novae, and redshifts of bright quasars and supernovae.
I. INTRODUCTION

Many colleges and universities have on-campus observatories that are integrated into the undergraduate astronomy lab curriculum. The telescopes are often equipped with sensitive, cooled CCD cameras that allow students to obtain impressive images of a wide variety of astronomical objects, including comets, planets, stars, nebulae, and galaxies. However, spectroscopic observations, in which the light is separated into hundreds or thousands of spectral channels, dominate the observing schedules of most professional telescopes. This is because spectroscopy allows astronomers to determine a large number of physical conditions that are either difficult or impossible to discern from an image. These include elemental composition, temperature, density, motion (both translational and rotational), and even magnetic field strength. The advantages of using spectroscopic data in undergraduate astronomy laboratories has long been recognized\textsuperscript{1–3}.

In spite of these advantages, relatively few small telescopes have the capability to conduct spectroscopic observations. This is because conventional spectrometers are expensive to build, very sensitive to vibration and temperature variations, and difficult to operate, since the target object must be placed on the spectrometer entrance with arcsecond accuracy. In addition, the spectrometer subsystem often interferes with CCD camera imaging or eyepiece observing, necessitating cumbersome, time-consuming equipment removal and replacement when the spectrocope is installed.

A transmission grating placed directly in the optical path provides a simple low-cost way to obtain low-resolution spectra with minimal equipment changes. This can be done either by inserting the grating into an eyepiece for visual observing\textsuperscript{4} or in a filter wheel using the existing imaging camera as a detector\textsuperscript{5–8}. However, the dispersed spectrum suffers from an optical aberration that severely limit the spectral resolution: The dispersed spectrum focuses on a curved surface rather than a flat plane (Petzval field curvature). This limit the effective resolution of simple transmission gratings to $R = \lambda/\Delta \lambda \lesssim 100$ over the visible wavelength range.

Grism spectrometers, which combine a transmission grating with a prism, minimize field curvature aberration by redirecting the dispersed rays closer to the optical axis. These systems can be used in large focal ratio (‘slow’) optical systems without additional corrective optics since the incoming rays are close to paraxial (e.g., the Hubble Space Telescope WFC3
grism\(^9\)). However, most small observatory telescopes have fast optics (f/5 - f/10) so the incident rays are significantly non-paraxial. This requires corrective optics to collimate the incident rays and refocus the exit rays onto the image plane.

Here, we describe a low-cost, compact grism system with corrective optics that can be constructed using commercial off-the-shelf optical components. It is small enough to fit into existing commercial filter wheels with the addition a small housing extender. The grism enclosure and filter wheel extension are easily fabricated using a 3-d printer. The spectral resolution \((R \sim 300)\) is sufficient to observe a wide range of astrophysically relevant targets, such as stellar spectral types, emission lines from hot star and novae, and red shifts of bright quasars and Type II supernovae.

II. THE COMPACT GRISM SPECTROMETER

A. Optical Design

The compact grism spectrometer (CGS) optical design consists of five elements: A high-efficiency transmission grating, two achromatic lenses for collimating and refocussing, and two wedge prisms. In principle, a single prism can be used, but a typical grism design requires a large \((\theta \sim 20^\circ)\) prism refraction angle, which is not commercially available as a stock item. Fig. 1 shows a ray trace of the optical design.

We now consider the design criteria for each element.

- **Diameter of optical elements.** Achromatic lenses, transmission gratings and wedge prisms are commonly available\(^{10-12}\) in both 25 mm and 50 mm sizes. For a compact design and to minimize weight, 25 mm diameter components are preferable, but to avoid vignetting, the lens’ clear aperture must be larger than the beam size \(\delta x\) at the grism,

  \[
  \delta x = d/f < 25 \text{ mm},
  \]

  where \(d\) is distance from the grism to the focal plane and \(f\) is the focal ratio.

- **Collimating lens.** The collimating lens corrects for the converging telescope beam, creating a parallel beam. The lens is a negative (diverging) achromat whose focal ratio is chosen to collimate the converging rays from the telescope optics. The exact focal
FIG. 1. Optical design of the compact grism spectrometer, showing ray paths at several wavelengths from 400 nm (magenta) to 800 nm (brown). The incident rays from the telescope (f/6.8) are first collimated by an achromat doublet lens, then dispersed by a 10° wedge prism, followed by a 600 lpmm transmission grating, then a second 10° prism, and finally refocused into the detector plane by a second achromatic doublet. The focal lengths of the collimating and refocusing lenses are determined by the f-ratio, location in the converging optical beam, and the back-spacing of the imaging sensor.

length depends on where the lens is place in the optical path. For a fully illuminated lens, a f/6.8 telescope beam can be collimated with a 25 mm diameter achromat lens with a focal length -170 mm. However, for a partially illuminated lens (i.e. closer to the focal plane), the (negative) focal length increases.

- **Wedge prism.** The wedge prism compensates for the wavelength-dependent dispersion angle of the grating. The prism refraction angle, which is nearly wavelength-independent, is chosen to redirect the center wavelength of the observed spectrum back onto the optical axis. For example, for a 600 lpmm grating and a center wavelength 550 nm, the grating dispersion angle is 19°. Commercially available stock wedge prisms\(^{11}\) range from 2° to 10° in 2° increments, so we chose to use two 10° prisms.

- **Transmission grating.** Stock transmission gratings range from 300 lines per millimeter (lpmm) to 1200 lpmm groove spacing, with larger values providing increased spectral resolution, but at lower efficiency. Also, higher resolution gratings require larger wedge prism refraction angles and larger sensor sizes. In order to cover a wave-
length range $\Delta \lambda$, a sensor located a distance $d$ from a grating with groove spacing $a = 1/lpmm$ must have a linear dimension $D_s$ at least,

$$D_s > \frac{\Delta \lambda}{a} d,$$

For the full visible wavelength range $\Delta \lambda = 300$ nm, $d \sim 50$ mm, and a 600 lpmm grating ($a = 1.67 \mu m$), the sensor size must be at least 9.4 mm.

- **Refocusing lens** The refocusing lens is a positive achromat, with a focal length approximately equal to the physical distance from the grating to the focal plane (sensor). For a two prism system, such as described here, the distance is somewhat smaller, since the second prism lies between the grating and the refocussing lens.

  We have found that both the collimating lens and refocussing lens focal lengths do not need to be exactly matched to the telescope focal ratio and sensor back-focus exactly, since a small change in telescope focus can compensate for the optical path difference.

- **Enclosure** The optical elements are housed in a plastic enclosure fabricated using a 3-d printer. Fig.2 shows the CGS in its enclosure, and installed in the filter wheel. For most commercial filter wheels, an enclosure extension is required to allow adequate clearance for the grism, as illustrated in Fig.3. This can be inexpensively printed using a 3-d printer.

**B. Wavelength and flux calibration**

An example of a raw dispersed spectrum recorded on the imaging camera is shown in Fig. 4. In order to obtain an astronomically useful spectrum, the raw image requires both CCD and spectral calibration. The CCD calibration, consisting of thermal and bias subtraction, and cosmic ray removal, is standard procedure for CCD imaging at most observatories and will not be discussed here. Note that a flat field correction, which is normally applied to images, is not needed for spectroscopic observations since the gain variations across the dispersed spectrum are corrected by gain calibration, as described below.

Spectral calibration has two components: Wavelength and flux calibration. The wavelength calibration is done in two steps. First, the target star is observed with a broadband
filter. Small pointing offsets are then applied to place the object exactly at the field center. This can be done either manually or by solving the for the center coordinates using an astrometric image solver (e.g., Pinpoint\textsuperscript{13}). After re-centering, the grism image is taken and major spectral features (e.g. Balmer sequence for an A-type star) are matched with corresponding pixel values. The wavelength-pixel data are fit with a low-order polynomial, and the corresponding coefficients stored in a configuration file.

The flux calibration, which corrects for wavelength-dependent efficiencies in the imaging sensor, transmission grating, and telescope optics, can be determined by comparing raw spectra with flux-calibrated spectra of standard stars taken a comparable spectral resolution and wavelength range. Fortunately, these are readily available in downloadable form\textsuperscript{14,15} and were used to calculate a table of gain coefficients for each spectral channel. Fig.5 shows an example of a raw spectrum and wavelength-flux calibrated spectrum.

III. SAMPLE CGS SPECTRA AND LAB PROJECTS

The grism spectrometer is installed at the Iowa Robotic Telescope\textsuperscript{16}, a 0.5m diameter f/6.3 Cassegrain reflector located at the Winer Observatory\textsuperscript{17}, about 80 km SE of Tucson AZ, and operated from campus at the University of Iowa in Iowa City. The imaging system consists of a 2048x2048 format 12\(\mu\) pixel back-illuminated CCD camera equipped and a 12-position filter wheel, of which one slot contains the CGS. This system is used by students and faculty at the University of Iowa for teaching and research. It is typically operated robotically using a queued observing list but can also be operated in realtime using a high-speed Internet connection.

A few examples of grism observing projects that have been done in undergraduate laboratories are shown below. They illustrate the range of astronomical objects that can be investigated spectroscopically.

- Fig.6 shows a sequence of four stellar spectra very hot to very cool stars, with surface temperatures ranging from 19,000\(^\circ\) K to 3,400\(^\circ\) K. The spectra illustrate how the Balmer series of hydrogen lines become dominant near spectral type A, then rapidly decrease for solar-type stars, with molecular metal band dominating the coolest stars.
• Fig. 7 shows the spectrum of an emission-line star, in which circumstellar gas is heated in the chromosphere or in a disk by rapid rotation. This hotter gas produces emission lines at longer wavelengths where the gas is optically thick, but at shorter wavelengths one see absorption lines arising from the cooler photosphere. This is a nice illustration of Kirchhoff’s laws.

• Fig. 8 show the spectrum of WR7, an extremely luminous \(280,000 \times L_{\text{sun}}\) star with a chemically-enriched high-speed wind whose emission lines dominate the spectrum. The line widths (\(\Delta \lambda \approx 2 \text{ nm}\)) are spectrally resolved, indicating wind speeds of several thousand km/s.

• Fig.9 shows the spectrum of two bright (\(V=14.4, 12.9\)) quasars whose red-shifts are readily obtained from the prominent H\(\alpha\) emission line that are displace from the rest wavelength of 656.3 nm. In addition to several other Balmer lines, both spectra also show prominent forbidden-line emission of doubly-ionized oxygen III \([\text{OIII}]\) arising from the narrowband region of the quasar.

IV. LIMITATIONS

The grism system described here is slitless, so that only point sources can be observed with good spectral resolution. In principle one could add a slit in front of the grism, but since it is in the converging light cone of the telescope, there would be substantial light loss from vignetting. Also, centering the target is critical for accurate wavelength calibration, particularly in the direction parallel to the dispersion axis. For example, with a 600 lpmn grating and a 3m telescope focal length, the wavelength displacement is about 0.5 nm per arcsecond. Finally, modification of some filter wheels to accommodate the grism height is more difficult with some cases than others. For example, some filter wheels have electronics boards that interfere with a simple housing extension modification, so users should carefully inspect their filter wheel design before deciding to incorporate it into a grism system.
V. ADAPTING THE CGS TO OTHER OBSERVATORIES

Details for design and construction of a compact grism system, including Winlens\textsuperscript{18} files for the optical design and OnShape\textsuperscript{19} files for the grism enclosure and housing extenders for several commercial filter wheels, can be found on the Iowa Robotic Telescope website. The Python scripts for calibration and display of CGS spectra are open-source and available on GitHub\textsuperscript{20} and include a user-friendly GUI interface (Fig.10).

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\* dominic-ludovici@uiowa.edu
\† robert-mutel@uiowa.edu


4 Rainbow Optics Star Spectroscope (http://www.starspectroscope.com/).

5 Rspec Star Analyzer (http://www.rspec-astro.com/star-analyser/).


Hubble Space Telescope WFC3 grism (http://www.stsci.edu/hst/wfc3-analysis/grism-obs/wfc3-grism-resources.html/).


Ross Optical (http://www.rossoptical.com).


DC3 Pinpoint (http://pinpoint.dc3.com/).


Winer Observatory (http://winer.org/).

Winlens (http://www.winlens.de/).

OnShape.com (http://www.onshape.com/).

FIG. 2. [top] Compact grism system, with 25 mm optical components, enclosed in a 3-d printed housing. [bottom] Compact grism installed in a 50mm diameter slot in a filter wheel. Note that the filter wheel housing has a 3-d printed wall extension with height 37 mm.
FIG. 3. Cross-sectional view of a filter wheel with the grism installed.

FIG. 4. Dispersed grism spectrum zero-order with stellar image at left. The image is focussed at the center of the dispersed spectrum so that the stellar image is strongly defocussed.
FIG. 5. (a) Uncalibrated spectrum of the B3V star HD158659. (b) Calibrated spectrum, (c) Gain curve applied to raw fluxes. (d) Calibrated spectrum of HD158659 from Jacoby et al. (1984).
FIG. 6. Grism spectra of stars from 380 nm to 750 nm, illustrating the spectral sequence from hot to cool stars: (a) B3V: 19,000° K, (b) A1V: 9,000° K, (c) F7V: 6,240° K, and (d) M5III: 3,400° K.
FIG. 7. CGS spectrum of the emission-line star HD76868 (B5e). Note the prominent chromospheric $H\alpha$ emission line, which arises from circumstellar material ejected by the rapid rotation of the star. The circumstellar gas is optically thick in the $H\alpha$ line, but with increasing frequency it becomes optically thin and the higher level Balmer lines are seen in absorption. The $H\beta$ line has both emission and absorption components. The width of the emission component is $\Delta \lambda \sim 0.9$ nm, indicating a spectral resolution $R \approx 300$. 
FIG. 8. CGS spectrum of the extremely luminous Wolf-Rayet star WR7 (HD56925) at the center of the emission nebula NGC2359. This star has an extended hot wind responsible for the broad emission lines of helium, carbon, and nitrogen.
FIG. 9. CGS spectra of two low-redshift quasars, each with prominent red-shifted Balmer emission lines, as well as a forbidden oxygen line. (a) 1E0754+394, \( V = 14.4, z = 0.096 \), (b) 3C273, \( V = 12.9, z = 0.158 \). Each exposure was 15 min.
FIG. 10. Graphical user interface to the CGS calibration and plotting program designed for ease of student use.