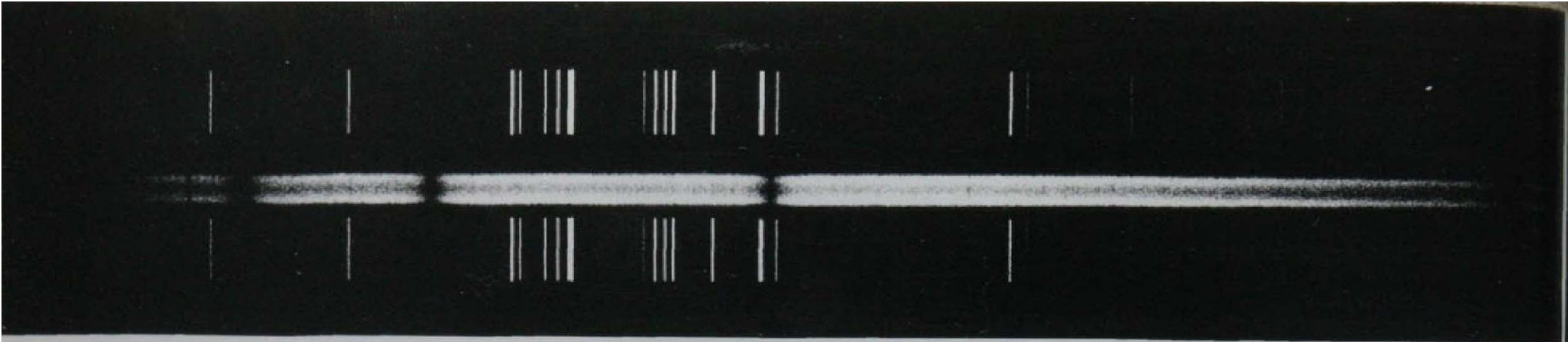

The Beloit College instrument obtained this spectrogram of 3rd-magnitude Theta Leonis, spectral type *A*2 V. It has strong absorption (dark) lines of the hydrogen Balmer series, their great width indicating that this is a main-sequence star. At the extreme right, in the blue-green region, is the Hβ line (wavelength 4861 angstroms), and the others leftward are Hγ (4340), Hδ (4101) and Hε (3970). Farthest left, in the deep violet, is the strong, narrow K line of ionized calcium (3933). Above and below the star spectrum are bright argon comparison lines, the first strong one from the right at 4510, the second from the left at 4044. To the left of the former line is the star's absorption line of ionized magnesium at 4481 angstroms. This grating spectrum has a uniform scale of one millimeter equals 5.17 angstroms, so wavelengths of other lines can be measured. The original three-minute exposure has a dispersion of 60 angstroms per millimeter.

A Grating Spectrograph for a College Observatory

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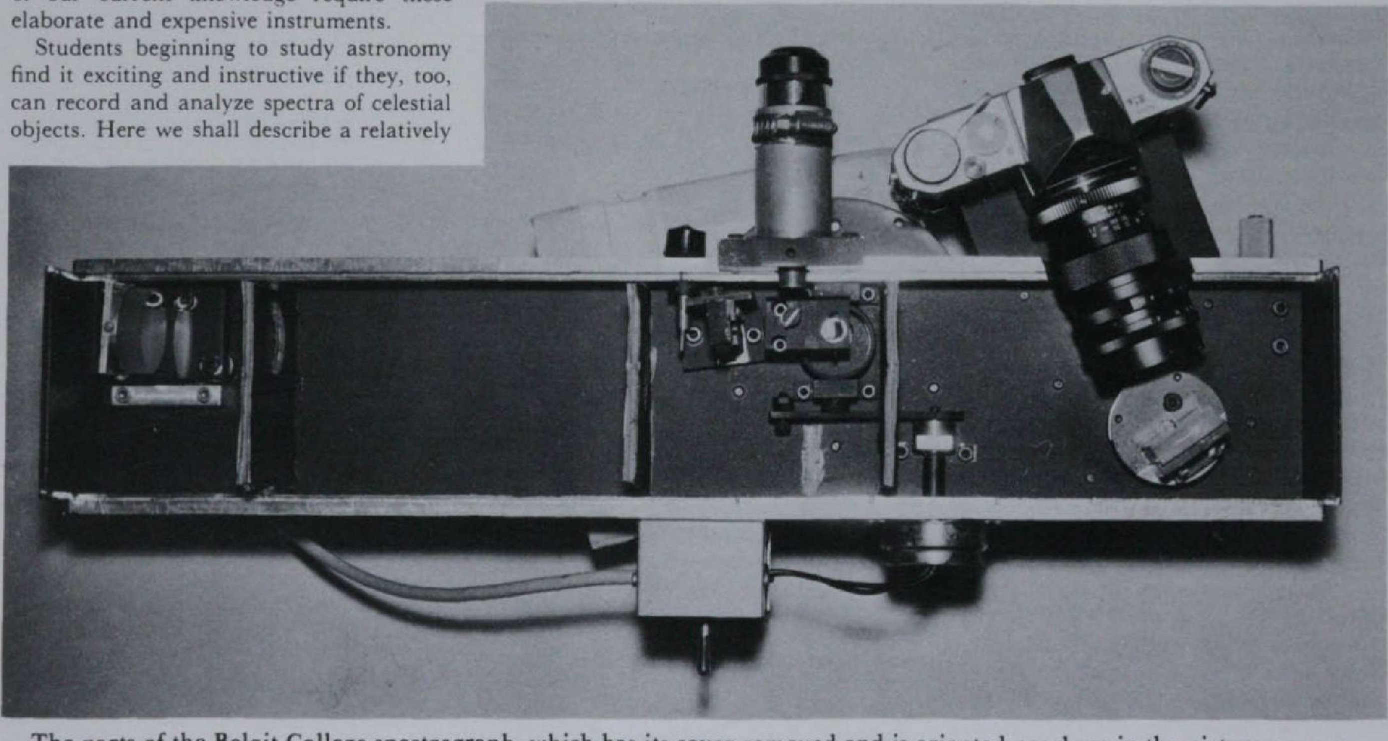
OVER A CENTURY AGO, spectroscopy was first applied to the analysis of light from celestial objects, and to this day the technique remains one of the most important tools of the professional astronomer. Much of what is known about the physics of stars, nebulae, and galaxies has been derived from light dispersed into its component wavelengths and recorded with spectrographs.

At observatories with large telescopes, spectrographs are often massive, complicated instruments that sometimes occupy entire rooms. Their detectors range from photographic plates to image-intensifier and television systems. Observations at the limit of our current knowledge require these elaborate and expensive instruments.

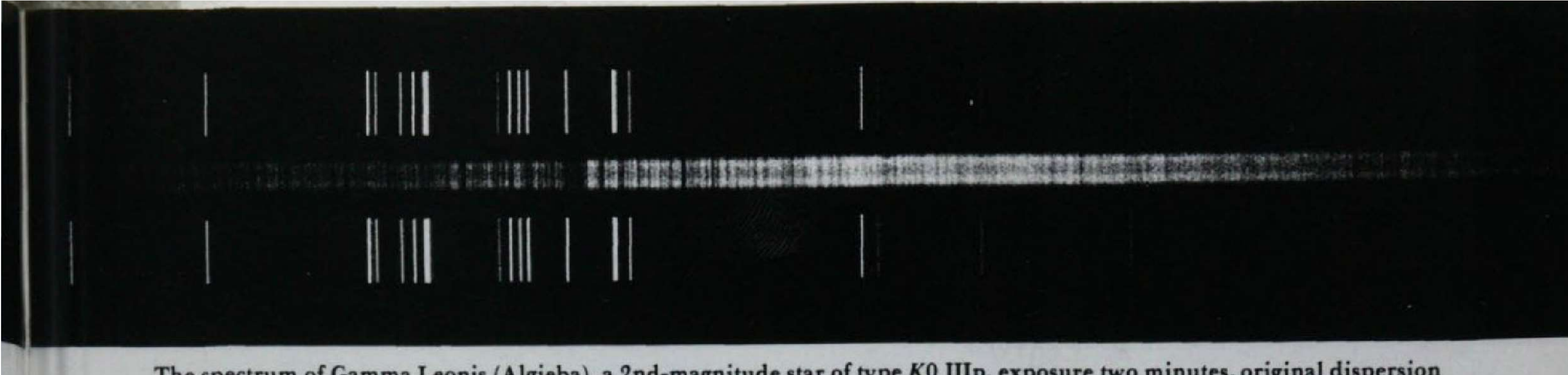
Students beginning to study astronomy find it exciting and instructive if they, too, can record and analyze spectra of celestial objects. Here we shall describe a relatively simple and inexpensive spectrograph suitable for student use with small observatory telescopes. Made in our physics department shop and mounted on the 22-inch Schmidt-Cassegrain telescope of the Thompson Observatory, the spectrograph has been used for a variety of observations by a number of students in our introductory classes. With a 35-mm. camera as the final element in the optical system, the spectrograph is simple to operate, and it can easily be mounted on a smaller telescope.

As the diagram shows, a small prism located about 45 millimeters inside the telescope focus deviates the light by 90 degrees. This has two main purposes: the body of the spectrograph is then perpendicular to the axis of a Cassegrain telescope, which makes mounting and balancing easier, and there is room to mount the camera in a convenient position. Placed just ahead of the prism in the light beam is a glass plate used for widening the spectrum in a manner to be described below.

The star image is focused in the plane of the fixed entrance slit (with light falling on the slit jaws being reflected into a slit viewer). The light passing through the slit is made parallel by a spherical collimator mirror of 250-mm. focal length. With our telescope providing an f/10 beam, we have a collimated beam diameter of 25 mm. This



The parts of the Beloit College spectrograph, which has its cover removed and is oriented nearly as in the picture on page 99, where it is seen attached to the 22-inch telescope. At left is the collimator mirror, in the center the entrance slit and guiding eyepiece, and at right the grating and camera. Three of four baffles are in place; made of corrugated cardboard covered with flock paper, they prevent the grating from "seeing" the entrance slit directly. At bottom are the switch box and motor for the rocking plate, which is at the location shown by the diagram on the facing page.



The spectrum of Gamma Leonis (Algieba), a 2nd-magnitude star of type *K*0 IIIp, exposure two minutes, original dispersion 60 angstroms per millimeter, just as for Theta Leonis opposite. The entrance slit width of 40 microns corresponds to 1.5 seconds of arc with the 22-inch telescope. All spectra with this article were recorded on Tri-X film and developed in Diafine. The exposure density is slightly greater at the top and bottom of each stellar strip because of the rocking-plate method of widening. With the aid of the argon comparison lines, the following dark features can be identified: at 4045 angstroms a neutral iron line; 4226, neutral calcium; 4300, the G band; 4383, neutral iron. Lines farther toward the red are shown in the smaller-scale spectrum on the next page.

mirror is tipped by the angle $c = 0.05$ radian (about 2.9 degrees), so that the return beam from the mirror just misses the entrance slit assembly.

The spectrograph's dispersing element is a high-quality plane reflection grating (600 grooves per mm.), which diffracts the light and directs it to the camera lens. The normal to the grating face, which measures 32 mm. on a side, is directed more toward the camera than to the collimator; in other words, the angle of incidence a at the grating is larger than the angle of diffraction b. This arrangement minimizes the aberrations of the collimator mirror and maximizes the spectral resolution that can be obtained, as detailed below.

To complete the optical system, we use a Pentax single-lens-reflex camera body and an f/3.5 Vivitar lens with a preset diaphragm and 135-mm. focal length; it is focused for infinity. The tripod mounting hole is used to attach the camera.

The angle of deviation at the grating in this design is larger than usually found in a spectrograph; for our instrument it measures about 65 degrees. This large angle permits placing the front of the camera lens quite close to the grating, thus minimizing possible vignetting of diffracted light of different wavelengths by the boundary of the lens aperture.

Lenses of different focal length can be used to provide different dispersions on the film, but unless the grating or entrance slit is changed, the spectral resolution will not be affected by choice of camera lens. The quality of the spectra obtained with this type of design depends on the details of the collimator and grating arrangement.

Matching the Parameters

Of particular importance are the tilt angle c of the collimator mirror, the focal ratio F of the beam reaching the collimator, and the anamorphic magnification (differing in perpendicular directions) of the grating. This final factor simply indicates the change in beam width of the light after reflection from the grating. The ratio of the incident beam width to the diffracted one is

$$r = \cos a / \cos b,$$

where a and b are the angles defined above. The importance of this factor is evident in the formulas below.

For any optical instrument, it is essential to have aberrations that are negligible at the resolution limit set by the detector. Important for a spectrograph are spherical aberration, coma, astigmatism, and field curvature. If we assume for the moment that the camera lens is free of aberrations, then field curvature is absent, since it depends only on the camera. The linear dimensions of the remaining aberrations in the camera focal plane are given by:

$$\text{Spher. Aber. blur circle} = fr/256F^3,$$
$$\text{Coma} = 3fcr/32F^2,$$
$$\text{Astigmatism} = fc^2r/F.$$

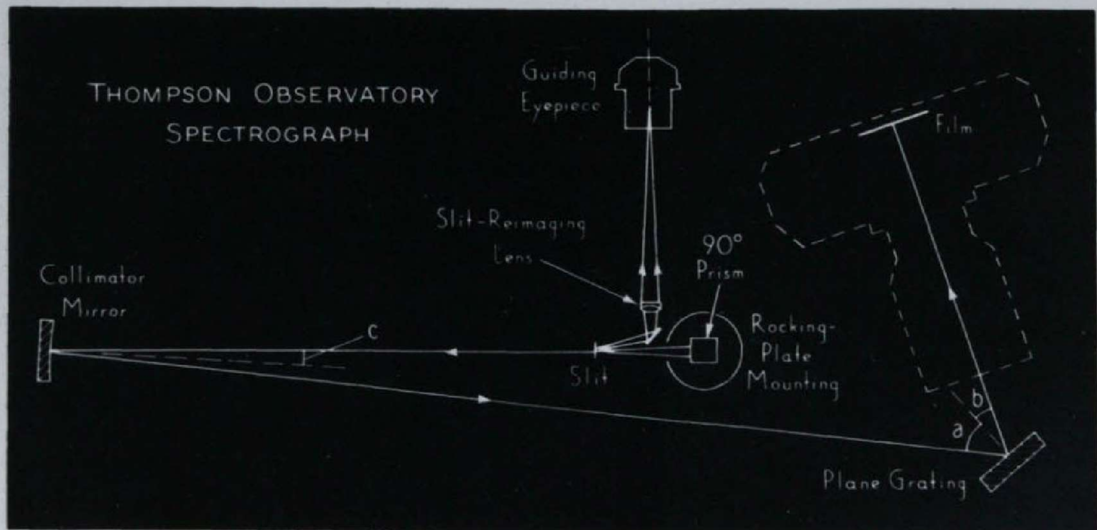
Here f is the camera focal length, r the beam-width ratio, c half the collimator-mirror deflection angle, and F the telescope focal ratio.

At $F = 10$ for our telescope, it is evident that spherical aberration is entirely negligible in this design. The expression for coma gives the dimension within which is concentrated something over 80 percent of the light at a single wavelength from a slit of negligible width. The relation for astigmatism gives the length of the tangential astigmatic image (perpendicular to the direction of the grating dispersion).

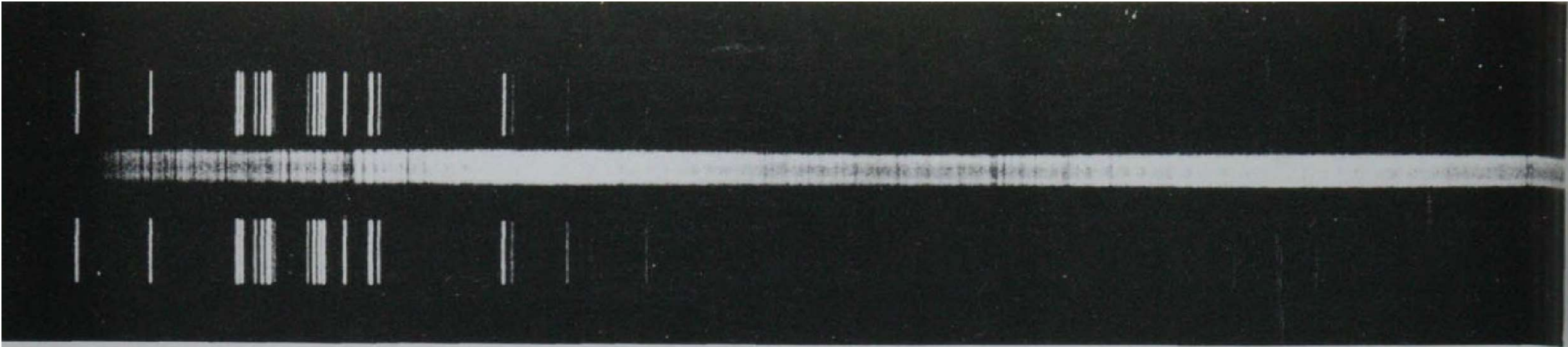
It is clear from these relations that we want to make angle c as small as possible, and that a grating orientation that makes r less than one is to be preferred. With our arrangement, $c = 0.05$, and $r = 0.83$ when a grating with 600 grooves per millimeter is used in the first order and set to place the wavelength of 4200 angstroms at the center of the camera field.

Using these numbers for our spectrograph (with $f = 135$ mm.), we find coma is 5 microns (0.005 mm.) and astigmatism is 28 microns. The former is well within the limit set by our detector, which is fast photographic film, while the latter is negligible compared to the width of a trailed spectrum.

The spectral resolution depends on the entrance slit width w, its projected width w', and the plate factor P, which is the dispersion or number of angstroms per millimeter



These optical parts of the spectrograph may be seen in the picture opposite. Light from the telescope enters perpendicularly to the plane of the paper, passes through the rocking plate, and is deflected to the entrance slit by the 90° prism. The collimator mirror is tipped at an angle *c*, while the grating's angle of incidence is *a*, its angle of diffraction *b*.



Another spectrum of Gamma Leonis, a one-minute exposure at a dispersion of 120 angstroms per millimeter (here enlarged 12 times). Since this is a cool star, its spectrum is stronger toward the red than is that of Theta Leonis. At extreme right is the doublet of neutral sodium (5890-96 angstroms) in the yellow-orange. Other features are mentioned on the preceding page, but the abundance of the lines of metals makes identification of individual lines more difficult.

at the focal plane. The relations are:

$w' = wrf/f_1$

$P = d \cos b/mf.$

The expression f/f_1 is the focal length of the camera divided by that of the collimator; d is the groove spacing on the grating and m is the grating order number.

The product Pw' gives the smallest wavelength difference that can just be resolved. For our spectrograph, $w = 40$ microns, $w' = 18$ microns, $d = 1/600$ mm. When $m = 1$ (first order), $P = 120$ angstroms per millimeter and $Pw' = 2.2$ angstroms. When $m = 2$, the numbers are 60 angstroms per millimeter and 1.1 angstroms, respectively.

Actual measurements of our spectra indicate close agreement with the calculations. We find w' in the range of 18-20 microns for a number of spectral lines across some 15 mm. of film. From our results we conclude that the camera lens itself makes a negligible contribution to the aberrations.

Auxiliary Parts

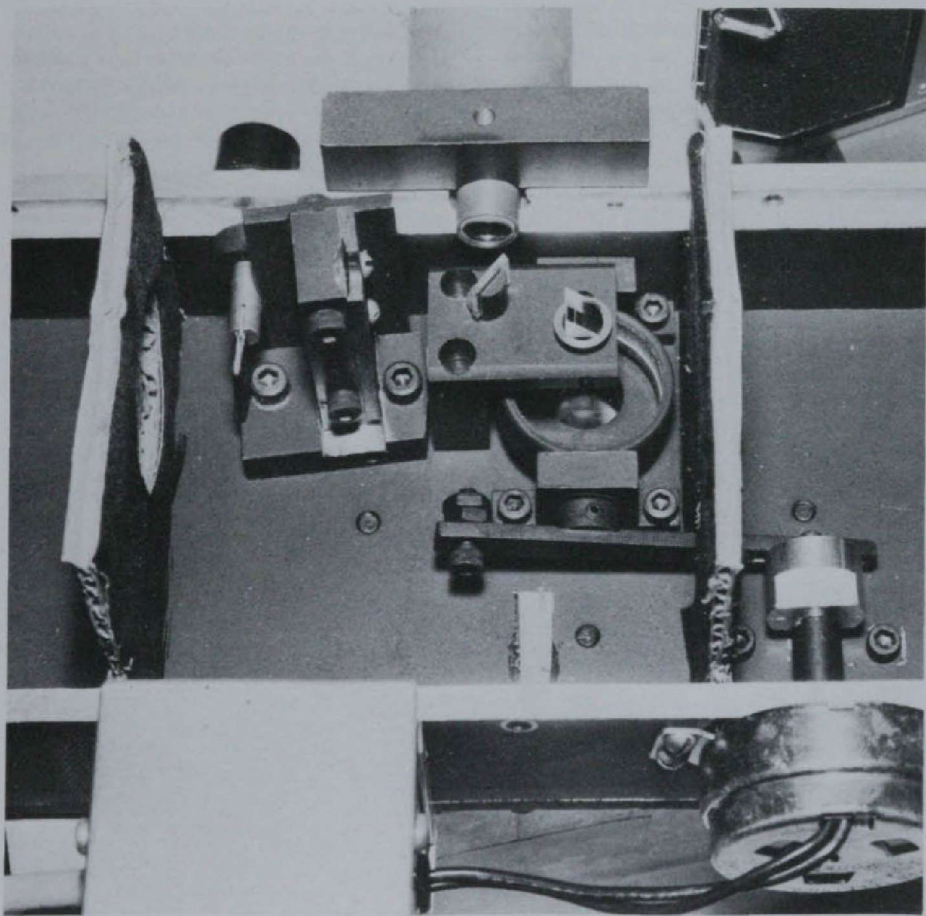
Simple and efficient operation of the spectrograph requires careful attention to a number of auxiliary components. Those we have found to be essential and have incorporated into our instrument are a slit viewer, rocking plate for widening stellar spectra, light source for a comparison spectrum, and slit shutter. A desirable but not essential feature is a grating mount that allows for quick interchange of gratings.

Slit Viewer. A properly exposed spectrum requires that the stellar image remain centered on the slit during the exposure. After trying a razor-blade slit, which proved unsatisfactory for guiding, we installed an aluminized glass plate with a 40-micron strip of aluminum removed down the center (from Deerfield Optics, Framingham, Mass. 01701). The plate is rotated by about six degrees around the slit length so that light which does not pass through the slit is reflected to a mirror placed next to the input beam of the telescope. Then the reimaging lens (Edmund Scientific No. 30,639, 25-mm. focus) forms a magnified image of the slit at the focus of the eyepiece, which is a standard 1¼-inch with a focal length of 18 mm. The net magnification is about 600, and with this system it is easy to keep the image properly set on the slit.

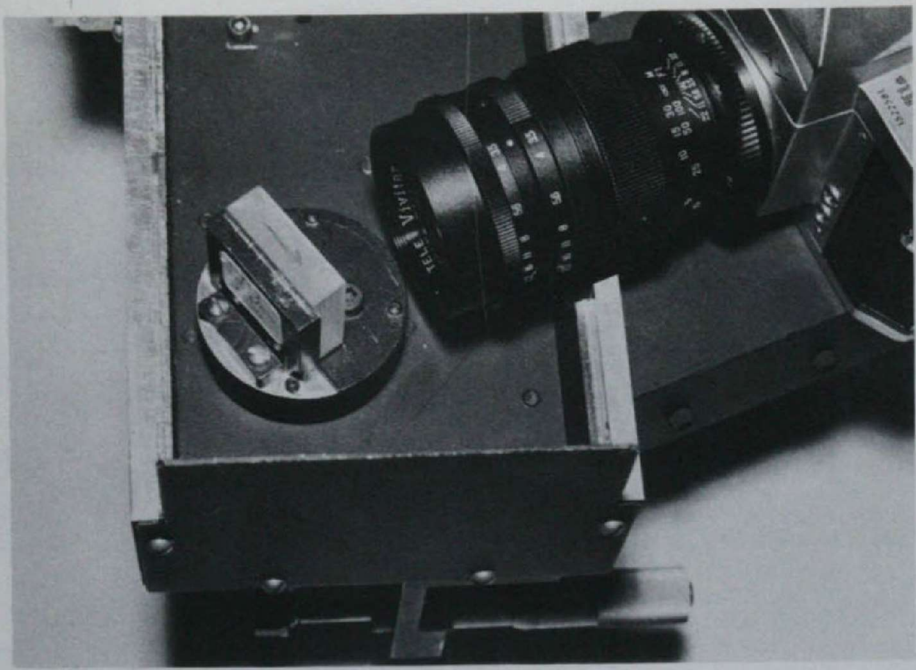
Rocking Plate. To widen the spectrum of each star, we use a 10-mm.-thick glass plate (Jaeger's No. 18E3181). From its position normal to the light beam, this plate is rocked through an angle $\pm p$ by a small 6-r.p.m. clock motor (Edmund No. 41,385). For a plate of thickness t, the widening on the film is approximately $(2tp/3) \times (f/f_1)$. In our case p is about five degrees and the widening about 300 microns. The motor is controlled by a switch on the side of the spectrograph body.

Comparison Spectrum Source. For quantitative measurements, a comparison spectrum is placed on both sides of the stellar spectrum. Our pencil-sized argon lamp (Oriel Corp., Stamford, Conn. 06902) is small enough to slide into position in front of the entrance slit whenever it is needed. For our purposes it has a sufficient number of lines in the blue, and with exposure times of one to three seconds the operation of the lamp is simple.

Attached loosely to the lamp shield is a 15-mil-thick piece of feeler-gauge strip with drilled holes that define the open portion of the entrance slit. This strip is guided by a slot just in front of the slit. When the stellar spectrum is taken, the lamp is pulled out and a single hole about 2.5 mm. in diameter is in place. When the lamp is pushed in, its light can pass through two holes, 1.5 mm. in diameter and spaced about 3 mm. on center. The result is that the comparison spectrum



At left in this center-section view is the entrance slit mounting, with its tilt to the light beam from the 90° prism clearly shown. The prism is supported by an L-shaped bracket that extends over the rocking plate, which can be seen inside its large circular housing. The latter is supported by two small ball bearings, the lower one being attached to the rocker arm that is actuated by the motor at lower right. At top center are the slit-viewer mirror and reimaging lens of the guider assembly. All photographs with this article are from Beloit College.



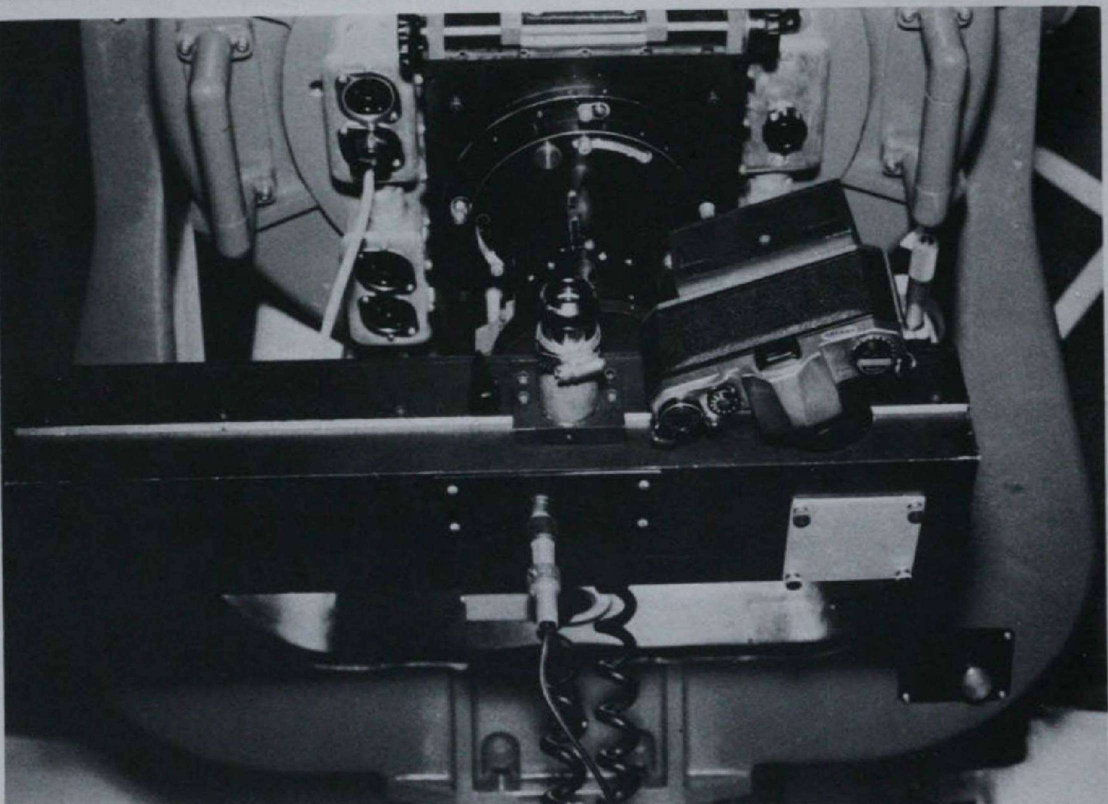
green one, the razor blade serves as a knife-edge for the standard Foucault test — the collimator is moved back and forth until the entrance-slit image coincides with the film plane.

Construction. All of the principal spectrograph parts were made from aluminum. The main plate, which carries all the optical components, is ⅜ by 4½ by 21½ inches. Side plates provide stiffness and support the slit-viewer eyepiece, motor, and mounting flange. The cover was made from a scrap section of ⅛-inch-wall rectangular tubing. The entire spectrograph weighs 7.1 kilograms (15.5 pounds), with the structural plates accounting for about two-fifths of the total. With our typical exposure, 10 minutes or less, we have seen no evidence of flexure.

The two available dispersions (from two gratings) permit a variety of student projects. At 120 angstroms per millimeter, the results are suitable for spectral classification by comparison with standard spectra. One interesting project is to have students take a set of spectrograms of a Cepheid variable to see directly how its spectrum changes with time. At 60 angstroms per millimeter, the dispersion is high enough for beginning students to measure Doppler effects due to radial velocity (motion along the line of sight). Short-period spectroscopic and eclipsing binary systems can be studied at this dispersion.

With this instrument we have made it easy for students to obtain high-quality spectra of celestial objects, and only a short time is needed for the beginner to achieve proficiency. Taking such spectra on his own gives a student greater appreciation of the problems faced by professional astronomers and of the results obtained by them.

Above: The setscrews of the grating's kinematic mount are at the corners of a right triangle. At bottom in the picture is the control micrometer for the grating table arm. A shaft with preloaded ball bearings supports the table. The rotation axis lies in the grating's reflecting face.



Right: The spectrograph operates at the Cassegrain focus of the fork-mounted 22-inch telescope. On the spectrograph's upper side are, left to right, the manual shutter knob, the guiding eyepiece, camera, and micrometer for setting the angle of the grating. The comparison light source and access plate to the grating are on the near side.

brackets the stellar spectrum, as the photographs of typical spectra show.

Manual Shutter. After the star image has been set on the slit entrance, the manual shutter behind it is opened. Then the camera shutter is also opened, to make the stellar exposure. When it is concluded, the manual shutter is closed and the comparison lamp is pushed into position. The manual shutter is reopened while the lamp is turned on briefly. Finally, the camera shutter is closed, the lamp is pulled out, the film is advanced, and all is ready for the next exposure.

Grating Support. As already noted, we have two gratings, each held in its own support with contact cement. The support, in turn, is held to a rotatable table with one spring-loaded screw. The grating's actual position is determined by three adjustable setscrews in a kinematic mount. After each support has been adjusted independently, the two can be interchanged without further adjustment.

Aligning and Focusing. The collimator is also held in a kinematic mount, which can be moved toward or away from the entrance slit for focusing. Initial optical alignment is most easily done by using a laser to define the optical axis of the system. The camera lens is set at infinity, the camera back is removed, and a razor blade is placed across the ways that define the film plane. With a strong spectral line, such as the mercury