THE SPECTROGRAPHS OF THE DOMINION ASTROPHYSICAL OBSERVATORY*

By E. H. Richardson

History and Summary

The coudé spectrograph of the 48-inch telescope bears the name of Dr. Andrew A. McKellar (1910–1960). Dr. McKellar lived to see the completion of his unique horizontal coudé spectrograph room and the ordering of the optics of the two spectrograph Schmidt cameras of 32-inch and 96-inch focal lengths.

The entire floor of the spectrograph room is, in effect, a concrete

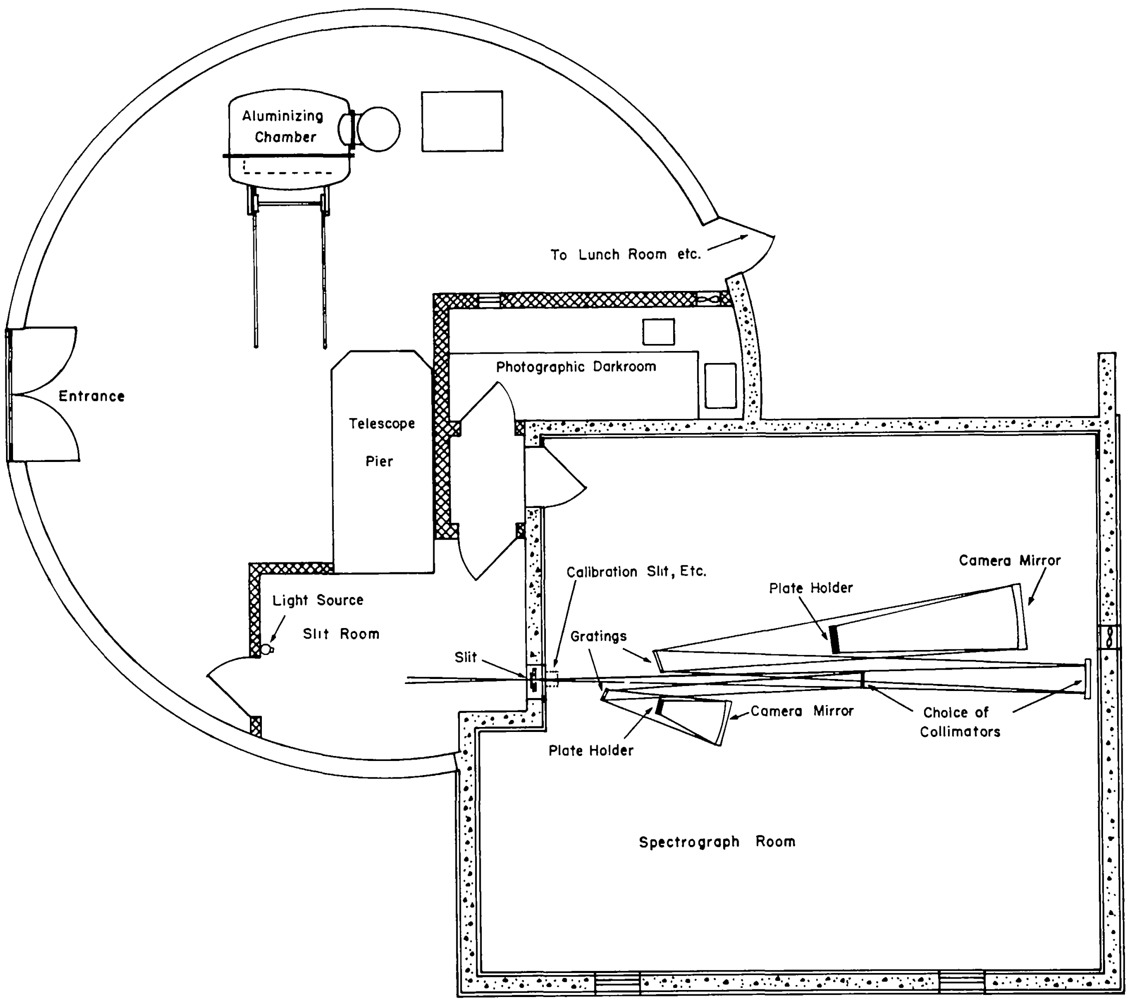

Fig. 1—Floor plan of the dome and coudé room of the 48-inch telescope.

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optical plate isolated from the walls. This horizontal arrangement facilitates access to the components of the spectrographs and makes possible simplicity in the mechanical mountings, and versatility in making changes and additions to the spectrographs.

The first stellar spectrogram was obtained on March 7, 1962, by R. M. Petrie. Since then, the collimator mirror has been replaced by a number of larger mirrors with aspheric (approximately hyperboloidal) surfaces in order to eliminate the twice-through Schmidt corrector plates of the 32-inch camera and to illuminate the entire surface of the rectangular gratings so that the most efficient use can be made of image slicers. A mosaic grating was put into operation with the 96-inch camera in December 1967. Later, a scanner was installed at the focus of this camera. A Carnegie image intensifier was located at the focus of the 32-inch camera. The layout of the spectrographs is shown in figure 1. Marginal rays are shown starting at the centre of the slit room at the fifth reflection of the telescope mirror system leading to the coudé focus. The 4000th spectrogram was obtained in September 1968.

Since 1917, more than 65,600 spectrograms have been obtained at the Cassegrain focus of the 72-inch telescope. Twenty years ago, a large (six-foot) optical plate was installed at this focus: it prevents flexure within the spectrograph and facilitates changes in the configurations and types of spectrographs. In 1967, an all-reflecting, off-axis, plane grating spectrograph was installed on the optical plate, and a low resolution scanner with an off-set guider was located under the mirror cell.

The characteristics of the spectrographs are given in Table I.

The Collimators

Each of the spectrographs now in operation uses a spherical mirror as the camera. The correction of the spherical aberration of these cameras by the appropriate figuring of the collimator mirrors is very satisfactory at moderate (about f/5) focal ratios of the cameras. However, for cameras of smaller focal ratios the correction should be carried out as close to the camera mirror as possible, that is, near the centre of curvature of the camera, and Schmidt plates or figured gratings would have to be used.

If the angle of incidence onto the grating, α, is not equal to the angle of diffraction, β, then the correction required at the collimator in the direction of dispersion (horizontal) differs from that required in the vertical direction by the factor $(\cos\beta/\cos\alpha)^2$. This factor arises because, firstly, the width of the collimated beam is changed on diffraction at the grating by $\cos\beta/\cos\alpha$, thus changing the effective focal ratio of the camera. Secondly, in the direction of dispersion, a small change in α must be multiplied by cos β/cos α to give the corresponding change in β. In principle, a collimator which is not a surface of revolution would be required to accommodate this factor because it is always unity in the direction perpendicular to the dispersion but differs from unity, in general, in the direction of dispersion. In practice, our collimators are figured as surfaces of revolution.

In the coudé spectrograph, the collimators take into account this cosine factor. Thus, the tips of the spectral lines are over, or under, corrected for spherical aberration depending on the grating used: for the 1200 grooves/mm, 400 grooves/mm and 300 grooves/mm gratings, α is greater than β and the factor is greater than unity; for the 830 grooves/mm and 600 grooves/mm gratings, α is less than β. The blur of the tips of the lines is not noticeable.

On the other hand, the collimator of the Cassegrain spectrograph of the 72-inch telescope is figured as though the cosine factor were unity (which is not the case in the direction of dispersion). That is, it is figured to favour the tips of the lines rather than the edges. This gives the best results because the collimator mirror is actually an off-axis portion of a larger mirror and, as the spectrograph is arranged, the centre of this larger mirror would be displaced perpendicularly to the direction of dispersion. Therefore, figuring this mirror as if the cosine factor were unity gives the best fit to the theoretically required surface.

Some physical and optical parameters of the collimators are listed in Table II.

The Coudé Spectrograph of the 48-inch Telescope

Slit room. Near the centre of this room the converging light beam emerging from the hollow polar axis of the telescope is reflected into the horizontal direction by the last (fifth) of the mirrors in the coudé system. This mirror is 5 inches in diameter and is set 48 inches above the floor. At this point, the beam is 2.6 inches in diameter. The side of this mirror is visible at the extreme right in figure 2. Also, the two viewing telescopes, one for the ordinary slit and, at the extreme left, one for the image slicers are visible. The slit is hidden but the micrometer that controls its width can be seen above the right end of the image slicer viewer. The telescope pointing up at 60 degrees is the present coudé finder. The electronics of the integrating exposure meter are seen at the right. The photomultiplier feeding this meter is positioned just inside the spectrograph and is illuminated by light reflected from the stellar beam by a fused silica diagonal window (at the lower centre of figure 7). In addition to its normal use as an exposure meter, this apparatus is used to

TABLE I

CHARACTERISTICS OF THE SPECTROGRAPHS

Configuration[1]	Typical $\frac{\cos\beta}{\cos\alpha}$	Region[2]	Dispersion (A/mm)	Approx. Exposure Times[3] (minutes)	Width of Spectrum (mm)	Projected Slit Width[4] (microns)	Width of Fe Line[5] (microns)
48-inch Coudé							
9682 IS	1.06	UV-G	2.4	120(60)	1.2	16	23–30
9681		R-IR	4.8				
32121 IS	1.08	UV-R	10.1	10(5)	0.6	17	17–24
32122		UV	4.9			17	
3282 IS	0.89	UV-G	6.5	14(7)	”	20	20–26
3281	0.91	R-IR	13.1			20	
3261	0.89	IR	17.9		”	20	
3262	0.89	Y	9.0			20	
3241	1.08	IR	30.5		”	17	
3242	1.08	Y-IR	15.2			17	
3231	1.02	UV-R	40.9		”	18	
72-inch Cassegrain							
21121	1.06	UV-R	15.3	3(1)	0.33	22	24–29
2161	1.03	UV-R	31.1		”	22	
2141	1.05	IR	46.1		”	22	
2142	1.05	Y-IR	23.1			22	
2131	1.02	UV-R	62.4	0.7(0.4)[6]	”	22	
21$\frac{3}{2}$1	1.01	UV-R	124.8		”	23	

[1]Code: focal length of camera in inches; hundreds of grooves per mm of grating; order of diffraction IS = image slicer.

[2]All of a given region is not necessarily covered at the same setting of the grating.

[3]For stars of 5th B magnitude at the zenith with seeing of about 3 sec of arc, using IIa-O emulsion developed in D-76M; (we are now switching to the new Mount Wilson developer, MWP-2, which is faster and which eliminates the Eberhard effect). Exceptionally short exposure times are given in parentheses.

[4]Equals slit width multiplied by $\frac{\text{camera focal length}}{\text{Collimator focal length}} \times \frac{\cos a}{\cos b}$

[5]The range of measurements is given. Using a projection comparator, the full visible widths of dark-grey comparison lines were measured. Also, from microphotometer traces, the width at half intensity were measured for comparison lines whose central transmissions were about 0.5. The profiles of 9682 lines are more sloping than usual because two of the gratings form sharper lines than the other two.

[6]On a number of occasions the exposure time was 0.1 minute on Ia-O emulsion with 38-micron projected slit width (an 11.8 magnitude star in one hour).

TABLE II

THE COLLIMATORS

Location	Diameter (inches)	Focal Length			Slit Off-Axis (degrees)	Angle of Camera Axis ($\alpha-\beta$ central)	Camera Focal Length	Typical $\frac{\cos\beta}{\cos\alpha}$	Beam Size at Collimator	
		Centre	At r[1] (inches)	r					With IS (inches)	Without IS (inches)
48-inch Coudé	10	177	180.25	4.35	1.4	16.5	32	1.08	6×7	5.9 diam.
	10	177	178.5	4.35	1.4	16.5	32	0.89	6×7	5.9 diam.
	17	298	299.08	8	1.3	9.25	96	1.07	12×12	12 diam.
72-inch Cassegrain	12[2]	68.33	70.70	6	0	11	21	—	—	4 diam.

IS = image slicer.
[1]The focal length of the zone of radius r.
[2]The mirror is 4 inches by 4 inches; its centre is 4 inches from the centre of the original 12-inch mirror from which it is cut.

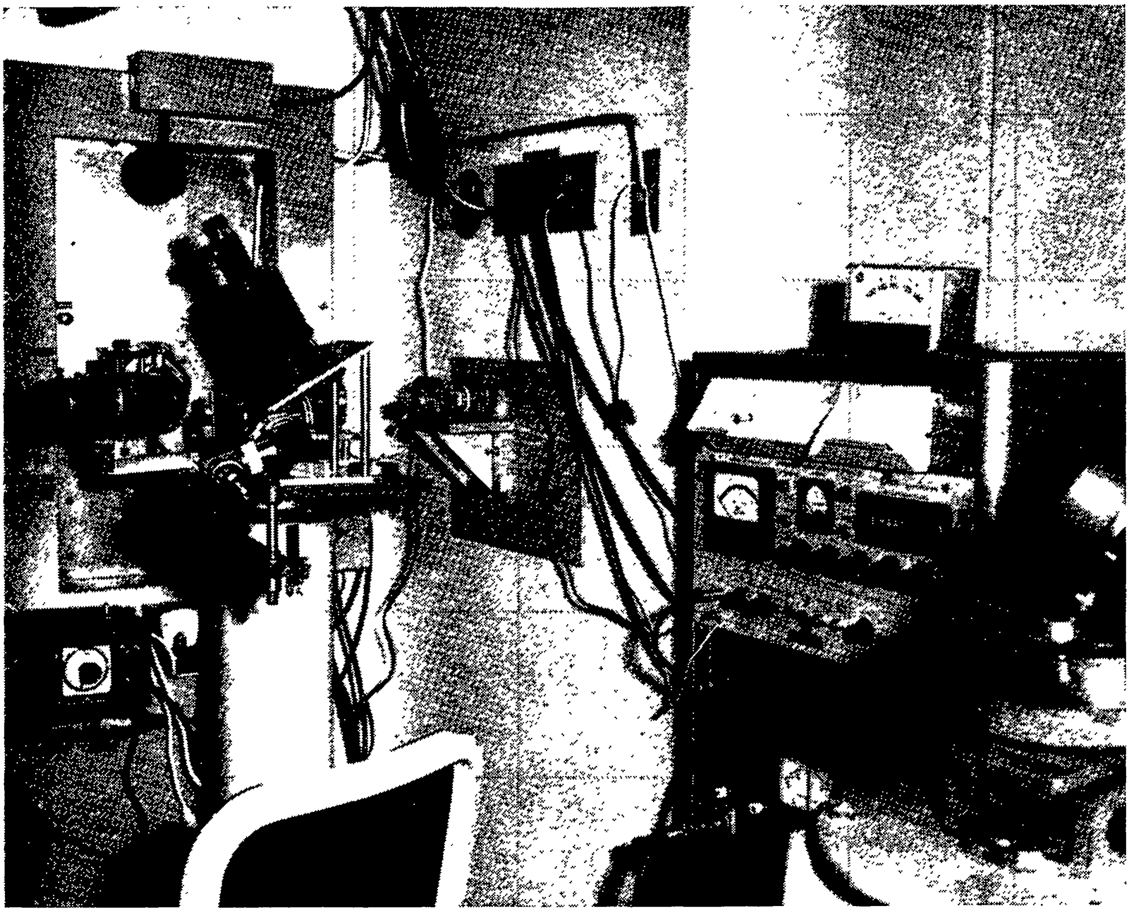

FIG. 2—The slit room between the fifth coudé mirror and the slit.

aid guiding with the image slicers: the continuous (un-integrated) flux is monitored and the position of the stellar image (which has mostly disappeared into the entrance slot of the image slicer) is adjusted to give a maximum reading. The observer can see a special meter in the coudé image slicer viewer as though it were adjacent to the entrance slot.

A closer view of the slit area is shown in figure 3. An image slicer, which incorporates a slit, is in place. The diffusing lens, on a plate hinged to the image slicer casing near the entrance lens of the image slicer, is turned over the entrance lens when the light from the iron comparison source is applied. This hollow-cathode source is mounted on the wall at the right edge of the picture, and the light is directed onto the optical axis through the "comparison lens" and the diagonal "comparison mirror" (thus, cutting off the starlight). The image-slicer viewer is in the centre foreground. The image slicer can be exchanged for the ordinary slit in about one minute. In this case, the hollow-cathode source mounted on the slit plate (at centre left) can be used to provide the iron light, without interrupting the stellar exposure, in the usual way through comparison prisms (extreme left) which are turned over the slit. By means of condensing lenses,

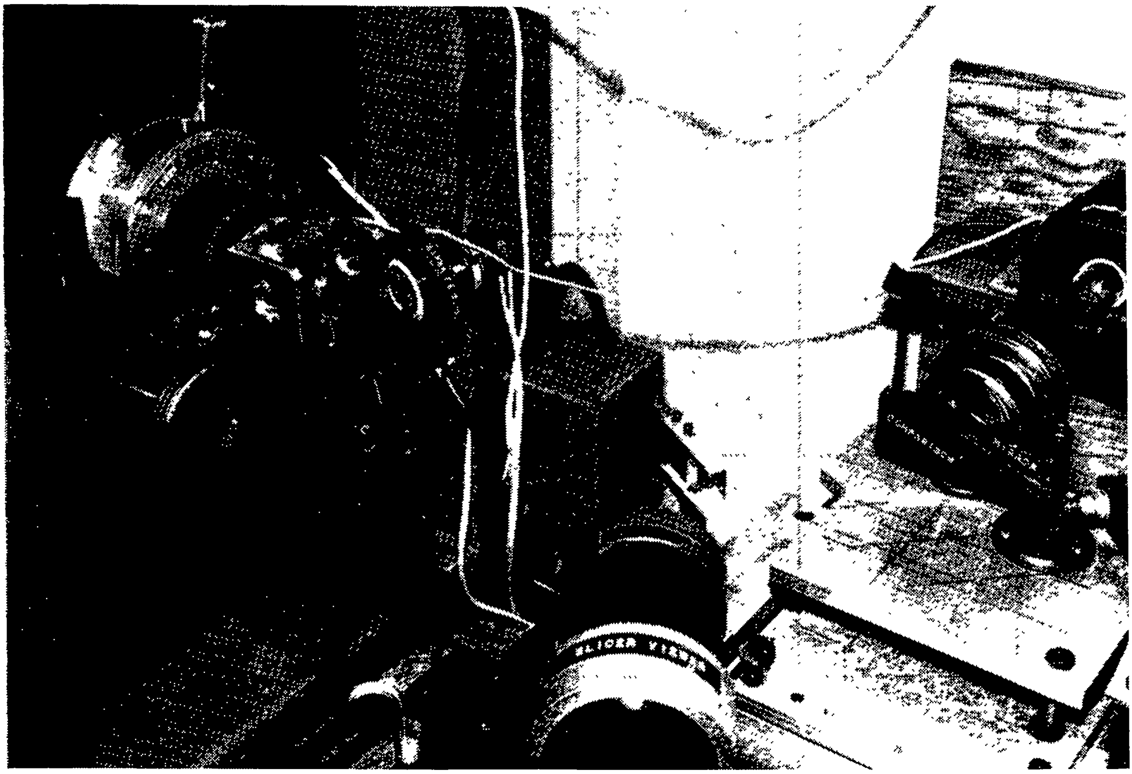

FIG. 3—The slit room in the vicinity of the slit.

the hollow-cathode exposure times are kept short—from 0.25 to 2.0 minutes. The timer triggers the starting of the lamps by means of a Tesla coil. The large knob at the left operates a Hartmann mask (to the right in figure 7) during focus tests.

96-inch focal-length camera. The mosaic grating of the 96-inch spectrograph is composed of four 6-inch by 7-inch gratings with 830.77 grooves/mm, blazed for the second order blue, giving 2.5 A/mm. In our standard code, this combination is referred to as 9682; the numbers refer to the focal length of the camera in inches, the number of hundreds of grooves/mm and the order of diffraction.

In figure 4, the alignment of the mosaic grating is being checked by Mr. Murray Fletcher. The plateholder mounting posts are in the right foreground. For testing, the image of a mercury line at the focus of the 96-inch camera is re-imaged by the lens in the right foreground and viewed through the periscope at high magnification. The periscope remains in place at all times because it lies within the "shadow" of the plateholder, but the lens is removed when the spectrograph is in use.

To the left of the mosaic grating (and to the right of the single grating of the 32-inch camera) is a disk of masks which permits the illumination of individual gratings and various combinations of gratings to facilitate

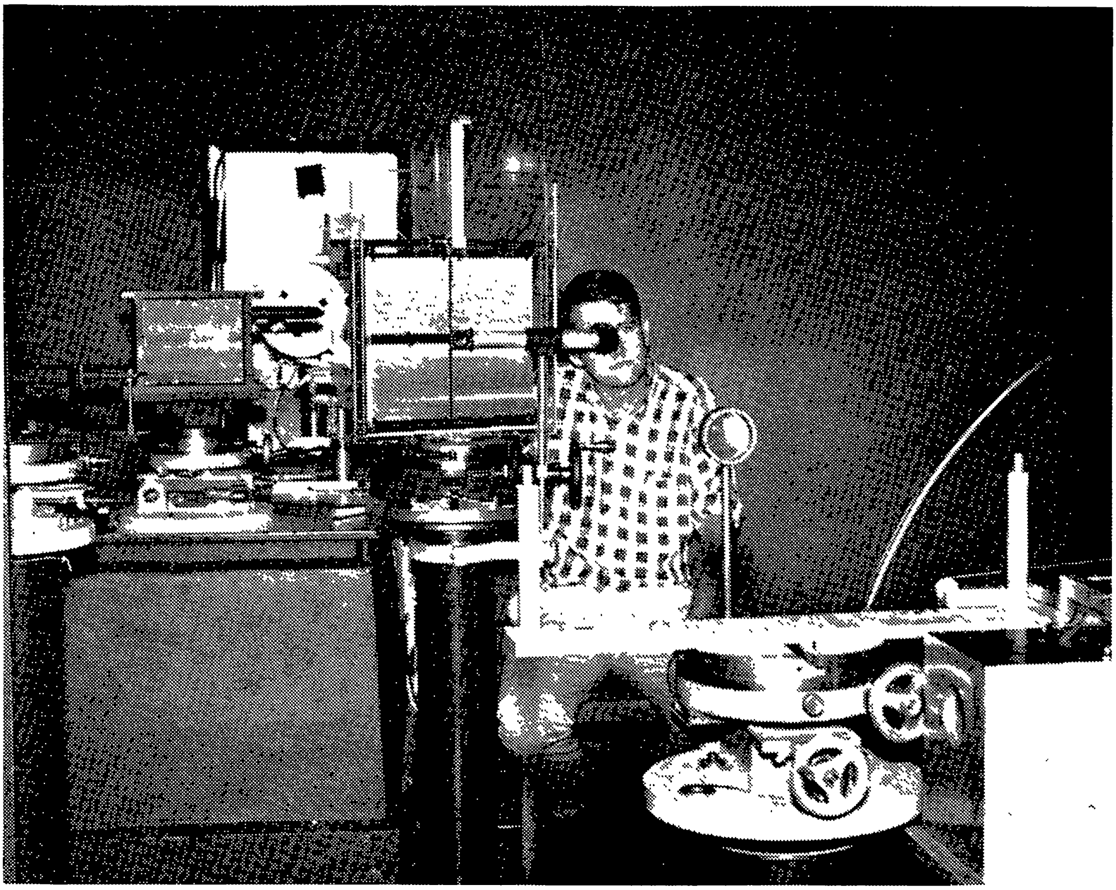

FIG. 4—The mosaic grating under test.

the alignment of the mosaic. This mask is 18 inches from the slit and the horizontal, diverging beam from the slit passes through the lower opening. The disk can be turned out of the beam.

The 96-inch focal-length camera mirror, which is 36 inches in diameter, is to the upper left of figure 5, and its collimator is to the immediate right in the background. The plateholder, in the centre foreground, will accommodate a 2-inch by 16-inch plate which, of course, is curved to a 96-inch radius. In practice, two 2-inch by 8-inch plates are used. Only 11 inches of the plate receives light from the full 12-inch beam because of the limited diameter of the camera mirror. A camera mirror of about twice the diameter, and a plateholder about 50 per cent longer would give a wave-length coverage comparable to that achieved with the other spectrographs. The resolution achieved with the mosaic equals that achieved previously using a single grating with the 96-inch camera.

The focal ratio of the camera, having a 96-inch focal length and a 12-inch by 15-inch grating, is f/7 horizontally and f/5 on the diagonal. However, the gratings are not in phase and the spectrum consists of four f/14 spectra precisely superimposed. The mounting, in which fine adjustment

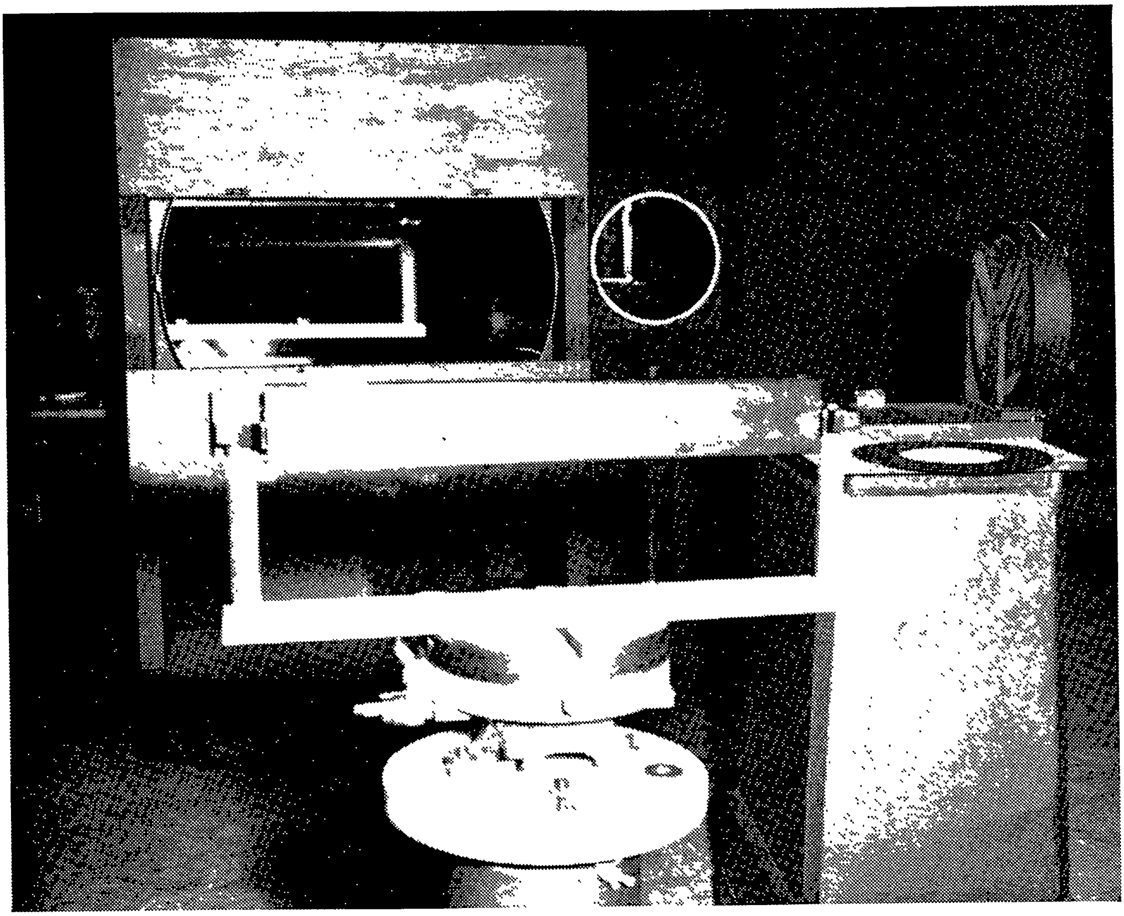

FIG. 5—The 96-inch camera mirror and the collimators.

is made by bending it under pressure exerted by leaf springs, is based on the design of the mosaic mounting in use for many years at the Mount Palomar observatory.

One of the four gratings has a slightly different dispersion from the other three, but the difference is imperceptible over the range of the plate. However, a major change in rotation of the grating would require a change in alignment of the mosaic.

In addition, each of these four plane gratings has a slightly different "focal length". This range of focal lengths was substantially reduced by the deliberate introduction of coma, achieved by displacing the centre of curvature of the camera mirror 1.5 inches to the left (as seen in figure 4) of the centre of the grating. This coma increases the focal length of the left pair and decreases the focal length of the right pair.

32-inch focal-length camera. Five gratings are available for use with this camera. As already mentioned, two of the gratings are operated with α smaller than β and three with α greater than β, so two collimators with different asphericities are required if good resolution is to be obtained with all five. The back of one of these collimators is seen at the right of figure 5. It can be rotated into the light beam. The other collimator (not shown) must be lifted onto the pier where it may be dowelled into place. With the image slicer, the focal ratio of the 32-inch camera is f/4.3 horizontally, f/5.3 vertically, and f/3.8 on the diagonal. The camera mirror is 24 inches in diameter, which is adequate to illuminate the full length of the 1-inch by 9-inch plate with the full beam.

In figure 4, part of the plateholder of the 32-inch camera can be seen at the left, a little over half-way up. The edge of the camera mounting forms the edge of the picture. An image intensifier can also be used with this camera, but is not visible in the picture.

Calibration system. The step-calibration is exposed during the stellar exposures. Light from the source (figure 1 and figure 6) in the slit room passes through the slit plate near the top and through a +1/4 diopter lens (figure 2) into the spectrograph room where it is reflected downwards (figure 7, at the top) through a rotating sector and a wide slit whereupon it is reflected back to the horizontal and to the collimator of the spectro-

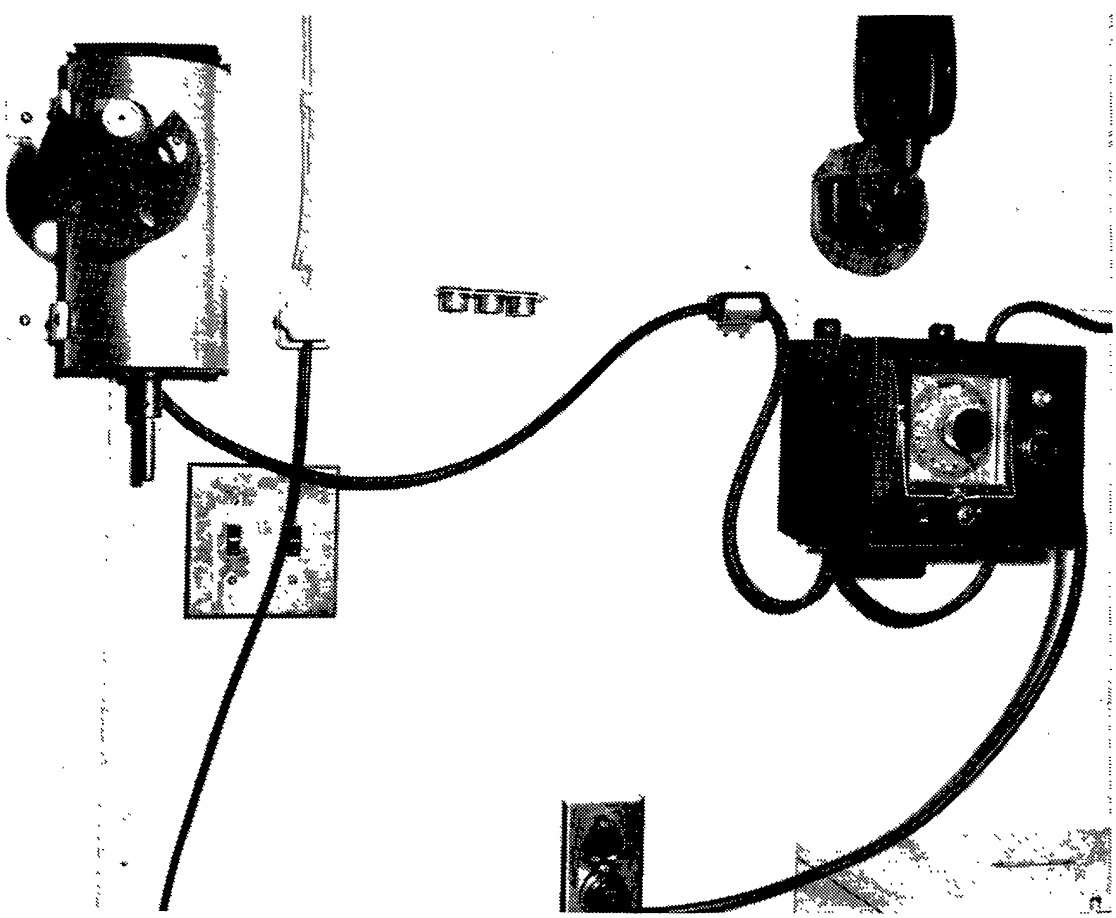

FIG. 6—The light source of the calibrator, located near the entrance to the slit room.

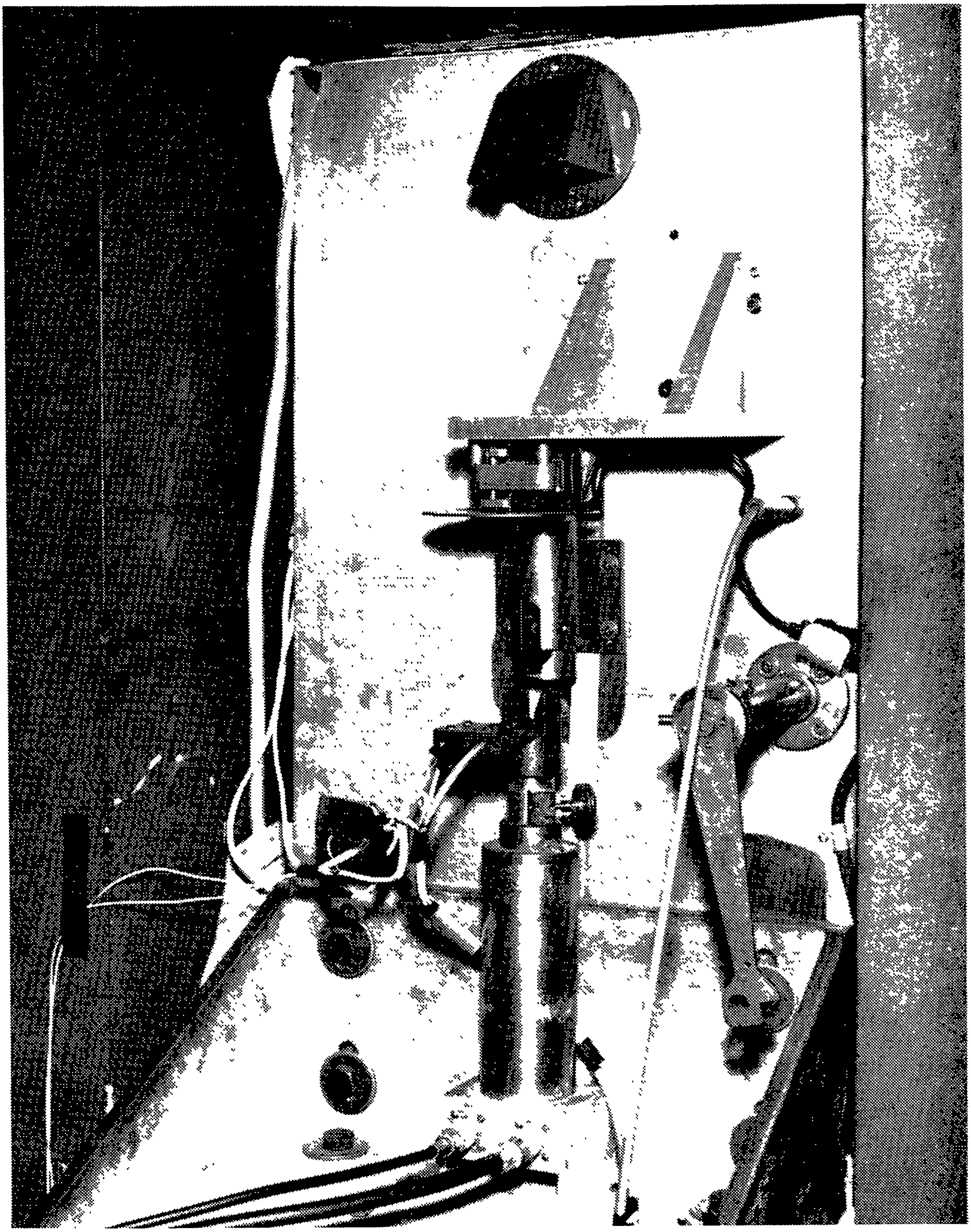

FIG. 7—The rotating sector, etc., of the calibrator located on the spectrograph side of the slit plate.

graph. The beam of calibration light is only about 2 inches in diameter at the grating. The rotating sector has 13 steps and is driven at 3600 revolutions per minute by a motor from a phonograph.

At the 72-inch telescope, similar rotating sectors are used in separate calibration spectrographs.

Superpositioning image slicers. Whenever the diameter of the stellar image is less than the length of the slit, an image slicer will decrease the exposure time. If the diameter of the image equals the normal length of the slit, then the slit would have to be lengthened for an image slicer to direct more light into the spectrograph. The width of the spectrogram would then be increased, however, and there would be no decrease in photographic exposure time unless the spectrograph was specially designed, but there would be a decrease in exposure time using a scanning spectrometer.

The starlight enters the image slicer through a cylindrical lens (figure 8) which produces two mutually perpendicular line images: a horizontal image which passes through the entrance slot separating the "aperture mirrors" and a vertical image which coincides with the entrance slit—the slot separating the "slit mirrors". A second lens, the "field lens", immediately behind the slit, focuses the horizontal image (the entrance slot) onto the grating of the spectrograph. Thus, it is seen that whenever the usual round stellar image on an ordinary slit must be trailed to produce a spectrogram of the desired width, that the introduction of these two lenses alone would eliminate the need to trail and also, in the same proportion, reduce the required area of the grating although its width would have to be the same.

The purpose of the multiple reflection mirrors of the image slicer is to direct the light which is intercepted by the slit mirrors, that is, the slit jaws, onto the portions of the grating which are not illuminated by the light which passed through the slit without reflection. The mirrors are separated by their common radius of curvature and their centres of curvature are arranged as shown in figure 8. The centres of curvature of the aperture mirrors lie at the edges of the centre of the slit. The light incident on a slit mirror is repeatedly reflected through the point at the edge of the particular mirror and a slice of this light must pass through the slit on each reflection; the light which does not go through the slit on each reflection must land on the other slit mirror whereupon it is reflected through the centre of curvature at the edge of that mirror, back to the original mirror, with a slice going through the slit and so on and vice versa. Each slice is superimposed on the previous slice.

Of course, it is necessary to prevent the light reflected back to the aperture mirrors (which results from each reflection through the centre of curvature of an aperture mirror) from passing back out through the entrance aperture. The centres of curvature of the slit mirrors are located above and below the entrance slot in the aperture mirrors so that the

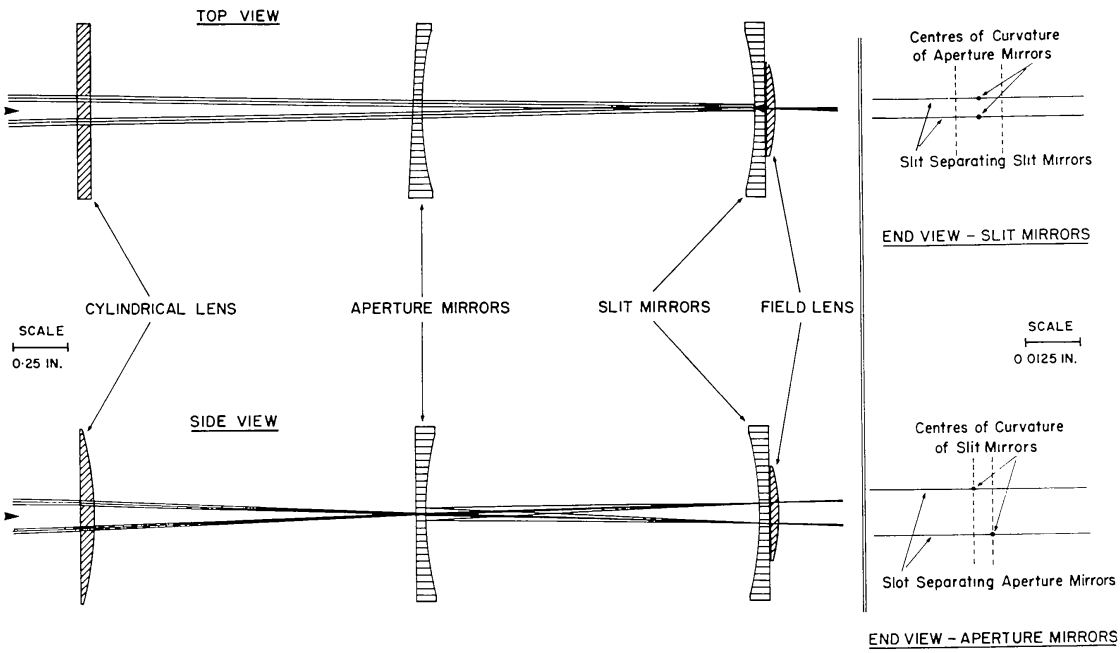

FIG. 8—The optical layout of the image slicer.

light striking one aperture mirror is reflected through the centre of curvature of that slit mirror which lies on the *other* aperture mirror; a stack of images of the slot appears on the aperture mirrors (see figure 9).

In the lower half of figure 9, this stack of slot images is shown as it is re-imaged by the field lens onto the collimator or grating of the spectrograph. On-axis Schmidt spectrographs have plateholders in the beam, therefore we displace the centre of curvature of one of the slit mirrors from the edge of the slot. This produces a gap in the stack of slices which is aligned to coincide with the back of the plateholder so that a slice from the centre of the stellar image is not wasted on the back of the plateholder; this method can be used when the image slicer's parameters are selected to fill the grating with no more than five slices, which is the usual case. With the image slicers of the coudé spectrograph, four slices get by the plateholders, and the speed of the spectrographs is increased by a factor of between 2 and 3, depending on the seeing.

The distribution of light across a spectrogram is that of a one-dimensional image of the primary mirror. The consequent decrease in intensity at the centre can be corrected by a beam re-arranger a few feet in front of the slit. This beam re-arranger consists of four small diagonal mirrors which reflect light from the upper and lower edges of the beam into the central shadow of the secondary mirror (figure 10). It is not presently used, however, because the central shadow of the existing secondary mirror is so large that the beam re-arranger narrows the spectrograms excessively and wastes too much light. In figure 10, A, B and C

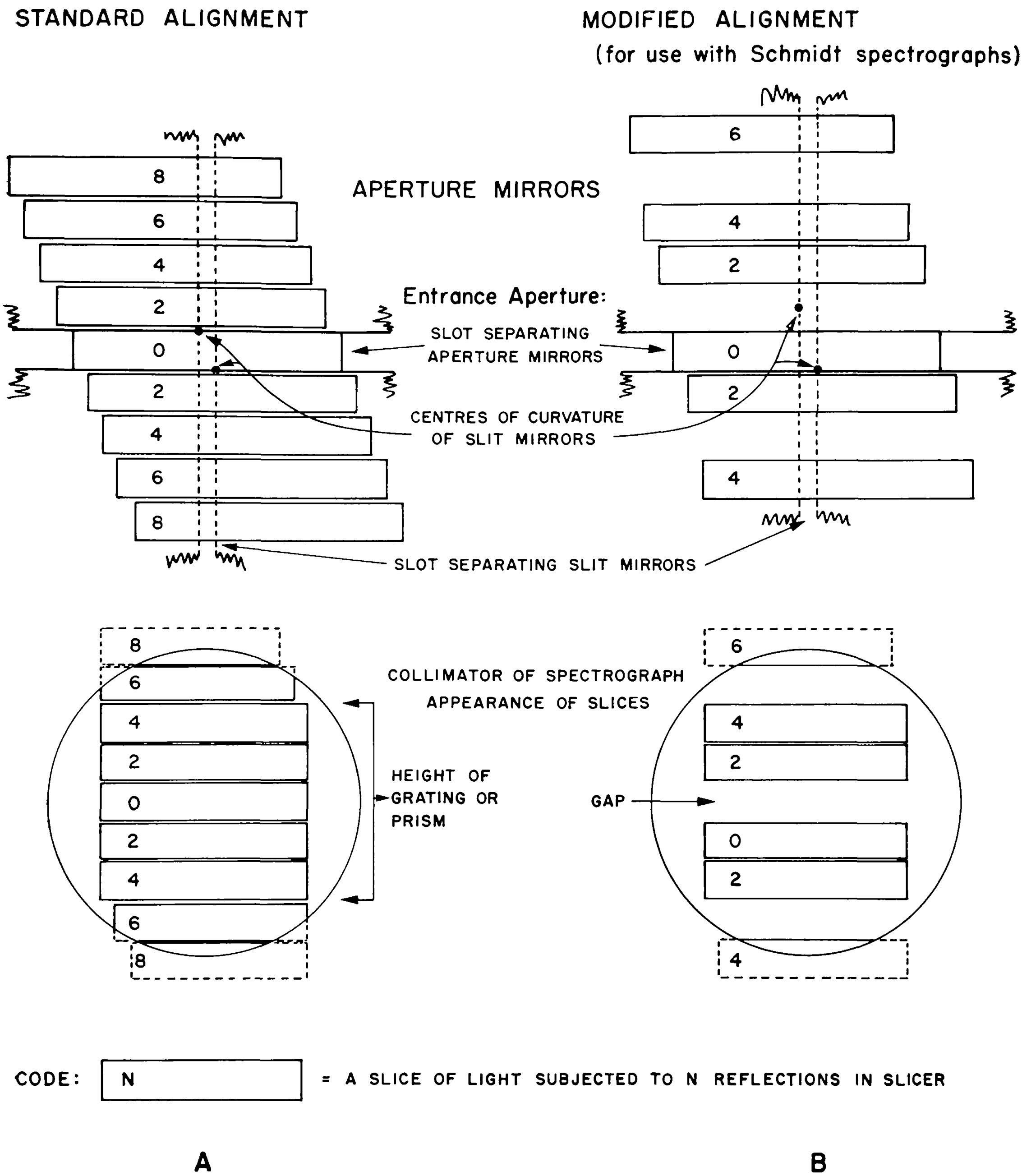

FIG. 9—The stack of slices on the aperture mirrors of the image slicer and on the collimator of the spectrograph.

show cross-sections of the beam at the collimator with the ordinary slit. The beam re-arranger was added for *C*; figure 10*D* shows a cross-section of the beam with the image slicer installed.

High reflectance coudé. The 16.5-inch diameter coudé secondary mirror will be replaced by a turret holding three 6-inch mirrors (figure 11). One mirror will be high-reflectance coated for the blue region, one for the red

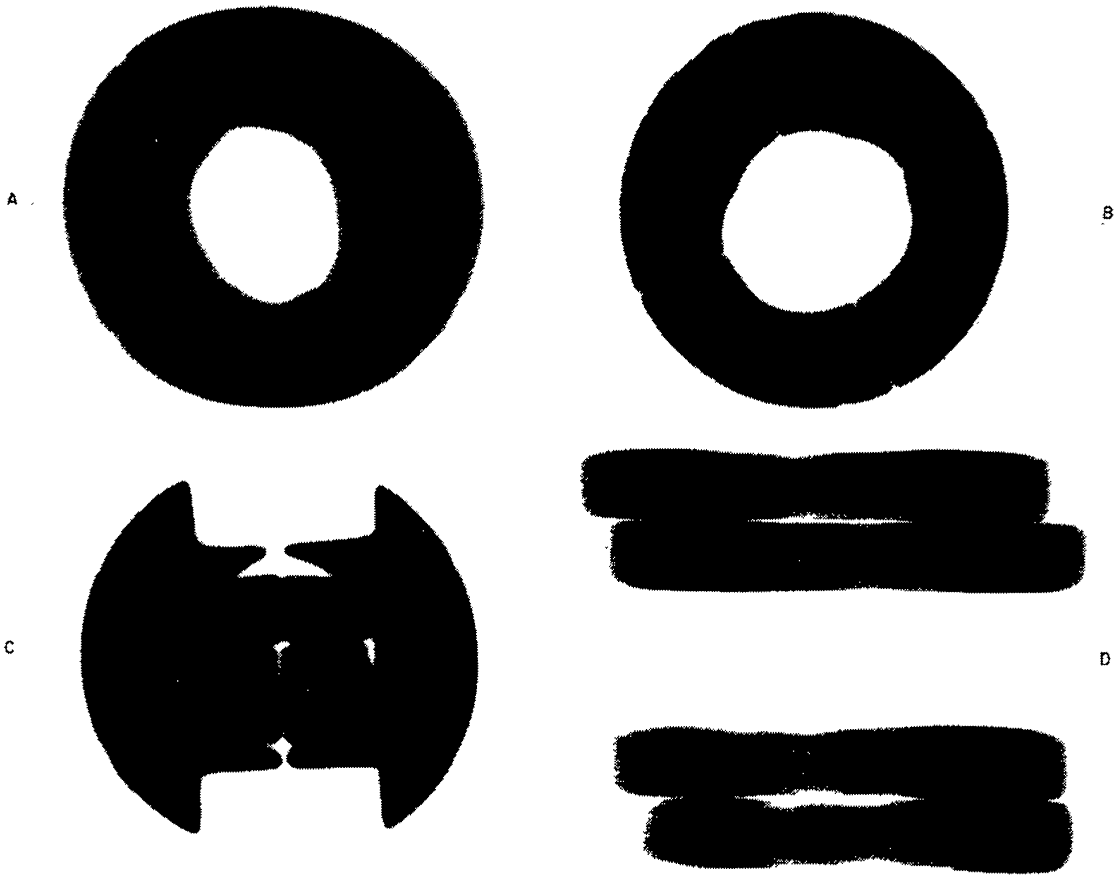

FIG. 10—Photographs of actual beam cross-sections at the collimator.

region and the third mirror will be given a standard aluminum coating These small secondary mirrors will change the focal ratio from the primary f/4 to f/145. Flat mirrors on the declination and polar axes will be similarly coated and mounted in the telescope. However, the off-telescope, stationary polar flat, (the "fifth coudé mirror" in figure 3) which reflects the light horizontally towards the coudé spectrograph, will consist of a fused silica totally-reflecting prism in contact with a calcium-fluoride and fused silica lens which will change the focal ratio to f/30. There will be two such antireflection coated lens-prisms mounted on a turret.

A 40 per cent increase in light flux is expected because of the reduction of reflection losses and central vignetting. Also, this system will greatly reduce the decrease in light intensity at the centre of the image slicer spectrograms.

Image rotator. The existing image rotator, using a Dove prism, involves a light loss (about 20 per cent) and produces some chromatism. It is almost never used. The Dove prism will be replaced with a wide-V prism (figure

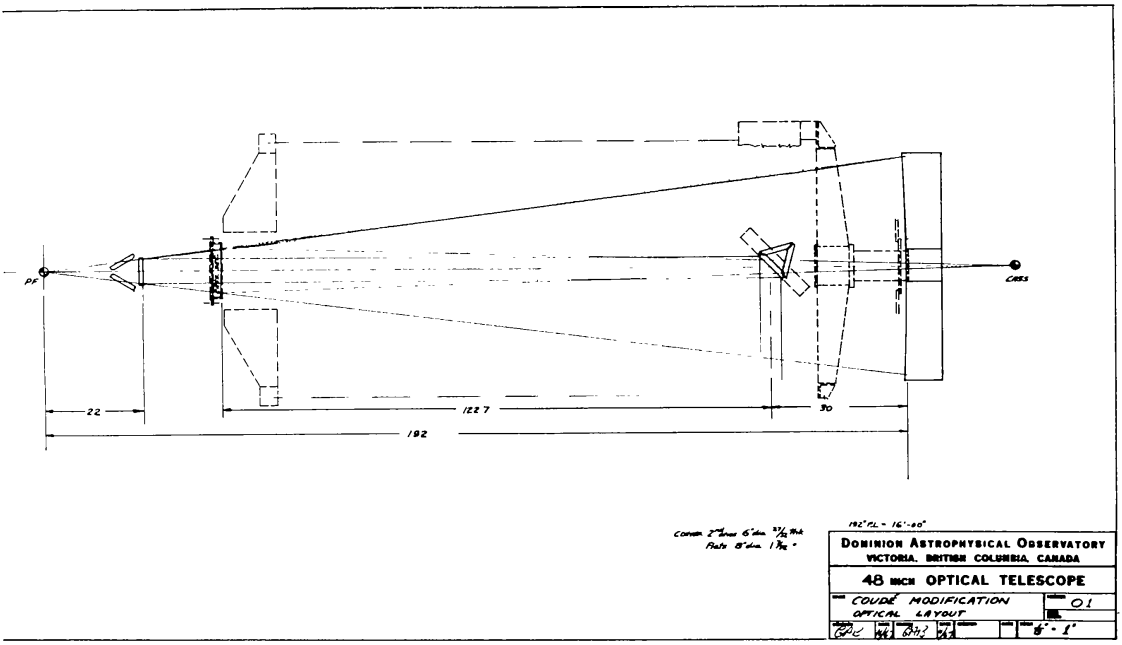

FIG. 11—The triple mirror secondaries in the 48-inch telescope.

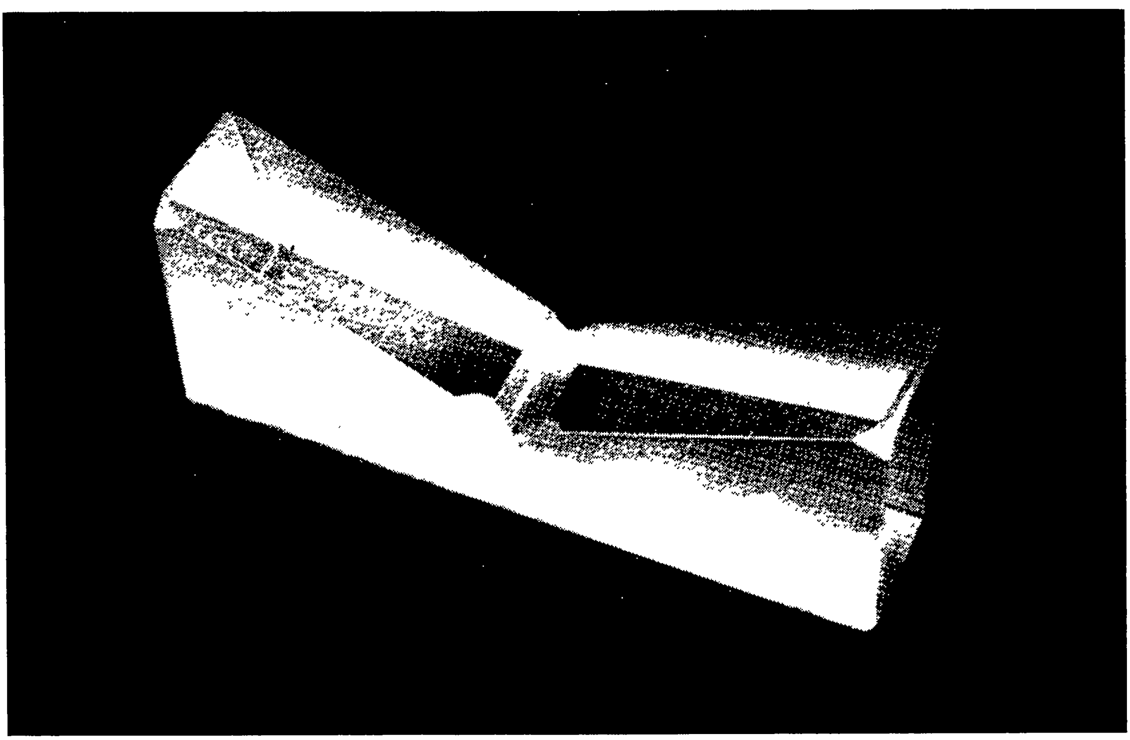

FIG. 12—The image rotator prism.

12). The light enters and leaves at normal incidence with three internal reflections. Two prisms have been made and will be given anti-reflection coatings for the blue and red regions. It is expected that the light loss will be reduced to less than 3 per cent.

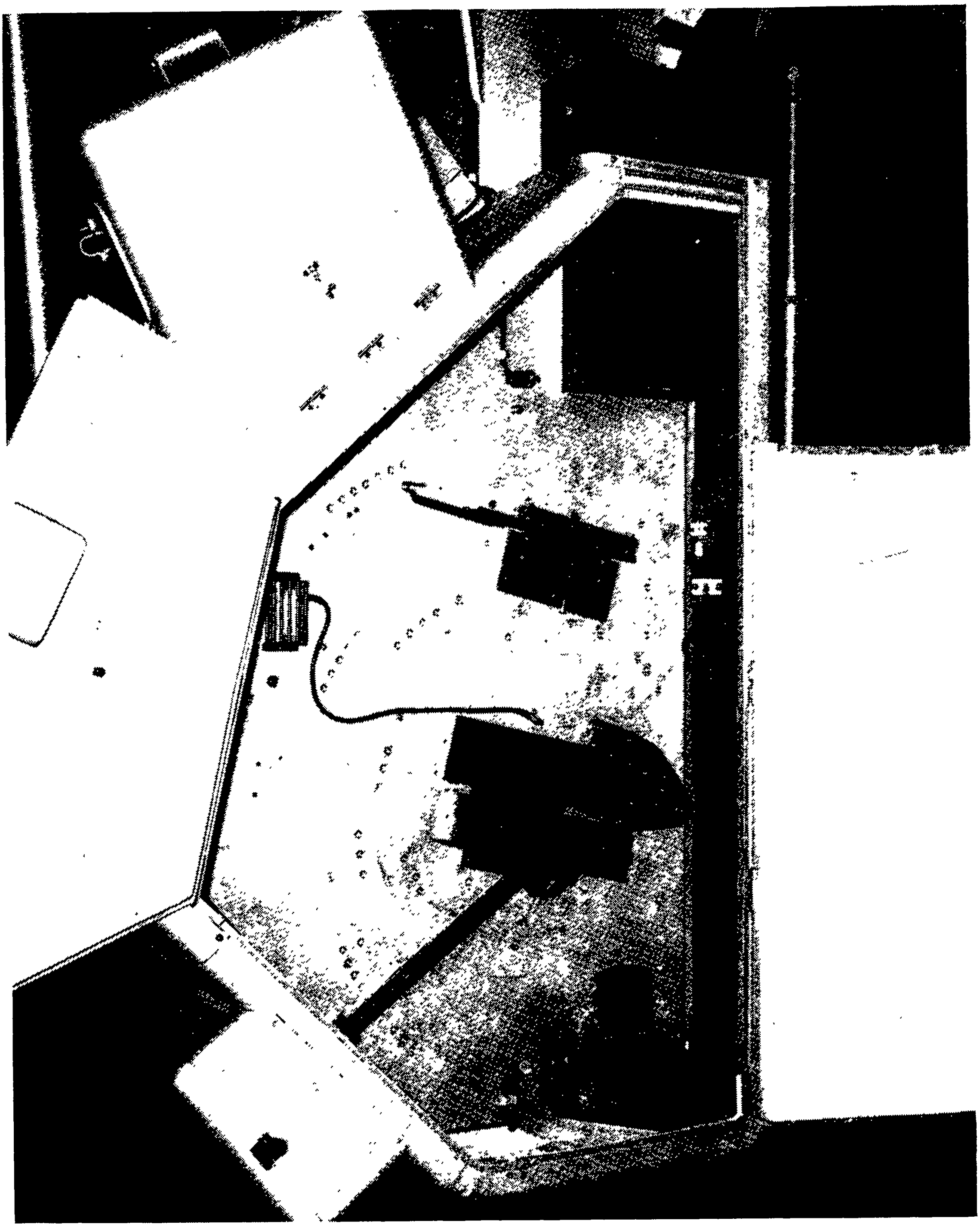

FIG. 13—The optical plate and spectrograph of the 72-inch telescope.

Cassegrain Spectrograph of the 72-inch Telescope

In figure 13, the periscope for viewing the slit is at the top. The diverging beam from the slit passes under the 4-inch by 5-inch grating and onto the off-axis collimator mirror at the bottom of the optical plate, 70 inches from the slit. It can be seen from the shape of the collimator's mounting that the mirror was cut from a larger (12-inch) mirror. The collimated beam returns to the grating, moving further away from the optical plate. The diffracted light goes down, clearing the top of the plateholder, to the camera mirror, a truncated 12-inch diameter mirror of 21-inch focal length, and finally to focus onto a 1-inch by 8-inch plate. The camera mirror is wide enough to give full-beam illumination to 4 inches of the plate. The calibration step-spectrogram is put on one end of the plate with a separate spectrograph. It is planned to make provision for an image intensifier by reflecting the beam through a hole in the optical plate from a diagonal mirror which can be placed before the plateholder. This can be done without any light loss by vignetting. A low-dispersion spectrograph using a concave transmission grating is now being designed.

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