I wish to thank Mr G. Burtt and Mr F. Knox, Physics and Engineering Laboratory, Lower Hutt, New Zealand, for providing the VLF data, and for valuable discussions.

Optical Systems for Spectroscopic Telescopes

T. DUNHAM, Jr*

Project Canopus—F.A.R.

and

Department of Physics, University of Tasmania

Astronomical spectrographs are usually mounted at one of three focal positions on a reflecting telescope: (1) the Newtonian focus, at the top of the telescope tube, with only one reflection from the primary mirror, where the spectrograph must be small and light, and designed for low resolution on faint objects; (2) the Cassegrain focus, behind the cell of the primary mirror, with a total of two reflections, where the spectrograph can be appreciably larger, to give intermediate resolution; and (3) the coude focus, at a fixed location below the end of the polar axis, with three, four or five reflections, where there is no limit to the size of the instrument, and where resolution is limited only by the brightness of the object and the light efficiency of the system. This is the ideal location for image tubes, Fabry-Perot interferometers, and equipment for Fourier spectroscopy.

It is logical to ask whether it may be possible to install interchangeable equipment for high, intermediate, and low resolution spectroscopy at the fixed coude focus of the telescope, without serious loss of efficiency. The Newtonian focus has been preferred for faint objects, largely because with Al coatings in average condition, about 85% of incident light is delivered to a spectrograph there. With similar mirrors, about 72% of incident light reaches a coude focus. Only about 52% of incident light reaches a coude focus after four reflections. There are obvious problems about setting and guiding on faint objects at the coude focus, but it seems likely that these can be solved without much difficulty.

If high-reflectance (HR) coatings could be used for all of the secondary mirrors of a coude telescope, then spectroscopic work on all objects—faint as well as bright—could be done at the coude focus. It seems reasonable to assume that a representative HR coating has a maximum reflectance of about 98%, and that this falls to about 90% at 1000Å on either side of the maximum. Thus a single coating can cover 2000Å, with an average reflectance of about 95%. To achieve this performance, three interchangeable mirrors must be used to cover the ground-based astronomical photographic spectral range from 3000Å to 9000Å. Some

---

*Senior Postdoctoral Fellow of the National Science Foundation during 1967-68 while much of this study was made.
metallic coatings with high reflectance over a wider spectral range than is possible with multilayer coatings are now available, and must be carefully evaluated. It is not difficult to interchange the two flats in the system, but it is not so easy to interchange the secondary convex mirrors, which are ordinarily about one-fourth the diameter of the primary.

Richardson¹ has solved this problem by reducing the size of the convex mirror, and has provided a turret for interchanging three HR convex mirrors only 6-in. in diameter at the top of the tube of the 48-in. coudé telescope at the Dominion Astrophysical Observatory. An f/145 beam is sent to the coudé focus, using two HR flats, for each of which three interchangeable coatings are provided. A fifth reflector turns the beam horizontal, and to one side, ahead of the slit. This is a low-reflection-coated 90° quartz prism in contact with a coated fluorite-quartz lens, which converts the f/145 beam to f/30 before it enters the spectrograph. Impressive gains in speed are to be expected with this system.

A system which is similar in many respects is being studied for a 50-inch spectroscopic telescope which the F.A.R. plans to install in Australia, in co-operation with the University of Tasmania (Figure 1a). By making the convex secondary mirror only 4 in. in diameter (hyperbolic figure, which deviates from the closest sphere by 0.7 μ), it is hoped that quartz prisms with low-reflectance (LR) coatings, about 4 in. × 4 in., can be used in place of flat mirrors. Three interchangeable LR prisms can cover 6000Å. Reflection and absorption losses can probably be held to less than 1% for each prism.

Vertical dispersion in a coudé spectrograph has marked advantages from the point of view of interchanging cameras and gratings. The beam comes to the coudé focus inclined 43° to horizontal at the site in Tasmania. It can be redirected to about 20° from horizontal, and converted from f/110 to f/30 by means of a coated quartz-fluorite-quartz prism-lens unit, similar to the unit employed by Richardson, but operating in a vertical plane. Light loss should not exceed 2% if three interchangeable units are employed.

Figure 1. a Proposed optical system for 50-in. coudé telescope: 4-in. diam. convex secondary mirror, two quartz reflecting prisms and a prism-lens unit, similar to that devised by Richardson, for redirecting the beam from 43° elevation to 20° elevation, and changing the cone from f/110 to f/30. The inserts show details of the prism-lens unit and an arrangement for interchanging several low-reflecting prisms for the polar axis and declination axis reflectors.

b Low dispersion (f/1.5) camera mounted in coudé spectrograph with 3-in. aperture beam from collimator operating with f/110 beam from telescope.
The prism-lens unit can serve two additional purposes: automatic guiding of the image on the slit by rotation about a horizontal axis, and widening of the spectrum by rotation about a nearly vertical axis.

Prisms with 4 in. × 4 in. faces will give a field about 2.5 arc in diameter, with 50% vignetting at the edge. If the telescope can be set with 1’ accuracy, this field is adequate. A large field is convenient, but its advantage must be balanced against efficiency of the telescope-spectrograph system. Until powerful coudé spectrographs become more numerous, particularly in the southern hemisphere, light efficiency is probably more important than convenience.

With an f/110 beam, short focus cameras for work on faint objects can be installed in the coudé spectrograph and can, with considerable saving in cost, be used with the same gratings as those provided for longer focus cameras. A collimator to yield a 3-in. parallel beam would be located 27.5 ft behind the slit (Figure 1b). A camera with 4.5 in. focal length (f/1.5) utilizes almost all of the light in a stellar image 2′ arc in diameter formed by a 50-inch telescope. If suitable optics are provided, setting and guiding on faint objects should not be essentially different from what is involved at the Cassegrain and Newtonian focus.

The gains to be expected at the coudé focus, and the performance relative to the Cassegrain and Newtonian, if high-efficiency secondary reflectors are used, in place of Al mirrors, are shown in Table I.

### Table I

<table>
<thead>
<tr>
<th>Focus</th>
<th>Number of reflectors (exclusive of primary)</th>
<th>Types of reflectors</th>
<th>Percentage light at slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian</td>
<td>0</td>
<td>(a) 1 Al Mirror</td>
<td>100</td>
</tr>
<tr>
<td>Cassegrain</td>
<td>1</td>
<td>(a) 1 HR Mirror</td>
<td>85</td>
</tr>
<tr>
<td>(b) 1 Al Mirror</td>
<td></td>
<td>(b) 1 HR Mirror</td>
<td>95</td>
</tr>
<tr>
<td>Coudé</td>
<td>3</td>
<td>(a) 3 Al Mirrors</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>(b) 1 HR Mirror +</td>
<td>1 LR Prism +</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 LR Prism-Lens</td>
<td></td>
</tr>
</tbody>
</table>

Interchangeable HR collimators can probably be installed in a coudé spectrograph more easily than in a Newtonian or Cassegrain instrument. If so, this increases the advantage of the coudé still further.

Since, with an HR convex secondary mirror and two LR prisms, 90% of the light that leaves the primary mirror can be delivered to the coudé focus, as compared with 85% delivered at the Cassegrain focus with an Al mirror, and 95% with a secondary, it seems logical to eliminate the Cassegrain spectrograph entirely, with considerable saving in cost, and to transfer its functions to the coudé where a wider range of collimators, gratings and cameras can be used for objects that differ greatly in brightness.

The advantages of a spectrograph at the Newtonian focus for very faint objects is marginal, as compared with an efficient coudé system (100% of the light from the primary mirror, as compared with 90%). Unless interchangeable HR collimators are provided for a Newtonian spectrograph, there is a question whether its installation can be justified.

Telescopes are expensive instruments, but they are essential for progress in astronomy. The increase of 47% in the efficiency of a coudé spectrograph that can be achieved by introducing high-efficiency secondary reflectors (90%, as compared with 61%) is so great that it must be given serious consideration. For medium- and high-dispersion spectrographs, with photographic recording and images of average size, the flux through the slit increases almost linearly with increasing telescope aperture. Accordingly, with a 47% gain in light at the coudé focus, a 50-in. telescope with high-efficiency reflectors can give the same spectroscopic performance as a telescope of about 70-in. aperture with conventional Al mirrors. The cost of achieving this gain with interchangeable reflectors is probably less than 10% of the cost of the entire telescope and spectrograph, whereas the cost for increasing the aperture from 50 in. to 70 in. is probably at least 50% of the cost of the installation. The expense of maintenance will, of course, be increased somewhat, since it must include the replacement of special coatings, but it seems likely that this will be unimportant in comparison with the saving in capital costs.

Plans are being made for a 26-in. telescope that will permit testing the effectiveness of a coudé telescope for faint objects, with an f/110 beam and high-efficiency reflectors, and also to permit testing the performance of an asymmetrical 4-mirror rolling horseshoe mounting.

---

2 Dunham, T., Proc. ASA, 1, 115 (1968).

### The Use of Fabry-Perot Filters for Spectral Scanning

M. D. WATERWORTH

Department of Physics, University of Tasmania

In designing a stellar spectrograph, it is pointless to exceed the resolving power necessary to obtain all the information from the spectrum of a star. This is limited mainly by atomic thermal motions, giving rise to the Doppler broadening of spectral lines, by turbulence and rotation of the stellar atmospheres in which the lines are formed, and by collisional broadening. Resolving powers of from 200 000 to 500 000 (λ / Δλ = 0.025 Å to 0.01 Å) are more than adequate to obtain all spectral information.

The photographic plate must necessarily still be used to record long regions of a spectrum. The plate may be measured photometrically to obtain moderately accurate absorption line profiles. Dunham has shown, however, that the granularity of emulsions causes errors in intensity measurements. Other factors, such as the Eberhard effect, scattering in the emulsion, and reflections from the glass plate, can also introduce errors into intensity measurements.

The photo-electric method of recording spectral information requires a point-to-point measurement of the light flux passing into a photo-detector. The accuracy of a photo-electric measurement at a single point in the spectrum, for a given time of observation, depends on the quantum efficiency of the photo-cathode. A figure of merit may be defined as the ratio of the time of observation required to achieve a 1/2 accuracy for a single observation with an ideal detector to the time of observation required to achieve the same accuracy with the method in question. The figure of merit for a photo-multiplier is, on the average, 0.10, and for a typical photographic emulsion 0.0016. The former figure is, in fact, the quantum...