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A DUAL-BEAM NASMYTH SPECTROGRAPH

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ABSTRACT

A recently-constructed double-beam spectrograph mounted on the Nasmyth focus of the Australian National University 2.3-m reflector is described. The spectrograph features two 150-mm collimator beams, with high throughput optics in each arm. Spectral resolutions range from 40 to 240 km s^{-1}. Flexure in rotation about the Nasmyth axis is elastic and has an amplitude of $\pm$ 16 μm in the camera focal planes. With S-20 and NEA Ga-As cathodes in large-format photon-counting arrays, the system detects 1 photoelectron Å^{-1} sec^{-1} from stars with $B = 15.0$ at 4000 Å and $R = 15.1$ at Hα. Some precepts from the optical configuration of this spectrograph may be applicable to the design of Nasmyth spectrographs for the large altitude-azimuth telescopes to come.

Key words: instrumentation–spectrograph–alt-azimuth telescope mounting

I. Introduction

A 2.3-m aperture telescope with altitude-azimuth mounting and rotating building has been constructed by the Australian National University on its site, Siding Spring Observatory. The telescope, which has an $f/2$ paraboloidal primary and $f/18$ Cassegrain secondary mirror, is configured to provide fields of 6.7 arc minutes at two Nasmyth foci and a Cassegrain focus. The two Nasmyth foci which are available through the elevation axis bearings of the telescope are easily accessed with a quick interchange facility. It was determined that one of these Nasmyth foci would be provided with an intermediate-resolution spectrograph with maximum versatility in the choice of resolution and with maximum efficiency over the wavelength range available to anticipated detectors. For these reasons it was decided to follow the example of the Hale Observatory (Oke and Gunn 1982) in dividing the spectrograph into two beams using a dichroic beam splitter following the spectrograph slit. In this way it was hoped that each arm of the spectrograph could be optimized for the wavelength region proposed, and it was determined that the wavelength of 50% transmission for the dichroic filter should be near 5800 Å. The final choice of this wavelength is governed by dichroic multilayer coating technology, regions of specific spectral interest, and the relative merits of detectors on either side of the dichroic cutoff.

II. Overall Design Considerations

Efficiency of throughput in grating spectrographs of intermediate dispersion is determined largely by minimizing internal losses in the optics and by adopting the maximum collimator/camera focal-length ratio that is technologically and economically possible (Bowen 1952). In the case of this spectrograph, considerations of available detectors suggested that 30 microns (2 pixels) at the camera focal plane should project to the spectrograph slit with at least a width of 1.5 arc seconds. The scale in the focal plane of the 2.3-m, $f/18$ telescope is 200 microns per arc second, so that a collimator/camera ratio of at least 10 to 1 was required. Given the requirements of intermediate resolutions for this spectrograph and the characteristics of available diffraction gratings, a camera focal length in both arms of the spectrograph of 232 mm (9 in) was adopted together with a collimator beam size of 150 mm (6 in). The implication, therefore, is that the collimator focal length is 2812 mm (9 ft).

Such large dimensions for the collimator focal lengths implied potentially significant flexure problems during the rotation of the spectrograph at the Nasmyth focus, let alone the difficulties of keeping the spectrograph within the building envelope. Since there was a requirement that the dichroic beam splitter be set at 45° to the optic axis of the Nasmyth focus, it was decided to fold each beam using the dichroic filter in reflection for the blue collimator arm and through a coated 45° prism for the red arm. In addition, the total envelope available to the spectrograph in the Nasmyth focus observing area was approximately half the total collimator focal length, and since the prospect of a two-armed rotating light beam with a 150-mm (6-in) aperture and 2.6 m (9 ft) in radius was somewhat daunting, it was decided to fold the collimator beam using highly-reflective flat mirrors in order to compact the total size of the spectrograph. This feature allowed a decrease in size of the spectrograph physically, reduced its moment of inertia (an important matter in servocontrol of the Nasmyth instrument rotators), and provided a convenient means of focusing the spectrograph through adjustment of the collimator focal length.

Table I contains the essential dimensional parameters of the double-beam spectrograph.

Other physical constraints on the spectrograph construction were that it should weigh not more than 500 kg (1100 lbs) and have a load moment on the instrument rotator bearing of no more than 3000 Nm (2200 ft lbs). Given the beam size and collimator focal length of the spectrograph, these weight considerations led to the decision that the grating suites for each arm of the spectrograph would not be mounted on motor-driven interchangeable turrets and thence stored within the spectrograph, nor would spectrograph focusing through the collimator-folding flat mirrors be motorized. An additional reason for not adopting remotely interchangeable gratings was that to achieve sufficient mechanical rigidity of the grating cell mountings, a significantly more complex mechanism must be adopted in the remotely controlled case.

The flexure loads on a Nasmyth spectrograph vary with position angle of the instrument rotator. Such changes can be quite rapid. In the case of the 2.3-m telescope, operating at its closest design approach to the zenith, the parallactic angle at the Nasmyth focus rotates through 180° in eight minutes. Control of spectrograph flexure and position-induced temperature effects on detectors in such a situation is therefore critical. With this in mind, the configuration of the folded-flat Schmidt cameras operating at $f/1.1$ was arranged so that the detector axes are always parallel to the Nasmyth focus axis of the telescope under all positions of rotation of the spectrograph.

The dichroic filter cutoff was chosen to occur around 5800 Å because the efficiencies of potential detectors change rapidly at that point, be they various types of CCD, or photon-counting system/CCD combinations, or photon counting systems separately with blue- and red-sensitive cathodes. In addition, it is generally difficult to procure dichroic filters which operate with high rejection over more than one octave of frequency. Therefore, if high reflectivity is required for a dichroic filter in the region of 3200 Å, a cutoff wavelength of less than 5700 Å is mandatory. An additional consideration is that a variety of detectors are available separately for use in the blue and red arms of the spectrograph; and, therefore, to allow for this possibility, six different dichroic filters with cutoff wavelengths between 5700 Å and 7000 Å were obtained and facility for ready interchangeability of the filters is incorporated in the spectrograph design.

TABLE I

Dimensional Parameters of Nasmyth Spectrograph

Telescope scale 2.3m f/18 focal plane scale: 5 arc sec/mm
Beam size: 150mm (6in)
Camera focal length: 232mm (9in)
Camera/collimator focal length ratio: 12.1
Projected width of 30μm (2 pixels at focal plane of telescope): 1.8 arc seconds
Total unvignetted field of telescope 6.7 arc minutes = 80mm which is 6.5mm on the camera focal plane.
Dispersion with initial grating suite: Blue: 17.4 to 140Å/mm.
Red: 34.8 to 280Å/mm.

In the blue arm of the spectrograph the collimator focusing flat, the collimator mirror, the gratings, and the folded Schmidt-camera reflecting surfaces are enhanced aluminum overcoated with magnesium fluoride. The transmitting surfaces of the field lens, the Schmidt correcting plate, and the camera field flattener are all antireflection coated in the wavelength range 3000 Å to 5800 Å. Similarly, in the red arm of the spectrograph following transmission through the dichroic filter, the collimator focusing flat, the collimator, the grating, and the camera-reflecting services are coated with silver and the transmitting surfaces in the red arm are all antireflection coated in the range 5000 Å to 9500 Å. Tests have shown that the deterioration of the reflectance of the silver surfaces is less than 1% over a twelve-month interval when the optics are in dry air. The spectrograph, including the optics near the cooled detectors, is continually flushed with pressurized dry air.

Figure 1 shows the spatial arrangement of the optical elements for the spectrograph and illustrates the configuration of the folded Schmidt cameras whose axes are parallel to the Nasmyth axis.

The initial suite of gratings for the spectrograph consists of four gratings blazed between 7500 Å and 8000 Å which are silver coated and five gratings which have magnesium-fluoride overcoated aluminum for the blue arm. The red gratings have 150, 300, 600, and 1200 grooves mm^{-1} giving resolutions of between 40 and 180 km s^{-1} (i.e., between 0.52 Å and 2.3 Å). In the blue, a similar range of resolutions is achieved with one of the gratings having a first-order blaze wavelength of 8000 Å and the other four being blazed between 3600 Å and 4000 Å in the first order. Grating interchanges are made manually and some care has gone to ensure that frequent handling of the gratings does not lead to deterioration of their surfaces. Each grating cell has a dark slide which is the handle by which the grating can be extracted from the spectrograph. It is therefore nearly impossible to gain access to the grating surface during the interchange of gratings.

It was considered from the beginning that the spectrograph could also provide an important element in the suite of imaging systems for the 2.3-m telescope so the spectrograph was designed, in addition, to be a *redacteur focale* operating at $f/1.5$ for the 2.3-m telescope. The

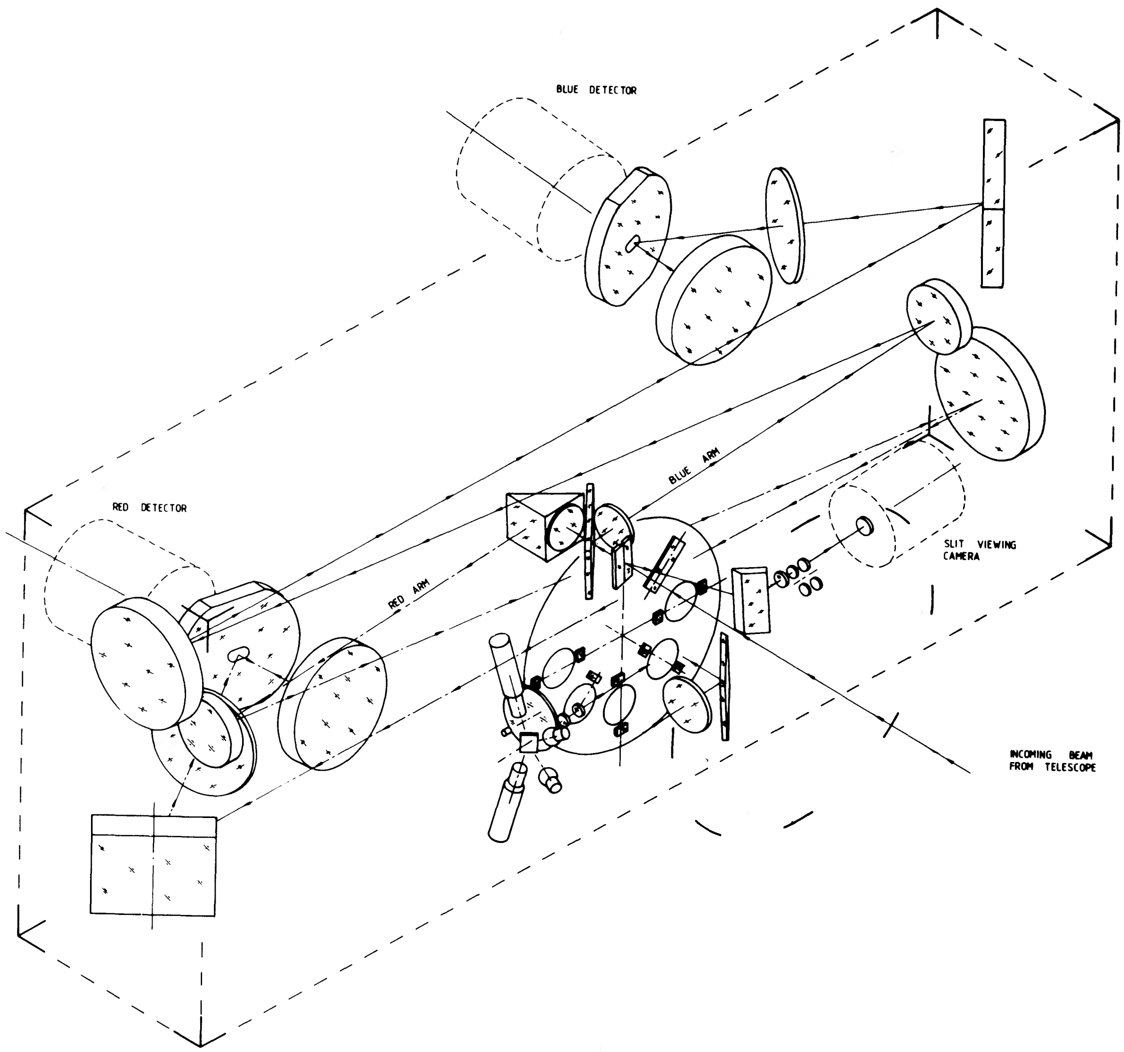

FIG. 1–An isometric view of the optical components of the spectrograph. Some of the major items shown are the comparison arc turret, ICCD slit viewing camera, the two arms (red and blue) of the spectrograph, and the detector axis configuration.

satisfactory achievement of this purpose required that no vignetting changes occurred in the field-imaging characteristics of the spectrograph over the 80-mm length of the spectrograph slit. This has been done through field imaging, in each arm of the spectrograph, of the telescope pupil onto the grating and by ensuring that all optics, including those in the cameras, are of sufficient aperture. An aluminum-coated plane mirror (for the blue arm) and a silver-coated mirror (for the red arm) are available for ready insertion in the system. A most important feature of this whole field-imaging capability of the spectrograph is that it allows multiobject spectroscopy over the 6.7-arc minute field using aperture plates without the losses that are associated with fiber optics in some other multiaperture systems. There are, of course, constraints on the spectral range available depending on the position of the object.

III. Construction

The spectrograph was designed and constructed at Mount Stromlo Observatory with the exception of the correcting plates for the cameras which were designed and manufactured by William James Optics Proprietry, Limited, Melbourne, and the diffraction gratings purchased from Bausch and Lomb, Inc. (now Milton Roy), Rochester. The body of the spectrograph and cameras is constructed from 1-cm (0.4-in) thick welded aluminum plate. The slit jaws were ground and polished, along with all other optics, in the optical shop at Mount Stromlo.

Ray tracing shows that the collimators, which operate at 6° off axis, could be satisfactorily made as spheres, and this has been done. Currently the blue camera correcting plate is a singlet of Homosil and gives images of less than 10 μm FWHM in the wavelength range 5400 Å to 3800 Å. A doublet corrector of Homosil and FK54 glass is under design which will achieve images of less than 12 μm FWHM in the wavelength range 5400 Å to 3000 Å. This optical performance in each camera applies across the 22-mm designed field in the focal plane.

In Figure 2 we show the general arrangement of the blue camera and grating mounting assembly for the blue arm of the spectrograph. In this and the red arm, we have kept the angle between the collimator and camera as small as feasible in order that the size of those gratings which are used at large blaze angles is kept small. We have adopted an angle of 32° for both arms, and it is only in the case of the highest dispersion blue grating (which has 1200 lines per mm operating in second order) that we have been driven to select gratings larger than 150 mm × 200 mm (6 in × 8 in) ruled area.

An accessories trolley sitting on the floor in the Nasmyth focus area is used for location of electronics for the spectrograph operation and for the detectors. It incorporates the distribution system for the dry-gas supply with which the spectrograph body and the detectors are continually flushed. It also has the storage area for the grating suite and for the dichroic filters. Low-pressure air guns are available for cleaning grating dark slides during grating interchange.

Detectors are protected within the spectrograph by symmetrically closing shutters which operate parallel to the fan beam of dispersed light from the gratings, the latter to minimize nonuniform collimator illumination if the shutters are used as beam attenuators. There is, in addition, a set of remotely-operated neutral-density filters above the slit which can be inserted for observation of bright objects such as velocity standards. A convenient feature is the provision of a circular variable-density filter in the comparison arc turret. Optimum intensity for com-

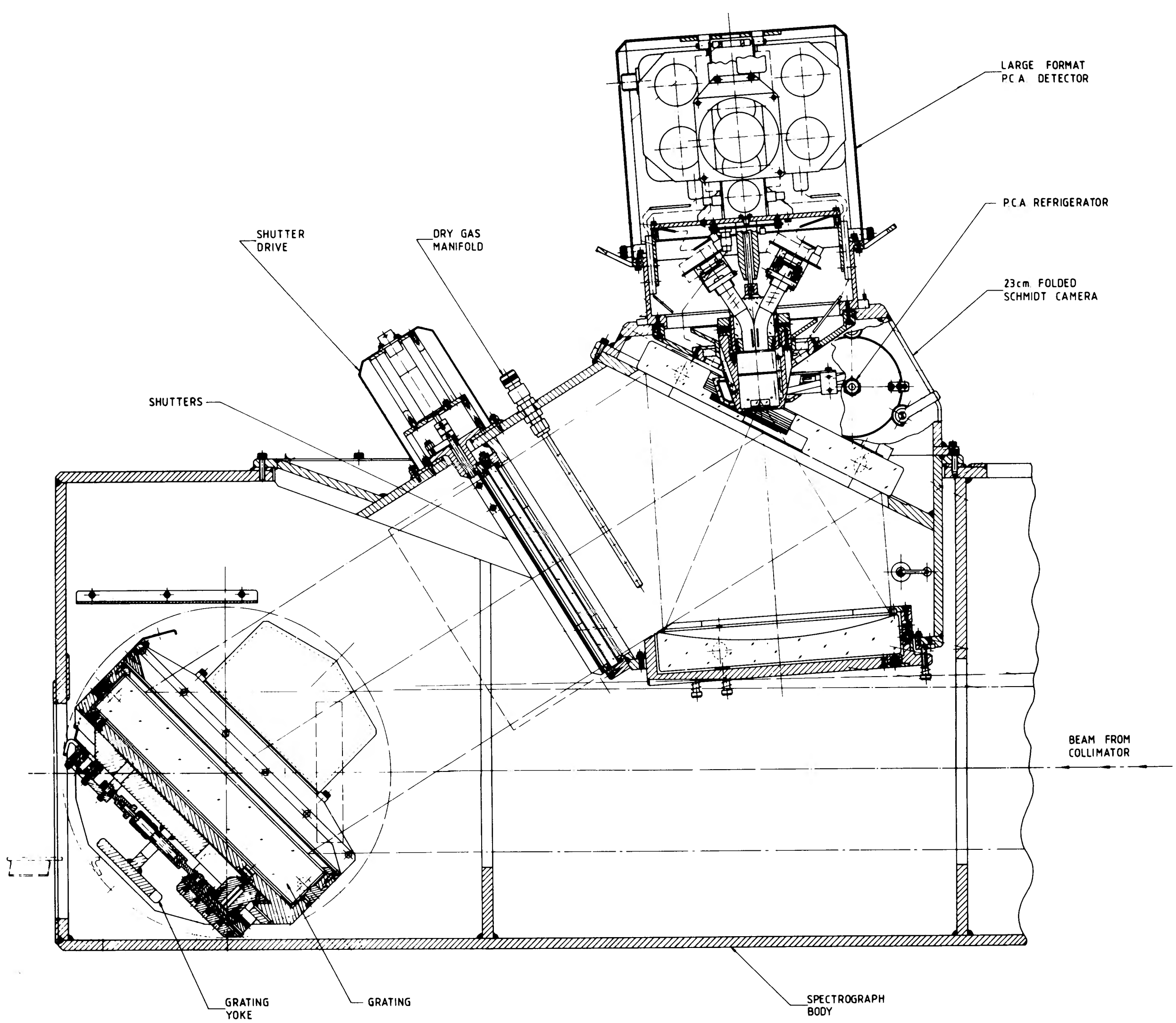

FIG. 2–A cross-sectional assembly drawing of the grating turret arrangement. The 23-cm (9-in) folded camera and the multiple CCD format photon-counting array for the blue arm of the spectrograph. The red arm is very similarly configured.

parison arc exposures from the turret of comparison arc lamps is therefore easily obtained.

An innovative acquisition and guiding system has been installed on the spectrograph which consists of an intensified CCD camera which views the slit at a focal ratio of $f/8$. The latter is chosen to match a typical seeing disk of 1.5-arc-sec diameter to the system resolution. The intensifier is a Litton XT0168 microchannel plate tube with S-20R cathode response fiber-optically coupled to a Fairchild CCD 3000 camera. The camera is modified to interrupt clocking for a variety of preset integrations extending to 100 frames (each of 30 mS). At dome temperatures of 10° C, dark current from the CCD produces 50% of saturated video signal per pixel in an approximately one-second exposure. Cooling the CCD to 0° C allows integrations of 100 frames duration without significant buildup of dark current. The advantages of this configuration are that the spatial stability and synchronization stability of the package against magnetic-field and temperature changes allow accurate autoguiding of objects on the spectrograph slit. A disadvantage is the small format offered by the CCD, though this is offset by the overall small size and lightweight nature of the camera head which is motorized and driven to cover the full length of the slit. The performance of the ICCD system is such that stars of $V = 20.5$ are detectable with CCD integration times of two seconds and with four integrated frames being averaged on a video processor. While not implemented as yet, it is anticipated that in average seeing, stars brighter than $V = 17.0$ will allow autoguiding of the telescope.

IV. Performance of the Spectrograph

The initial tests for the spectrograph in terms of efficiency of throughput and stability are encouraging. Figure 3 shows the measured flexure of the spectrograph as a function of parallactic angle. It can be seen that the displacements are elastic and do not have an amplitude greater than ± 16 microns in the focal plane of either camera over the full rotation of the spectrograph. These results allow us to calibrate the flexure at any angle for a given spectrograph detector combination and even allow accurate wavelength calibration on objects where the spectrograph rotation is rapid, provided the detector is one with frequent readouts. Observations which critically depend on instrument stability can be made at times of slow parallactic angle change or with the position angle of the spectrograph such that differential flexure is at a minimum. Observation of spectrophotometric standards in the slitless mode suggest that at $\lambda = 400$ nM with an S-20 cathode detector, one photon per second per Å is detected from a star with $B = 15.0$. This number is to be compared with the computed efficiency (slitless) of the spectrograph of 28% which leads to a predicted efficiency of one photon per second per Å from a star with $B = 15.0$ magnitude. A significant loss occurs in polarization in reflection from the dichroic filter which is attenuated by all the gratings. This loss amounts to 25% of the blue light entering the spectrograph slit. The range of wavelengths observed in each arm of the spectrograph depends on the detectors used and, in the observations made to date, we have used a blue large-format Photon Counting Array with an S-20 cathode on a quartz substrate. On the red arm we have mounted an NEA Ga-As cathode, the photoelectrons from which are detected by a similar large-format photon-counting system. These detectors are the subject of the companion paper which follows.

We show, in Figure 4, a plot of the instrumental response of the spectrograph as determined from observation of the spectrophotometric standard star LTT 8702 = EG 149.

As illustrations of the spectra produced by the instrument, we reproduce in Figure 5 the spectrum of the planetary nebula NGC 1535 and in Figure 6 the integrated spectrum of NGC 1049, a globular cluster in the Fornax dwarf system. Figures 7 and 8 show these spectra as displayed on the video processor (RAMTEK) used with

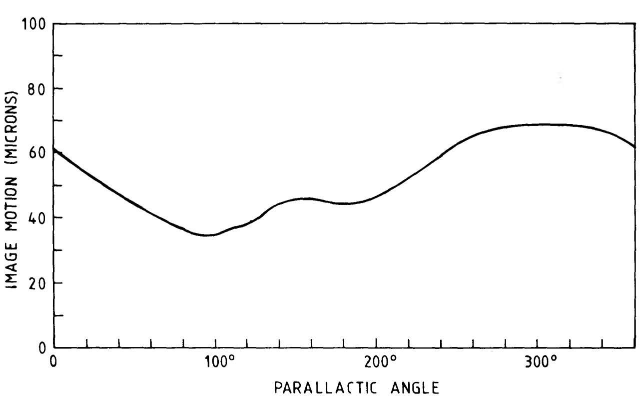

FIG. 3–A plot of the motion of the slit projected in the image plane of the blue camera as a function of parallactic angle. It will be noted that the semiamplitude of the flexure variation is 16 microns and the motion is elastic but not completely sinusoidal.

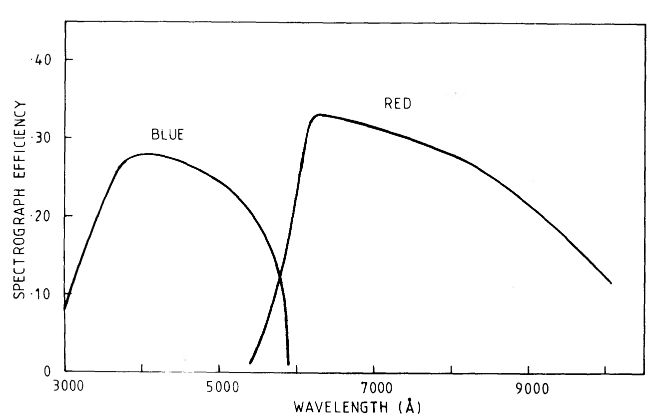

FIG. 4–Wavelength dependence of spectrograph efficiency in the slitless mode.

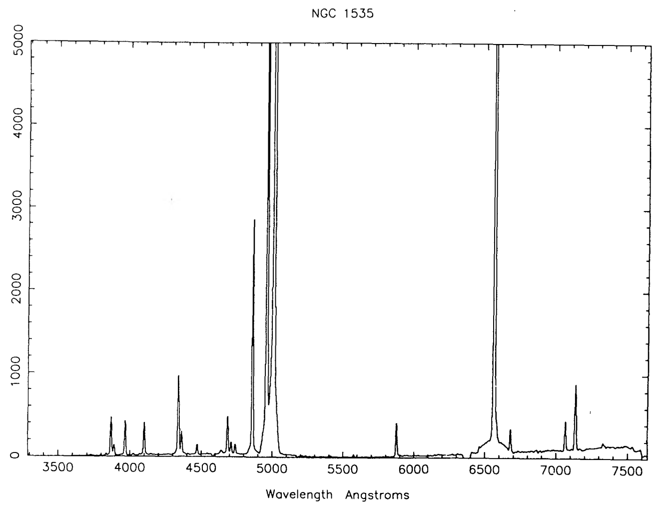

FIG. 5–The spectrum of the planetary nebula NGC 1535 obtained simultaneously in the two arms of the spectrograph. The exposure time was 200 seconds. Note the high-velocity wings to the Hα and Hβ profiles and their absence in the [O III] lines.

the photon-counting arrays. Figure 9 shows a general view of the spectrograph and service trolley mounted at the Nasmyth focus of the 2.3-m telescope.

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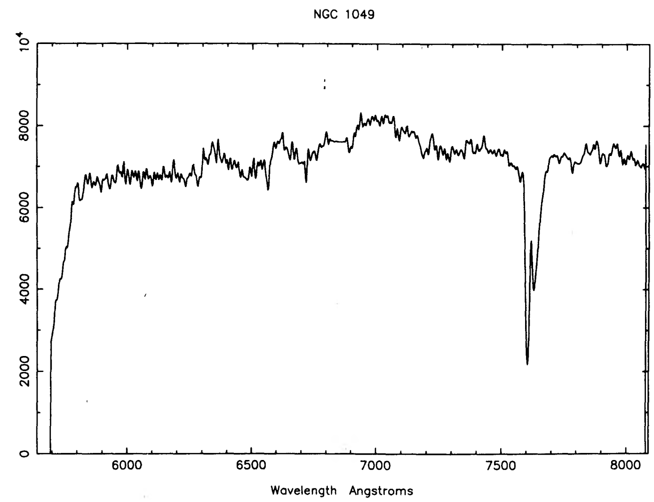

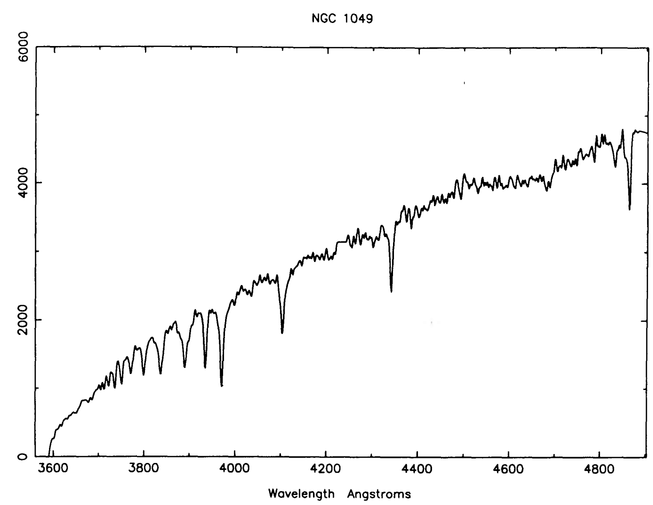

FIG. 6–Red and blue spectra of the integrated light of NGC 1049, a globular cluster in the Fornax dwarf system. The exposure time was 3000 seconds.

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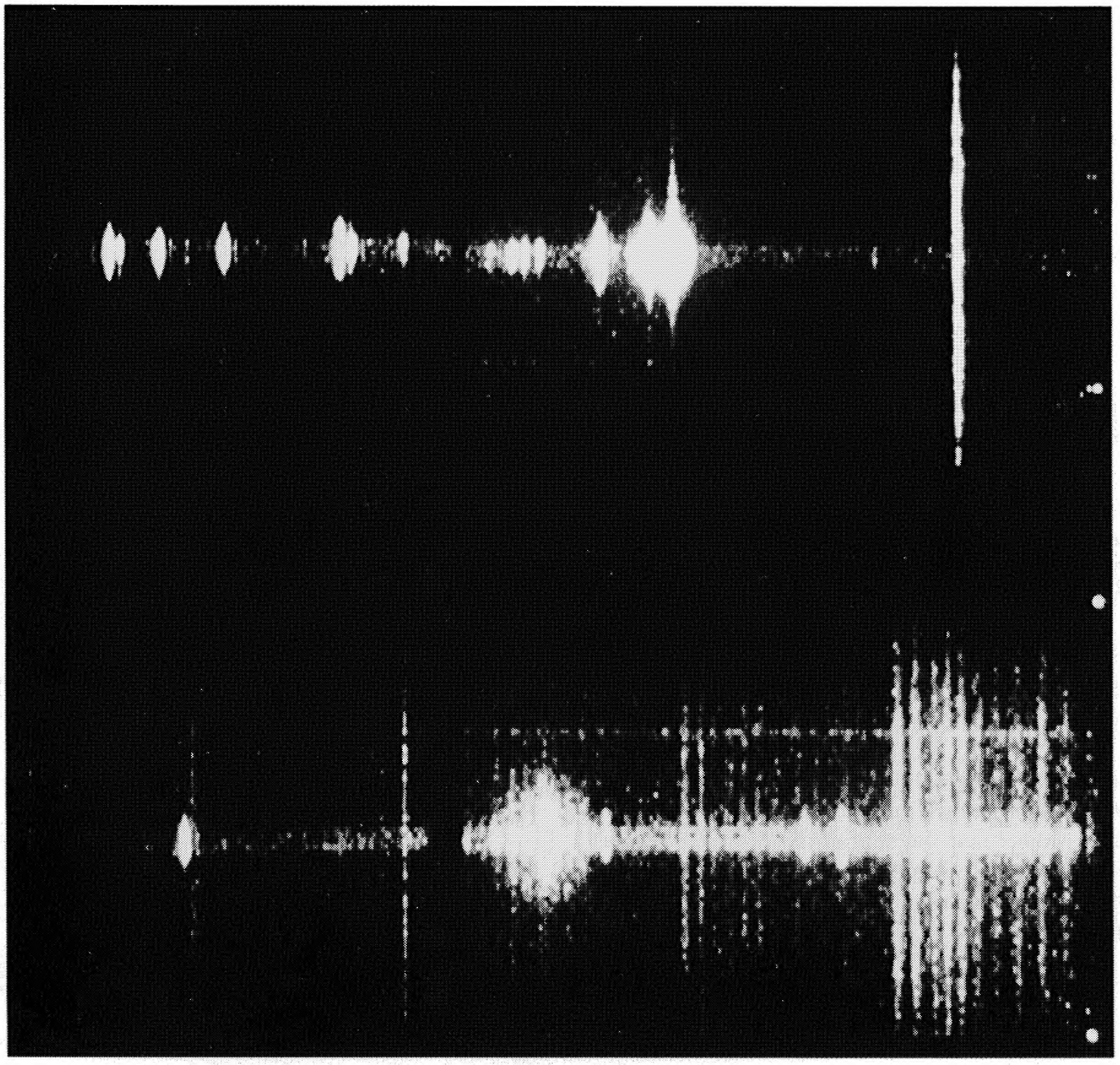

FIG. 7–A photograph of video display of the spectrum of the planetary nebula NGC 1535.

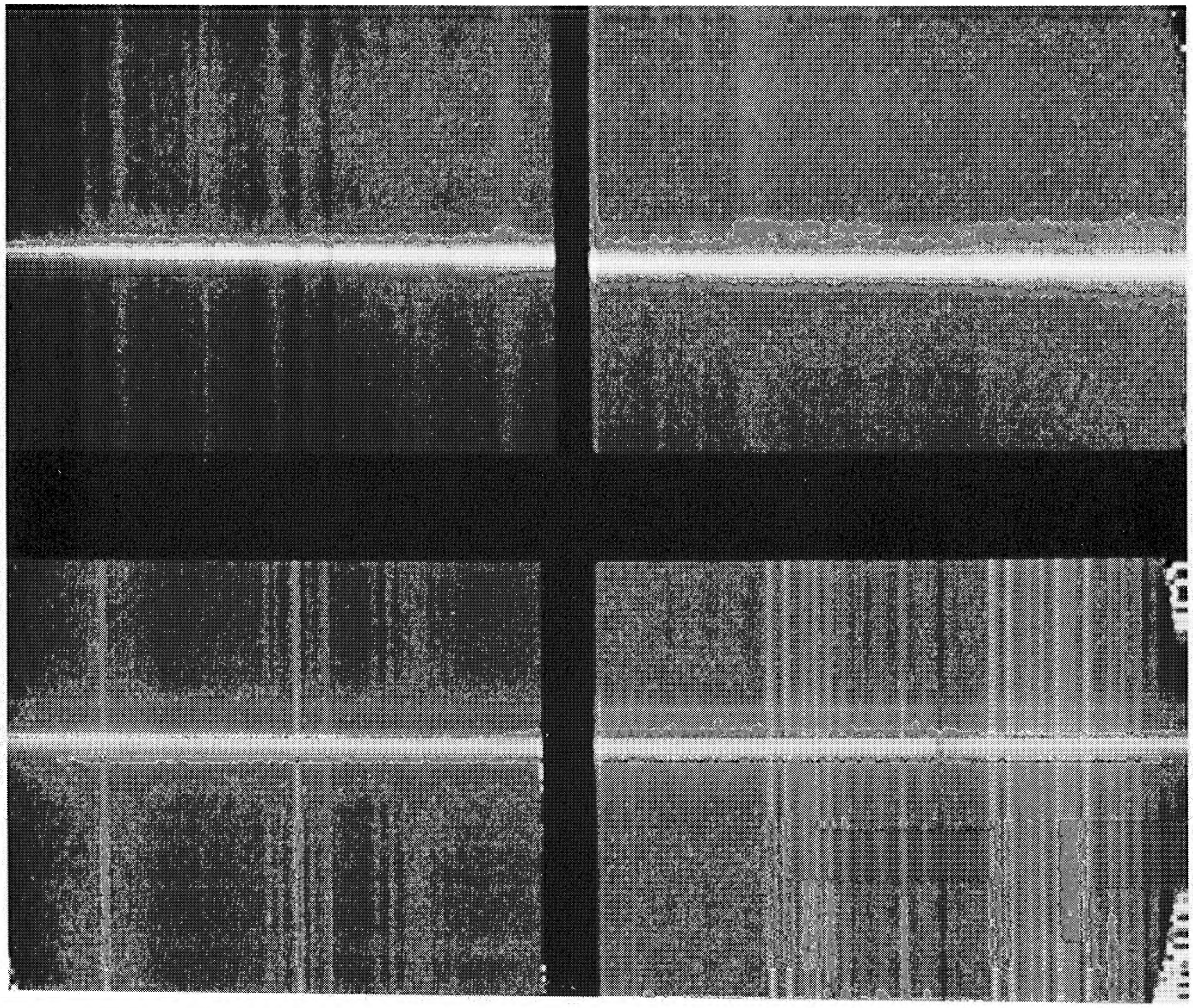

FIG. 8–A photograph of video display of the spectrum of NGC 1049, a globular cluster of the Fornax dwarf galaxy.

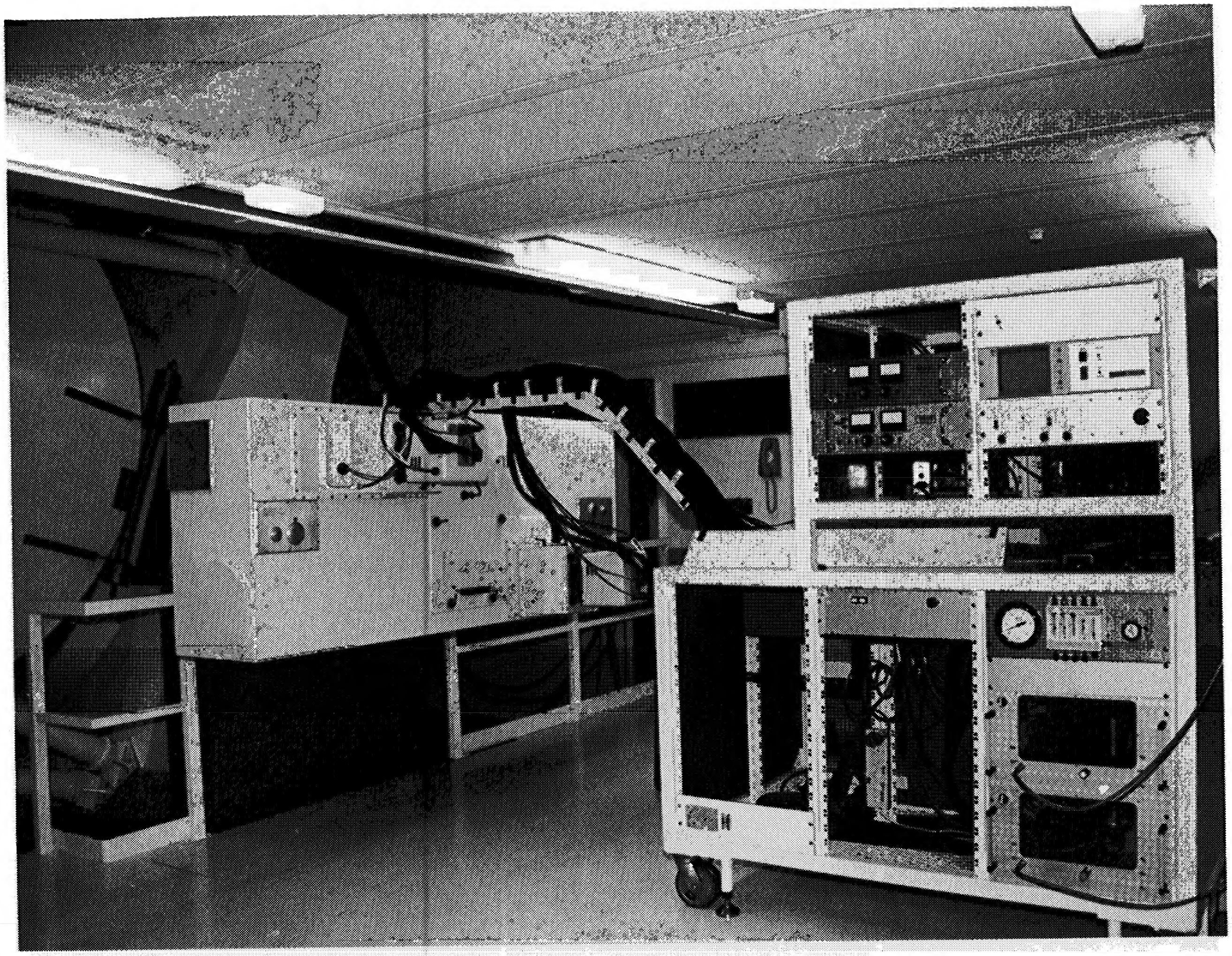

FIG. 9–A photograph of the Nasmyth observing area of the 2.3-m telescope with the double-beam spectrograph and service trolley. The blue and red detector systems are visible along with a twisting cable boom carrying electronics, refrigerant gas, and dry-gas-leads to the service trolley described in the text.