reduction of the digitized spectra was performed on the PDP11/34 computer at the same Institute. While the wavelength and intensity calibrations were easily performed on all spectra, the determination of the radial velocities proved to be very tricky because of the low dispersion and the high rotational broadening of the spectral lines. Therefore an 'ad hoc' data processing code is under development, and hence the analysis of the spectra has not yet been completed.

The result of this work will be published, when completed, in the *Astronomy and Astrophysics Supplements.*

List of Preprints Published at ESO Scientific Group

June–August 1983

253. P. A. Shaver and J. G. Robertson: Absorption-line Studies of QSO Pairs. *Memorie della Società Astronomica Italiana.* June 1983.
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259. P. Bouchet and P. S. Thé: Notes on the Open Cluster NGC 1252 with the Variable Carbon Star TW Hor as Probable Member. *Publications of the Astronomical Society of the Pacific.* June 1983.
260. C. Kotanyi, E. Hummel and J. van Gorkom: Are there Jets in Spiral Galaxies? "Astrophysical Jets", workshop held in Torino, Italy, 7–9 Oct. 1982. June 1983.
261. A. F. M. Moorwood and P. Salinari: Infrared Objects Near to H_2O Masers in Regions of Active Star Formation. III. Evolutionary Phases Deduced from IR Recombination Line and Other Data. *Astronomy and Astrophysics.* July 1983.
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264. R. Terlevich and J. Melnick: Studies of Violent Star Formation in Extragalactic Systems. II. The Relation Between the Initial Mass Function and Chemical Composition. *Monthly Notices of the Royal Astronomical Society.* July 1983.
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272. P. A. Shaver: Absolute Distance Determination for Objects of High Redshift. 24th Liège International Astrophysical Symposium "Quasars and Gravitational Lenses", June 21–24, 1983. August 1983.
273. M.-H. Ulrich: Line Variability in Active Nuclei and the Structure of the Broad Line Region. XI. Texas Symposium on Relativistic Astrophysics, Austin, December 12–17, 1982. August 1983.
274. G. Contopoulos: The Genealogy of Periodic Orbits in a Plane Rotating Galaxy. *Celestial Mechanics.* August 1983.
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Fiber Optics at ESO

Part 2: Fiber Optics Multiple Object Spectroscopy at the 3.6 m Telescope

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During a 6-day test period late in November 1982, a prototype optical fiber device (nicknamed "Fiber Optopus") was tested at the 3.6 m telescope Cassegrain focus. The principle of this device, described in more detail in the following paragraphs, is such that the light from up to 50 randomly separated points on the sky (within the Cassegrain focus field of view) can be simultaneously guided via separate flexible optical fibers to the entrance slit of the B&C spectrograph. By making use of a two-dimensional detector such as a CCD the individual spectra, corresponding to each sampled point on the field, can be recorded simultaneously. When fully operational, the Fiber Optopus should enable a very strong reduction in telescope time to be achieved in observing programmes involving low resolution spectral mapping of extended fields. This feature will be of great interest to astronomers wishing to observe clusters of faint objects requiring long integration periods.

Technical Description

The prototype system, represented schematically in fig. 1, depends on the following essential components:

- the Fiber Optopus containing 50 free optical fibers, appropriately terminated in magnetic connectors,
- a starplate for the particular field to be viewed,
- three coherent fiber bundles and a TV camera for guiding,
- the Boller and Chivens spectrograph,
- a two-dimensional detector (CCD).

In addition, auxiliary calibration lamps, power supplies and a handset for the remote control of these functions and of the TV camera are provided. A description of the instrumental components developed specially for multiple object spectroscopy is given below.

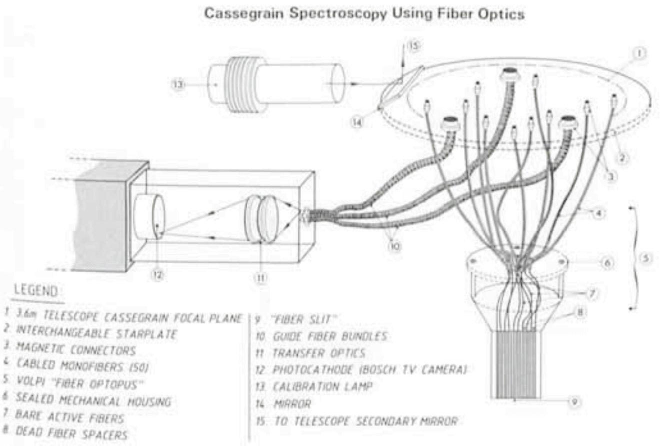

Fig. 1: *Schematic representation of the multi-fiber spectroscopic feed: Here, only 10 of the 50 individual fibers are shown. Light gathered from individual points, designated by precisely located holes in the starplate, is delivered to the Boller and Chivens spectrograph via the mechanically aligned fiber outputs (9). Guiding is achieved by use of coherent fiber bundles (10) and a TV camera.*

Fiber Optopus

The name of this device was chosen because of its optical fiber composition and its octopus-like appearance, as can be appreciated from the photographic illustration in fig. 2. The Optopus, which is the heart of the multiple object spectroscopic system, consists essentially of 50 independent fibers of 200 μm core diameter (about 1.5 arcsec on the sky). Each fiber is protected by an external numbered cable, terminated at one end by a magnetic male connector, and assembled at its other end into a common solid housing.

Inside the housing, the protective cables are removed and the protruding bare fibers are aligned in numerical order in a straight row (interspaced with single dead fibers for better spectral separation at the detector). The ensemble of bare fiber ends (clamped and epoxied into the housing) is optically polished, and thus replaces the conventional Boller and Chivens entrance slit by a line of consecutive circular 200 μ diameter output spots, each of which produces individual spectra on the spectrograph detector.

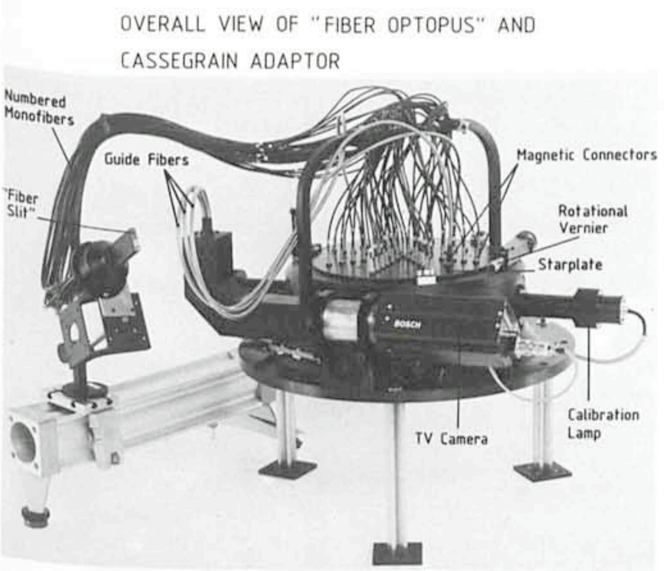

Fig. 2: *Photographic view of the Optopus and associated hardware, before installation on La Silla. The metallic housing attached to the TV camera contains transfer optics for the guidestar images.*

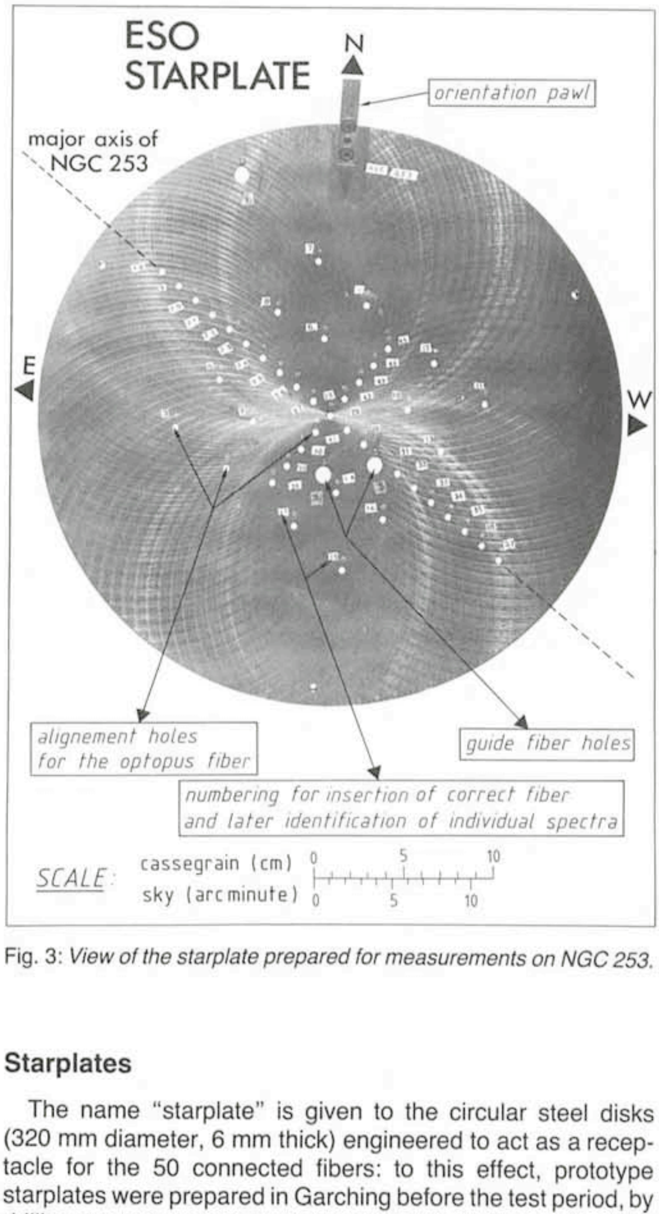

Fig. 3: *View of the starplate prepared for measurements on NGC 253.*

Starplates

The name "starplate" is given to the circular steel disks (320 mm diameter, 6 mm thick) engineered to act as a receptacle for the 50 connected fibers: to this effect, prototype starplates were prepared in Garching before the test period, by drilling accurate connector holes according to the scale of the 3.6 m at the Cassegrain focus.

In order to simplify the production of starplates, which are in principle dispensible items, the fiber connection was achieved by means of simple cylindrical holes reamed to an accurately known diameter. Due to the rather cumbersome design of the magnetic connectors (10 mm diameter) a minimum separation between holes of 10.5 mm was imposed, corresponding to a lower limit of 85 arcsecs for the proximity of objects to be observed with the same starplate.

The guidestar cables, described below, were connected to the starplate via 8 mm diameter cylindrical holes. As can be seen in fig. 3, these holes were also associated with small orientation pins which ensured congruent movements of the observed guidestars when viewed on the TV monitor.

Although it is known that there is a Cassegrain field curvature corresponding to roughly 3 mm between centre and edge of the field, no correction for the resulting defocusing was attempted. This will however be essential in our definitive system.

Guiding System

Since with the use of the multiple fiber adapter the conventional spectrograph slit is removed and replaced by the Optopus output slit, guiding by means of the normal slit viewing system is impossible. Furthermore, since the field is sampled by many fibers at scattered positions, it is very important to establish the correct rotational positioning of the starplate in order to ensure correct alignment of all fibers with their respective objects. The solution adopted for Optopus spectroscopy consists in using coherent fiber bundles which allow any randomly positioned star to be viewed at the fixed bundle outputs via a TV camera. Two sufficiently bright guide stars should be adequate for establishing the correct (α, δ) and rotational alignment of the starplate. The image guiding bundles used for this purpose are each 1 m long and consist of 4 mm diameter (i.e. 30 arcsecs) tightly packed, coherently ordered bundles of 50 μ fibers. An image focused onto such a bundle can be viewed at the other end in the form of a mosaic of about 5,000 points. Under good seeing conditions (~ 1.5 arcsecs) a guidestar would thus cover about 14 mosaic points, allowing good visual determination of its output image position (coverage of only 3 or 4 fibers would give rise to jittery movements at the output). A crosshair reference system was designed to visualize the output image position corresponding to the exact geometrical centre of the cylindrical connector at the input end. This was achieved by photographically reducing a crosshair to a line thickness of about 40 μm. By illuminating the centre of the bundle input end with a small spot the crosshair was precisely located (using a microscope) and glued in the laboratory to the corresponding output image centre. Laboratory measurements showed the resulting crosshair positional accuracy to be better than 50 μm (~ 0.4 arcsec) for all three guide fibers.

By means of two transfer doublets the bundle output faces were imaged onto the photocathode of the TV camera, and a focus adjustment was provided by a sliding movement for the lens barrel. At the beginning of the experimental run, rotational inaccuracies of the starplate (as seen by the positions of the guide stars relative to their respective crosshairs) were initially corrected via the vernier movement on the fiber adapter (fig. 2), allowing small rotations of the starplate relative to the optical axis of the telescope. The angular reference pawl, fixed in exactly the same way to each starplate (fig. 3), was designed to ensure that no further vernier adjustments were necessary with starplates subsequent to the first. Thereafter, correct guiding was ensured by visually maintaining the brightest guide star centred on its crosshair.

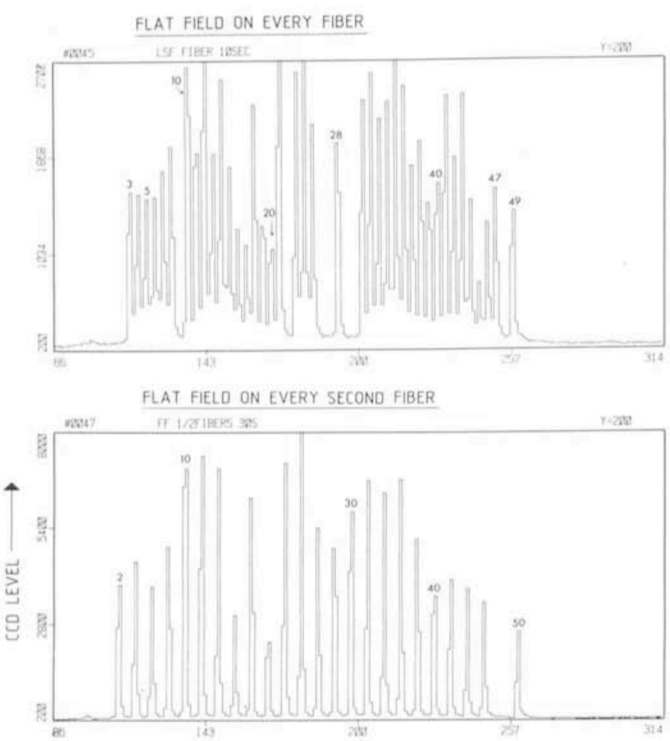

Fig. 4: *Cross-sectional views of one CCD line showing varying fiber output intensities at a given wavelength. When every second fiber is removed the crosstalk effects apparent in the upper figure disappear. The fibers apparently missing from these figures were either unplugged or broken (in the case of nos. 1 and 48).*

Hardware Tests and System Performance

Initial setting up of the fiber system involved firstly the task of shifting the Boller & Chivens spectrograph to a specially prepared structure within the Cassegrain cage, and replacing it by the Optopus adapter which was bolted onto the Cassegrain flange. Thereafter, initial alignment requirements included focusing the spectrograph collimator, rotating the detector and Schmidt camera to give spectra aligned along the CCD pixel rows (small angular offsets can easily be detected in the form of Moiré fringe patterns on the CCD image), focusing of the telescope by the standard Foucault test and thereafter via a guide bundle near to the optical axis, and checking of all electrical functions proper to the Optopus system. No major difficulty was encountered during these operations. The routine operation of starplate changeovers was sometimes hindered by overtight connectors, although the sorting of fibers in order to maintain the correct numerical correspondence between fiber and sky positions was generally the most time-consuming operation. A complete starplate changeover generally took 15 to 20 minutes.

(i) Guiding

The guiding system performed very well since visual balancing of the guide star image in the 4 quadrants created by the crosshair proved to be quite a simple task. In cases when the guidestar lay close to the edge of the usable field, the image was somewhat dilated (due to field curvature defocusing) but guiding was nevertheless possible. In practice it was found that stars fainter than magnitude 12 were not satisfactory for guiding purposes with the present TV camera. This weakness was attributable to slow transfer optics, to losses in the guide bundle fibers, and to poor sensitivity of the camera. The future generation Optopus system will be improved in this respect by using a more sensitive (perhaps a CCD type) TV camera and improved transfer optics.

(ii) Spectral crosstalk

One considerable difficulty encountered was related to the "tail" of incompletely transferred charge left behind by a relatively strong signal during readout. This phenomenon gives rise to considerable crosstalk between spectra from adjacent fibers, as can be seen in fig. 4. Removal of every second fiber, however, virtually eliminates the crosstalk problem. The strong differences in effective transmission through different fibers, noticeable in this figure, are thought to be due mainly to focal ratio degradation which occurs within the fibers. The fibers used are particularly prone to this effect (often associated with "microbending"), which tends to spread the output beam well beyond the focal ratio of the input, if care is not taken to minimize mechanical pressure on the fibers. The transmission losses due to absorption were measured in the laboratory and found to be less then 20 % for almost all fibers in the wavelength range from 4500 Å to 9000 Å.

Astronomical Applications

During the test run a number of spectral images of potential astronomical interest were acquired in order to assess the system's capacity for investigating extended nebulae, galaxies and star or galaxy clusters:

(1) A two-hour exposure of the galaxy NGC 253 was recorded using sampling points along its major and minor axes in addition to a few points on the sky (see fig. 3). It should be possible to study the behaviour of the galaxy's rotation curve over a field of 20 minutes, when these data are reduced.

(2) The coordinates of Hα emission line regions obtained from a triplet plate of the 11th magnitude spiral galaxy NGC 300 were used to produce a starplate for studying more closely the HII regions in this galaxy and their associated spectra.

(3) In order to simplify the observation of extended nebulous structures, a starplate was prepared with a uniform grid of 7 × 7 points spaced at 107 arcsec intervals, thus covering a field of roughly 11 × 11 arcminutes. As an example, we show here in fig. 5 a negative reproduction of part of the Orion nebula on which an overlay of the fiber grid, as it was used in the observation, has been printed. The central guide fiber was aligned with θ_2 Orionis (the brightest of the Trapezium group), and correct rotational alignment of the plate was verified by moving the telescope 428 arcsecs south – and verifying that θ_2 was centred on the "upper" guide fiber. A second verification could be similarly made by moving the telescope 428 arcsecs west of its original position, and checking the image on the third guide fiber. The white numbers indicated on the overlay can be used to identify the fiber numbers which were plugged in sequentially back and forth across the grid. This grid was also used for observations of the Tarantula and Eta Carinae nebulae.

The complete CCD image obtained from Orion is shown in fig. 6, where the emission lines of H_γ, H_β, H_γ, [OIII], [OI], HeI, [NII], [SII] and [AIII] have been indicated. An enlarged portion of this spectrum is shown in fig. 7, revealing more detailed structure in the [NII] and [SII] emission lines. Close inspection of these figures reveals that the spectra are rotated slightly

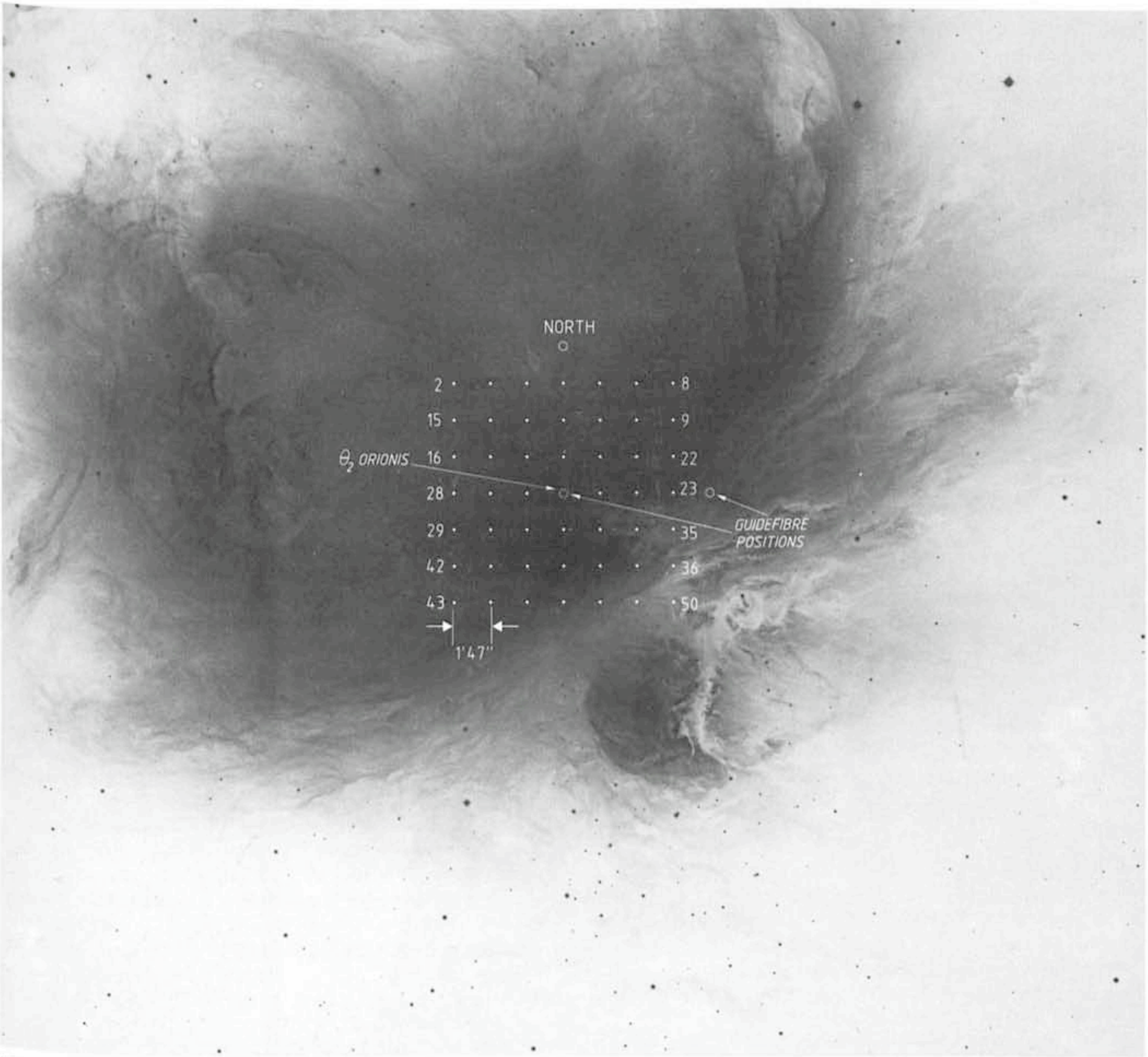

Fig. 5: *Reversed image of part of the Orion nebula, with a white overlay indicating the locations of a 48 fiber grid and of 3 guide fibers. The central guide fiber was centred on θ_2 Orionis (the brightest of the Trapezium stars). The scale here is that equivalent to a 3.6 m prime focus plate (18.9 arcsec/mm).*

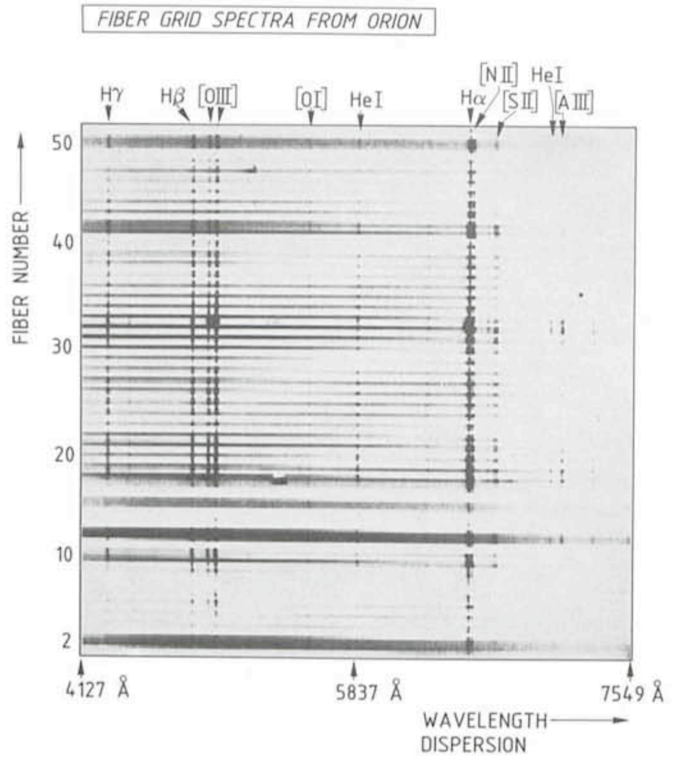

Fig. 6: *Multifiber CCD spectra taken from Orion with the grid starplate illustrated in fig. 5 using a low dispersion grating (171 Å/mm). Dispersion is shown horizontally, with the individual lines corresponding to fibers 2, 3 . . . (48) . . . 50. One can easily discern the H_α, H_β, [O III], He I, H_α and [S II] emission lines. [O I], [N II], and [A III] can also be perceived.*

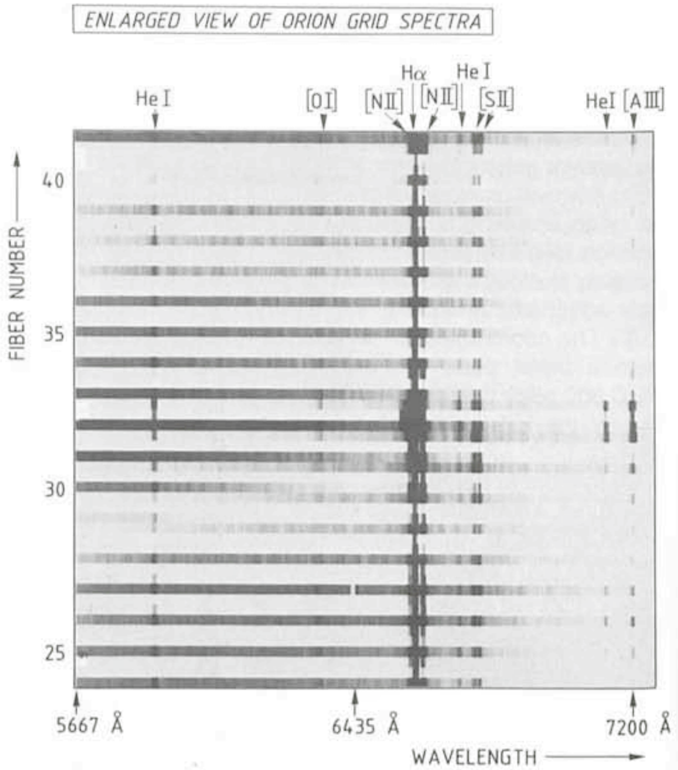

Fig. 7: *Enlarged view of part of the CCD spectrum shown in fig. 6, clearly showing the He I, [N II], H_α and [S II] emission lines present in some or all of the fibers numbered 24 to 41.*

clockwise with respect to the CCD lines. This inconvenience renders the data reduction difficult if extreme care is not taken with correcting for the variable distribution of energy over two or more pixels, for a given fiber at different wavelengths. The crosstalk problem alluded to in fig. 4 is an additional source of difficulties. The CCD chip and all spectrograph optics must be absolutely stable and immune to flexure between the time of spectral and flat-field exposures, if the flat-field correction is not to introduce inappropriate noise to the pixels of interest.

For future studies of galaxy dynamics it will in many cases be convenient to use a standard starplate consisting of a guide fiber located in the centre, together with 50 sampling fibers positioned along either of two orthogonal axes. Having centred the galaxy nucleus on the guide fiber it should be a simple task to rotate the plate in such a way as to align its sampling axes with the major and minor axes of the galaxy. Fairly precise knowledge of the individual fiber positions can be determined a priori, by specifying a plate rotation through a known angle relative to a fixed reference.

Conclusions

Although the Optopus system was developed in a rather short time (6 months) the test run has put into evidence the great potential of multiple object spectroscopy using fiber optics.

Many problems became apparent during the tests, and it is hoped that the 2nd generation device now being developed at ESO will be free of these difficulties, enabling it to exhibit optimal performance in all respects. In particular, the following improvements or modifications will be carried out:

- use of more suitably adapted fibers (in terms of desensitivity to microbending),
- use of connector microlenses to adapt the fiber input beam to f/3,
- design of miniconnectors around 3 mm in diameter (~ 21 arcsecs minimal separation between adjacent fibers), with a more secure fixation principle,
- correction for field curvature in the starplate,
- replacement of the present TV camera by a more sensitive type (perhaps with a CCD detector) to allow guiding on stars down to magnitude 16,
- arrangement of the output fiber slit so as to cover the entire CCD width by the 50 output fibers, thus ensuring adequate empty spacing between adjacent spectra (~ 4 pixels).

Proper functioning of the entire multiple fiber spectroscopy system will also implicate the use of computer software for the following purposes:

- Direct production of magnetic tape programmes for the starplate drilling machine: the drilling coordinates should be determined according to user-interactive measurements of Schmidt plates at ESO, or from accurate data supplied from elsewhere. The drilling instructions will include depth control for field curvature correction.
- On-line data reduction of the raw spectra using software similar to that designed for CASPEC, with the additional capacity for producing contour maps of extended fields in terms of wavelength, temperature, radial velocity, etc.

The new system hardware will be ready for tests at the beginning of the observing period starting in April 1984, and it is hoped that fiber OPTOPUS will be available to visiting astronomers for the following observing period.

Acknowledgements

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