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Successful Commissioning of FORS1 – the First Optical Instrument on the VLT

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1. Introduction

1.1 The Project

FORS, the **FO**cal **R**educer/low dispersion **S**pectrograph, was the first VLT instrument to be designed and built outside ESO. Following a Call for Proposals in 1990, the contract to realise the project was awarded in 1991 to a consortium of three German astronomical institutes (Landessternwarte Heidelberg and the University Observatories of Göttingen and Munich). Due to its large variety of observing modes, a heavy demand for observing time was expected for the envisaged instrument. Therefore, ESO decided from the beginning to order two nearly identical instruments from the consortium. An account of the start of the project is given in [1]. In April 1992 the Preliminary Design Review was held followed by the Final Design Review in February 1994. Immediately afterwards, the consortium started to transform the approved design into hardware. The performance of the instrument and its components was continuously tested in the laboratory during the different stages of

Figure 1: FORS1 installed on UT1. The instrument with the electronics boxes is well visible as well as the tripod on the M1 cell that carries the cable hose. This cable hose (a flexible metal hose) contains all electric power, LAN and cooling water lines for FORS.

Figure 2: FORS1 on the telescope simulator during flexure tests in the integration hall of DLR at Oberpfaffenhofen near Munich.

manufacturing and assembling. In November 1996 extensive tests of the integrated FORS1 instrument were started in an Integration Facility of the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) in Oberpfaffenhofen near Munich. A telescope and star simulator allowed to tilt and rotate the instrument and to simulate stars in the field of view. Electro-mechanical functions, image motion due to flexure, optical performance, the calibration units and the instrument-related software were checked for their conformity with the specifications given by ESO and were optimised if deemed necessary. For details see [7] and [8].

Within the consortium the tasks were distributed as follows:

• Heidelberg: optics, data reduction software, telescope and star simulator

• Göttingen: mechanics, auxiliary devices

• Munich: instrument-related software, electronics, project management

The detector system, based on a SITe 2048 × 2048 CCD with 24-µm pixel size, was developed by ESO.

The manufacturing of the twin instrument FORS2 will be completed by the end of 1998. After the performance tests, which will take about half a year, FORS2 will be shipped to Paranal in summer 1999. It will be installed on VLT UT2 at the end of 1999 and released for observation in March 2000.

1.2 Design Parameters

FORS has been designed as an all-dioptric Cassegrain instrument for the wavelength range from 330 nm to 1100 nm and it will cover the following observing modes:

• Direct imaging with two image scales (0.2 and 0.1 arcsec/pixel, corresponding fields of view of 6.8′ × 6.8′ and 3.4′ × 3.4′, respectively)

• Low-dispersion grism spectroscopy (resolutions between 200–1800 for 1 arcsec slit width, reciprocal dispersion 44–228 Å/mm)

– Multi-object spectroscopy (MOS) of up to 19 targets with individually adjustable slits

– Long-slit spectroscopy (mask with 9 slits with fixed widths between 0.3 and 2.5 arcsec)

• Imaging polarimetry and spectro-polarimetry (linear and circular; FORS1 only)

• Echelle spectroscopy (FORS2 only), with resolutions up to about 5000 for 1 arcsec slit width, reciprocal dispersion 15–40 Å/mm

• Multi-object spectroscopy with slit masks (FORS2 only), for survey-type programmes where more than 19 objects are observed or special slit shapes are needed.

A more comprehensive description of the instrument performance is given in [2], [3] and [4]. The grisms used in FORS are described in [5].

The main scientific objective of FORS was to extend ground-based spectroscopy and photometry to significantly fainter objects than could be reached so far. Among the tasks of FORS will be the quantitative analysis of the properties of galaxies at distances up to 10 billion light-years and beyond. Thus it will become possible to obtain information on the universe in its early phases resulting in fundamental insights into the creation and development of galaxies. Investigations of clusters of galaxies and of single stars in galaxies may shed light on the nature of the dark matter. Spectroscopy of luminous stars, supernovae and planetary nebulae in remote galaxies will allow us to obtain a better knowledge of the expansion of the universe and will provide information on the origin of chemical elements outside our own Galaxy. Even in our Galaxy new discoveries concerning e.g. the late phases of stellar evolution or the creation of stars and planetary systems are to be expected (see also [6]).

2. The Final Steps

By the beginning of 1998 the FORS project started to home in on the final round. The instrument had already been tested extensively in the DLR facility. In January ESO's Optical Detector Team delivered the final scientific CCD system, together with one of the first copies of the newly developed FIERA CCD controllers.

Another round of tests followed which also served as the "First Verification Test" specified in the contract to be done before shipping the instrument to Chile. During these tests particular attention was paid to proving that the image quality in all observing modes conformed to the specifications. During another extensive set of measurements we checked for image motion due to instrument flexure (Fig. 2). This is particularly important for FORS as a Cassegrain instrument that is subjected to wide variations in spatial orientation during tracking. The results are published in [8] and fully comply with the finite element calculations done during the design phase. Other tests included the setting accuracy of the slitlets for the multi-object spectroscopy, which is crucial for the successful use of that mode. Moreover, we tested already in Europe the complete control system, from the workstation software through the local area network connection to the software running on the three instrument local control units ("board computers") and their co-operation with the FIERA detector controller. In addition, the interface to the Telescope Co-ordination Software (TCS) was tested with the TCS simulator at ESO/Garching. All tests were passed successfully, and by the middle of June FORS was removed from the telescope simulator to be packed for shipping.

It had been decided to transport FORS by air to Chile. This meant first a transport by truck from Oberpfaffenhofen to Frankfurt airport and from there by airplane to Santiago de Chile. The packing therefore had to take into account the specific requirements of this multiple transport: The instrument was taken apart as far as necessary to allow safe packing in dedicated boxes. The boxes for the major instrument sections consisted of sturdy frames on which wooden boxes were sitting, damped by specially dimensioned coiled steel springs. All other components like drive units, electronic racks, filters, grisms, etc. were packed in aluminium containers. Altogether the shipment consisted of 22 boxes. After the transport had arrived in Santiago they were loaded onto two climatised trucks with air suspension for the final 1200-km journey to the VLT Observatory on Paranal. Thanks to the very professional way this was handled by the truck drivers, also this 2-day trip passed without problems – under the

Figure 3: Re-assembly in the Auxiliary Telescope Hall on Paranal with FORS1 on the integration stand in the background, the control cabin at right and the Cassegrain carriage (foreground left) which is used for all major transport and handling operations.

watchful eyes of the accompanying project manager.

In the meantime, the preparations on Paranal for the re-assembly of FORS1 were nearly complete: erection of a specially designed integration stand, setting up of a local-area network for our workstation and many other little things which would allow us to start integration of the instrument immediately after its arrival on the mountain.

Re-assembly in the Auxiliary Telescope Hall (ATH, Fig. 3) in the Paranal base camp went very smoothly. The instrument sections were unpacked, transport locks and dampers removed, and the main optics inserted. In parallel the electronics were activated. Finally, all instrument sections were put together on the integration flange and the detector system attached. Another round of tests involving functional checks of all motors and series of screen flats and pinhole exposures followed which proved that we were really ready for installation on the telescope.

In the morning of September 10, the ATH crane was used to put FORS1 (well packed in plastic foil to protect it against dust during the following 3-km journey) onto the loading area of the large Paranal air suspension truck. It is a strange feeling to watch the work of the past 9 years hover 5 metres above the ground, supported only by a couple of thin wires!

Very slowly and carefully, the truck moved up to the top of the mountain, accompanied by an escort of cars forcing all other traffic out of the way, and some colleagues constantly having an eye on the truck with its precious load (Fig. 4). After nearly one hour, the convoy arrived in front of UT1. The following operation proved to be the most time consuming of the whole transport and installation: getting FORS1 and the carriage down from the transport truck using the huge M1 cell lifting platform. The carriage with FORS1 on it was then lifted through the trap door opening onto the telescope fork base with the enclosure crane and soon afterwards FORS1 was mounted at the UT1 Cassegrain flange! Finally the CCD detector in its cryostat was attached at the FORS1 bottom end as well as the tube tripod carrying the cable hose with the electrical power, LAN and cooling water lines. The next day saw the first test of the complete FORS1 system in the telescope environment (Fig. 1) which also went without problems. Next was the loading of all auxiliary optics (filters, grisms, Wollaston prism) in the corresponding openings of the filter and grism wheels.

Figure 4: FORS1 on its way to the telescope.

3. At Last: First Light!

On the evening of September 15 finally everything was ready: The sky over Paranal was clear, the enclosure was opened, the telescope pointed to a photometric standard star field close to zenith, the image analysis was performed by the active optics system and the instrument shutter opened for a 10-second exposure through the Bessell V filter. The excitement in the control room was growing while the image appeared on the Real Time Display station: the stars looked neatly small and round – we had successful First Light! The camera focus had been pre-set to the value calculated according to the current temperature, and as the following series of exposures showed this was exactly the right setting.

The rest of this night and the subsequent ones were used to conduct a quick series of observations in all instrument modes to confirm that the overall performance was as expected. In the fourth night a thorough verification programme began during which we made exposures in all observing modes, with all available filters and grisms. Altogether about 20 Gb of data were taken during the 21 nights of the first commissioning period. Some of these data were reduced in a preliminary way and made public immediately (see http://www.eso.org/outreach/press-rel/pr-1998/pr-14-98.html and http://www.eso.org/outreach/press-rel/pr-1998/phot-38-98.html); now work is going on with the remainder to prove that the instrument indeed fulfils the specifications. A preliminary assessment is given in the following section.

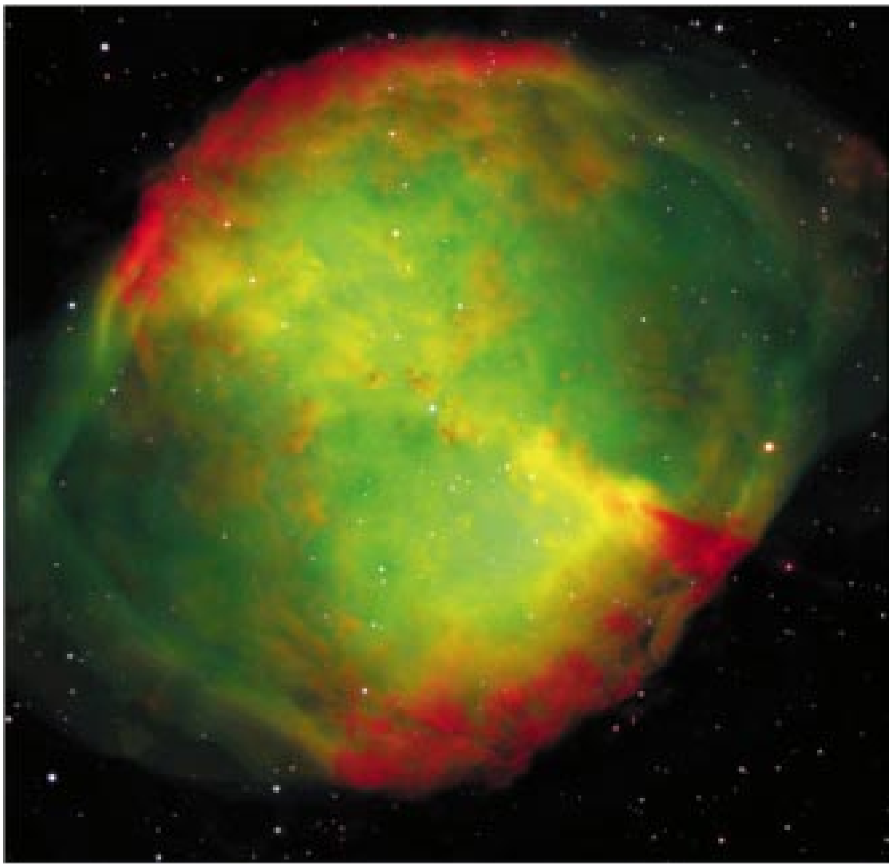

Figure 5: Colour image of the Dumbbell planetary nebula (M 27), obtained on September 28, 1998. This is a three-colour composite based on two interference ([OIII] at 501 nm and 6 nm FWHM – 5 min exposure time; H-alpha at 656 nm and 6 nm FWHM – 5 min) and one broad-band (Bessell B at 429 nm and 88 nm FWHM; 30 sec) filter images. North is up; East is left.

4. Preliminary Results

During the first commissioning phase, all observing modes of FORS1 were systematically tested with astronomical targets. The commissioning tests span a very wide range from photometric calibration through astrometric tests to extensive polarimetric observations. The second main topic during this phase was the proper interaction between telescope, instrument and the software user interfaces (see below). Most optical tests were done both in high and standard resolution mode and for a large number of optical components. Although these repetitive tests dominated our work we also obtained some eye-catching souvenirs, e.g. observing the splendid face-on spiral galaxy NGC 1232 and the Dumbbell nebula M27 (Fig. 5), both of which fit very well in the field of view in standard resolution mode.

After attaching FORS1 to the telescope, the standard maintenance procedures for preparing the instrument for astronomical work were executed. They include an automatic check of all electromechanical functions, insertion of optical components as well as the alignment of CCD, grisms and Wollaston prism. At the end of this stage the instrument was ready for the “first astronomical light”. This first light was used for some initialisation procedures like telescope/instrument focusing or determination of the angle between the CCD rows/columns and the telescope axes. After this was done, the instrument was ready for astronomical work. The first observations were performed with an engineering Instrument Control Panel which allows the execution of single exposures. Later on, FORS templates as executed by BOB (the broker of observation blocks) were used.

The Telescope Control Software with the real telescope behind it and real sky images constituted two new interfaces for the FORS Software. They introduced modifications in its uppermost layers, i.e. in the Observer Support Software (OSS), in the FORS templates and in the Observation Software (OS). The remaining software modules i.e. the Maintenance and Instrument Control Software were working perfectly almost without any modifications.

The Observer Support Software is a Graphical User Interface based on ESO SKYCAT, which will be used for the preparation of observations in all observing modes. It allows e.g. the preparation of the MOS set-up, i.e. it specifies the telescope pointing position, the telescope rotator position and assigns targets and MOS slits. The astronomer will use this tool in advance for preparation of the observations.

The FORS templates provide support for the following observing modes: imaging (IMG), imaging polarimetry (IPOL), long-slit spectroscopy (LSS), multi-object spectroscopy (MOS) and multi-object spectropolarimetry (PMOS). For each mode two templates exist: one for internal calibration (screen flat and wavelength calibration) and the other for science observation and external calibration (sky flat and standard stars). Templates necessary for all modes are collected in the category *ALL* (e.g. dark, focus or acquisition templates). The templates are built in such a way that all features of FORS can be used in their full variety.

Observation Software is triggered by the FORS templates to perform the set-up of instrument, detector and telescope and to execute the exposure. It writes also the header information in the output FITS file. In interaction with FORS templates, this module is also responsible for the alignment of targets and slits for spectroscopic observations.

One of the main characteristics of FORS is the very high stiffness of the instrument. Any motion of the image on the detector would degrade the instrument performance.

Therefore, a passive flexure compensation scheme was part of the FORS design. The passive system compensates any motion of the collimating optics by tilting the camera.

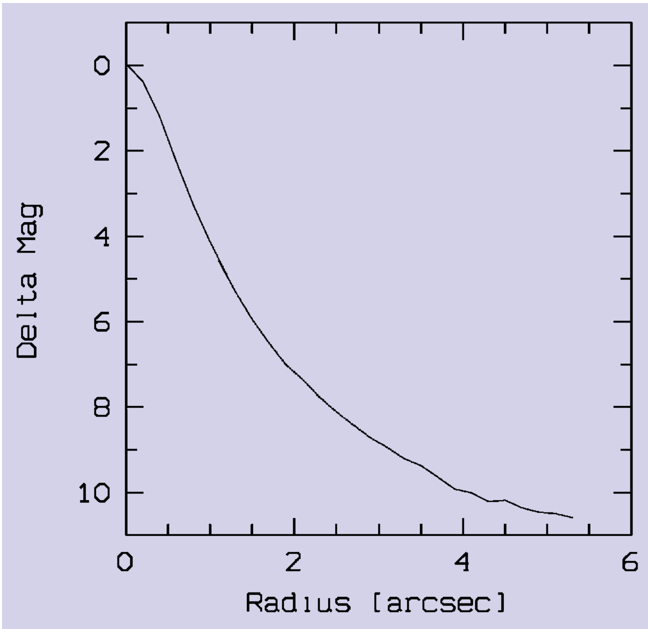

Figure 6: Profile of a stellar point spread function in standard resolution mode.

Tests with our telescope simulator confirmed that the internal image motion from the focal plane of the telescope to the focal plane of FORS is smaller than a quarter of a pixel during long exposures of one hour in standard and two hours in high-resolution mode.

External flexure and motions of FORS relative to the guide probe and the guiding accuracy were tested with a long time series observation of an empty field, which showed that the external flexure and the guiding can be kept within a fraction of a pixel during several hours of observing time and thus complies with the contractual specifications.

In direct imaging, the image quality measured on the detector was always limited by the outside seeing. Most of the time it was better than the values indicated by the DIMM seeing monitor and always compatible with the measurements by the adapter guide probe. The best FWHM values achieved range from 0.48″ for a 4-min. exposure in the U band to 0.35″ in the I band (1 min.). No image degradation due to the FORS1 optics could be detected over the whole field of view. The variation of the stellar FWHM over the field is less than 3% with both collimators. A composite PSF profile for the standard resolution collimator is shown in Figure 6. The radius of the PSF 10 mag below the peak brightness is about 4″, an excellent value.

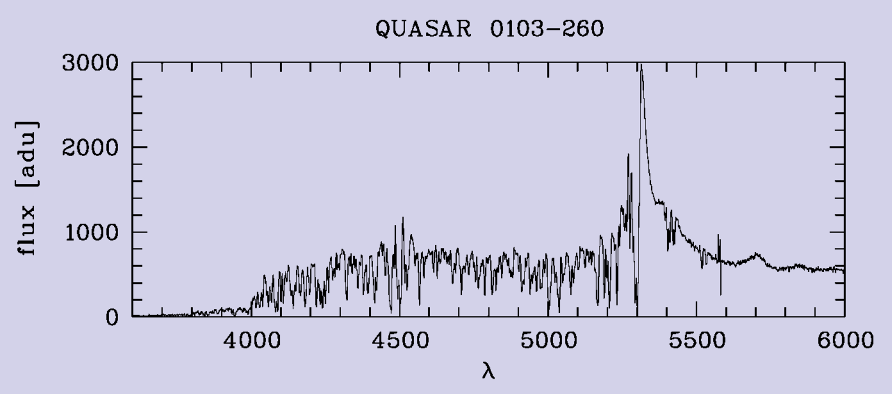

Figure 7: A spectrum of the quasar Q0103-260. The quasar shows a prominent Lyman alpha forest.

The characteristics of all grisms were analysed in long-slit and multi-object mode using test observations of various different types of targets. The measured spectral resolutions were found to match very well the theoretically calculated values for two-pixel sampling. As an example we present in Figure 7 a section of the spectrum of the distant quasar Q0103260 (visual magnitude V = 18.8, redshift z = 3.36). This spectrum is based on a 30-minute FORS exposure taken with a 1.0″ slit and the 600B grism (600 lines/mm blazed in the blue spectral range). The prominent emission line at 530 nm is the Lyman-α resonance line of atomic hydrogen, redshifted from 122 nm to 530 nm. To the left of the Lyman-α emission line we see clearly the "Lyman-α forest" formed by numerous Lyman-α absorption lines of hydrogen clouds of lower redshift located between the quasar and us. Q0103-260 is a particularly interesting object for studying the Lyman forest since this quasar is in a region close to the south galactic pole with its exceptionally low density of foreground stars and foreground galaxies. Therefore, it will be possible to obtain with FORS on the VLT very deep images and spectra of faint very distant objects in the field around this quasar in order to search for objects that may be connected to the hydrogen absorption features in the spectrum of the quasar.

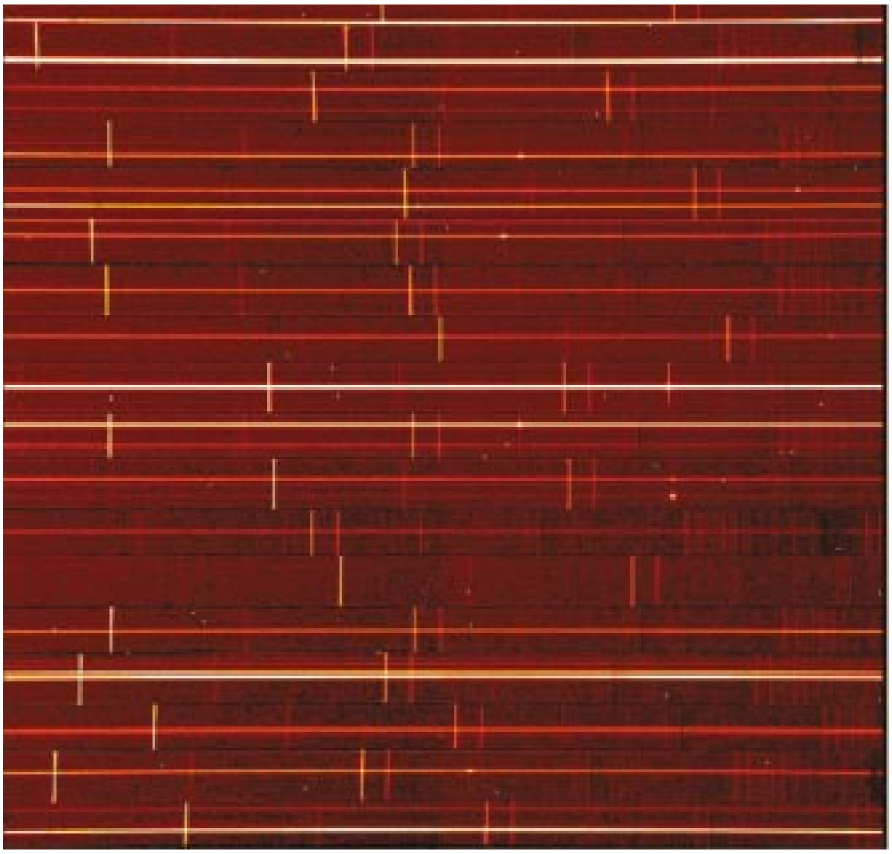

Figure 8: Multi object spectroscopy of stars located in the open cluster NGC330 of the Small Magellanic Cloud, exposure time 6 minutes. The spectra appear as bright lines spanning the full field in horizontal direction. The shorter, bright vertical lines are spectral emission lines originating in the terrestrial atmosphere (airglow); they show the extent of the individual slits. Note that in some slits more than one star spectrum has been registered, thus further increasing the observing efficiency.

Several multi-object spectra were also taken to test the functionality of the object acquisition and the instrumental behaviour in the MOS mode. In Figure 8 the spectra of 19 stars (including several Be stars) in the open star cluster NGC330 in the Small Magellanic Cloud are shown.

Imaging polarimetry was done for a sample of unpolarised and polarised standard stars, both for linear and circular polarimetry. Systematic errors due to the fact that our retarder plates are built as mosaics are less than $2 \ 10^{-4}$. Also linear and circular spectropolarimetry was done to calibrate the angular zero point of the half-wave plate as a function of wavelength and to evaluate possible cross-talk between the Stokes parameters. As an example, the circular polarisation of the 14.8-magnitude magnetic white dwarf GD229 is shown in Figure 9. The sharp features in the polarisation spectrum around 420 nm, 530 nm, 630 nm and 710 nm correspond also to broad 'absorption' features in the flux spectrum. Most of those can be explained by stationary Zeeman transitions in a magnetic field of 25 to 60 MG. The very low noise of 0.15% was reached with two exposures of 10 minutes. At this level the noise is in good agreement with the photon noise and no systematic effects appear.

As pointed out above, FORS was developed mainly to do spectroscopy

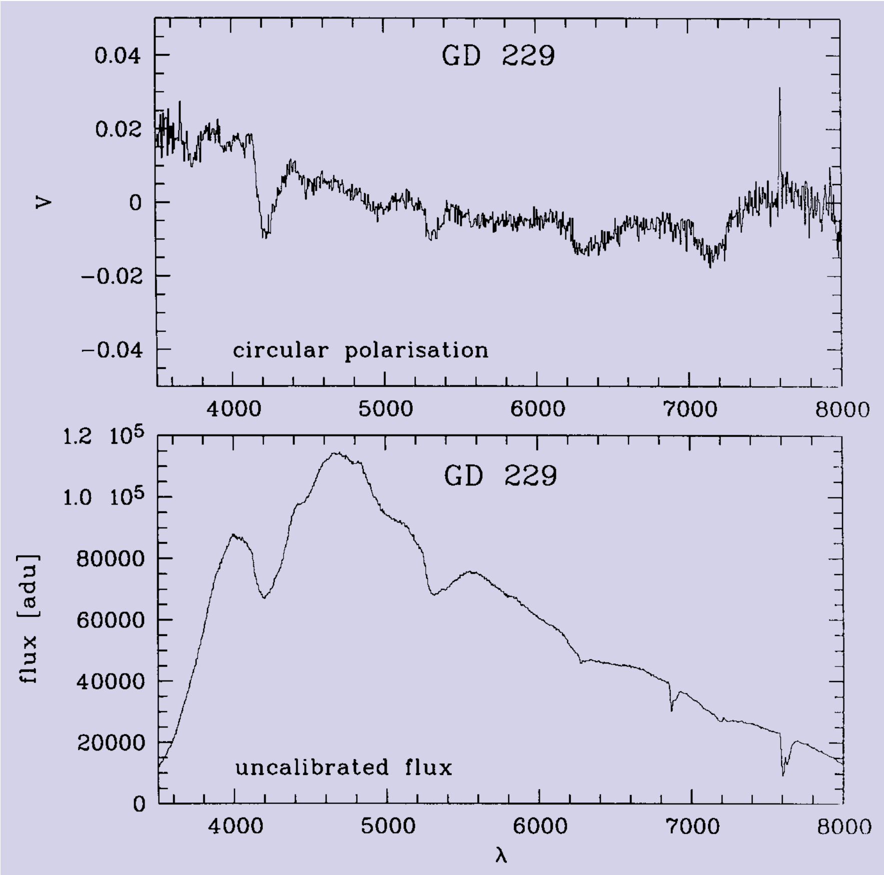

Figure 9: Circular spectro-polarimetry of the magnetic white dwarf GD229. The amount of circular polarisation is shown on the top and compared to the flux spectrum below.

on very faint objects. Therefore, we made spectroscopic test observations of distant galaxies up to 25 magnitude in R and I. Moreover, we successfully obtained spectra of faint gravitational arcs around two galaxy clusters. The reduction and evaluation of these data is still in progress.

5. A Bright Future Ahead

The FORS schedule foresees a second commissioning period after the assessment of the data from the first commissioning; after this the instrument is officially handed over to ESO who performs one week of Science Verification in January 1999. The beginning of Observing Period 63 on April 1, 1999 marks the start of regular observations of FORS on UT1 and the arrival of the first Visiting Astronomers on Paranal. By that time also a core team of telescope and instrument operators will have taken up duty to carry out the approved observing programmes. 182 proposals have been submitted for observations with FORS1 alone during its first 6 months of service – proof of trust that the instrument will live up to the expectations! And the extrapolation of our experience gained during the commissioning truly lets us expect that FORS1 on the VLT will be a world-class facility for the exploration of the very faintest objects.

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