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The UHRF: Spectral resolution to the limit

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ABSTRACT

Until recently the study of cool clouds of insterstellar matter had been limited by the relatively low spectral resolutions provided by extisting spectrographs. The Ultra-High-Resolution Facility (UHRF) recently commissioned at the Anglo-Australian Telescope has changed dramatically this panorama by delivering for the first time resolutions approaching one million, near the diffraction limit of the largest échelle gratings available. The instrument shares the east coudé room with the University College London Échelle Spectrograph (UCLES), in what is now one of the most powerful spectrographic installations worldwide. This contribution describes the characteristics of the UHRF, including its design, manufacture, testing and commissioning. The UHRF incorporates a novel image slicer (described elsewhere in these proceedings), which allows ultra-high-resolution observations on faint objects. Astrophysical results from the first observing runs are presented to demonstrate the UHRF performance in both resolution and throughput.

1. INTRODUCTION

The study of cool interstellar matter has been one area of astrophysical research affected by the lack of adequate instrumentation to provide spectral resolving powers in the region of $\lambda/\Delta\lambda \approx 10^6$ that are needed to resolve the profiles. Some pioneering work has been done on bright stars using relatively inefficient techniques achieving resolutions of about one fifth to one half of the above value (see for example the work published by Hobbs[1] on ζ Ophiuchi using a triple étalon Fabry Pérot interferometer).

This situation was stressed by Barlow[2] who suggested the implementation of a very long camera at the time when the University College London Échelle Spectrograph (UCLES, Walker *et al.*[3,4]) was at its early stages. This camera would be able to approach the diffraction limit of the large échelle grating of UCLES ($\lambda/\Delta\lambda \approx 10^6$). Although this option was not funded at the time, the project received decisive technical and financial momentum a few years later, when Peter Gillingham (then at the Anglo-Australian Observatory, AAO) implemented a temporary Littrow spectrograph to take advantage of the supernova SN1987a and observe cool sodium clouds towards the Large Magellanic Cloud (Gillingham[5] and Pettini[6]). As a consequence of the success of this experiment, the instrument now known as the Ultra-High Resolution Facility (UHRF) was developed and installed in the same coudé room of UCLES.

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2. OPTICAL CONCEPT AND LAYOUT

The UHRF follows the basic principle of the Gillingham spectrograph: it uses the largest échelle grating available mounted in the Ebert configuration behind a collimator lens which works in double pass. Capability for astrophysical work in the UV was a very important requirement, so all transmission optics had to be made of fused silica.

Accommodating such an instrument within the space left by UCLES in the coudé room was a major task. The idea was to share the facilities available in the slit area of UCLES (such as wavelength calibration and acquisition and guiding units), which implied sharing its main optical axis. A large box containing the collimating lens and the échelle grating would be placed in front of the collimator unit of UCLES. As the diameter of the collimated beam would be at least as big as that of UCLES, it was necessary to include a diverging lens behind the slit area in order to expand the beam. The large box was called 'collimator-échelle unit' and was finally mounted on a rail system which allows it to be placed in and out of the main optical axis (see figure 1).

The critical items in the entire design of the UHRF were the selection of the échelle grating and of the system for cross-dispersion. On the one hand, a finer échelle (say, 79 or 316 grooves/mm) would allow the use of a prism cross-disperser to provide enough separation between the échelle orders due to its wider free spectral range. On the other, a coarser échelle (31.6 grooves/mm) would provide shorter orders but would require gratings for separating them. It was finally decided to take the second option because it was not clear whether a prism-based cross-disperser would give diffraction-limited performance (as a grating-based one does). In addition, the very long orders of the finer échelle gratings implied an impractical range of scanning angles. The selected échelle grating is from Milton Roy Co. It has been ruled at 31.6g/mm on a blank of 204 by 408mm and its blaze angle was measured at OSL as 64.95°.

It became evident that the UHRF would require a choice of several gratings for more efficient cross-dispersion at different wavelength ranges. It was not possible to find a suitable layout with the cross-disperser placed within the full-size collimated beam. A novel solution was adopted: the cross-disperser would be half the way down the converging beam from the main collimator, preceded by a diverging lens used to produce a smaller collimated beam. After the cross-disperser, another lens would produce the image of the spectrum on the detector. The cross-disperser unit is shown in figure 2 and the final layout of the Anglo-Australian Telescope (AAT) coudé room (including components of both UCLES and the UHRF) appears in figure 3.

It was anticipated that precise focusing would have to be done for each instrumental configuration, so Hartmann shutters had to be included near the collimator area.

3. OPTICAL DESIGN AND MANUFACTURING

The main goal of the optical design was to achieve near diffraction-limited performance producing an image of a slit as narrow as 30 or 40μm. The throughput was optimized by selecting a collimated beam overfilling the projected échelle grating by 25 percent (Diego and Walker [7]). Consequently a slightly wider slit could be used to transmit more light and also to minimize diffraction effects at the slit, which would throw light away from the collimator (Gillingham[5])

Having the collimator in double pass, the beam separation at the échelle grating was kept to a minimum 2°. Nevertheless, this still produces large astigmatism (elongated images along the slit, which fortunately do not affect spectral resolution).

In addition, it was understood that the UHRF would not be very useful without image slicing. The inevitable consequence of this was that a fair amount of cross-dispersion would be required to accommodate the wide échelle orders projected by the long slit produced by a some sort of image slicer. A major piece of research and experimentation on image slicers was carried out and resulted in the successful development of the Confocal Image Slicer

(CIS, patent pending, Diego[8]) described in a separate contribution in these proceedings. A very strong cylindrical lens was planned to collapse the width of the spectrum on the detector in order to minimize effects by cosmic rays, read-out noise and dark current, all of them proportional to the detector area.

Another goal was to provide lower resolution modes to increase versatility. This was done by compressing the beam before the detector with a choice of two singlet lenses of different curvatures and by shifting the detector to the resulting focal positions (figure 3).

A choice of four 110mm square gratings for cross-dispersion was provided. The UV grating has 2400g/mm and is used between 3000Å and 3800Å. The B grating has 1800g/mm and is used between 3900Å and 4900Å. The V and R gratings have 1200g/mm and are used from 4900Å and 6000Å, respectively. It would also be possible to isolate échelle orders with interference filters which could be placed in filter wheels available behind the slit. In this case the cross-disperser gratings would be replaced by a choice of flat mirrors coated for red or blue wavelengths.

The ray-tracing model of the UHRF needed to be dynamic as the optical configuration would change as a function of wavelength:

- Not being achromatic, the main and secondary collimators would have to be displaced along the optical axis, as the detector would have a fixed position.
- As the UHRF would work in single échelle order mode and typically only a few angströms would fit in the 20 or 30mm of detector length, it would be necessary to tilt the échelle grating and rotate the selected cross-disperser grating with high accuracy and repeatability in order to locate the desired spectral region.

Following the UCLES philosophy (Diego[9,10]), the UHRF ray-tracing model calculates all angles and positions and is also used to drive the control of the real instrument.

The main collimator is a plano-convex lens with a clear diameter of 300mm. It was entirely produced at OSL, where the convex surface was given a quasi-hyperbolic shape to eliminate spherical aberration.

The secondary collimator was left as plano-concave with spherical surface. The imaging lens is also a plano-convex figured at OSL to an aspherical shape. Figuring this lens was done in the same room (at OSL) in which the UHRF was being assembled and tested, so the lens could be placed in its position within the UHRF providing a null-test against which the figure could be produced to compensate any residual aberrations from the entire instrument. The same procedure was used to figure the focal-reducing lenses used for lower resolution modes.

In good agreement with ray-tracing results, the measured width of the image of a narrow slit is less than 40μm along its 20mm length and anywhere within a field 40mm long.

4. MECHANICAL DESIGN

Special care was taken to ensure rigidity and to avoid friction and backlash in all mechanisms. The collimator-échelle unit is mounted on a triple system of linear displacement: first it can be placed in and out of the main optical axis in order to leave it accessible to UCLES. This is done by a linear actuator and recirculating ball bearings along cylindrical rails (figure 1, a and b); then there is a similar system for positioning the unit along the optical axis as a function of wavelength (coarse collimation); finally, the box containing the échelle grating and the main collimator is hanging from a 'flexural cradle' (friction and backlash free) pushed by a motor-mike for fine collimation. Inside the box, the échelle grating is mounted on knife pivots in the same way as that of UCLES (Diego *et al.*[11]) and its tilt angle is adjusted by a motor-mike pushing in a tangent-arm arrangement. This allows scanning along the échelle orders (see figures 4 and 5).

The cross-disperser unit is a large box containing a turret, the secondary collimator and the imaging lens for the ultra-high-resolution mode (figure 2). The turret has six positions (four gratings and two flat mirrors) which are selected by a rotation-and-plunger mechanism. At the centre of the turret there is a tangent-arm pushed by a motor-mike linked simultaneously to all six cells which rotate about a vertical axis to allow the selection of échelle orders (figure 6). The cell of each grating has an offset angle according to the corresponding blaze angle.

The same rotation-and-plunger mechanism is used to select one of the focal-reducer lenses located on another turret between the cross-disperser unit and the detector (figure 3).

A detector carriage can accommodate either the Imaging Photon Counting System (IPCS, Boksenberg[12]) or any of the CCDs available at the AAT. This carriage is mounted on a long rail which allows it to be placed in the focal positions corresponding to the three spectral resolution modes.

5. CONTROL

All changes in the optical configuration are fully motorized, encoded and remotely controlled from a local micro-computer (68000 based). The position and focus of the spectrum are encoded by Linear Variable Displacement Transducers (LVDT) placed in the relevant mechanisms. The LVDT's are directly attached to the moving components in order to provide absolute positions and repeatability.

Encoder values are calculated by a hybrid model running from the Observatory main computer under the ADAM environment (*STARLINK* Project, UK). The model contains information from the ray-tracing model and empirical data obtained during the commissioning phases, incorporating residual alignment and other minor errors. The final model is still under development and will allow any wavelength to be automatically positioned and focused. In the meantime, most of the wavelengths relevant to interstellar work have been located 'manually', counting échelle orders and identifying known lines in the comparison ThAr spectrum. The high accuracy, stability and repeatability of the LVDT encoding system are good enough to re-locate at any time any of these wavelengths within a few pixels. The corresponding encoder values are included in a temporary user manual being produced by the AAO (Spyromilio[13]).

6. COMMISSIONING AT THE AAT

Commissioning the UHRF was a lengthy process in which the general alignment had to be verified many times to bring it as close as possible to the theoretical model. The process was also affected by the commissioning of the very first prototype of the Confocal Image Slicer delivering 17 slices, followed by a more refined version delivering 35 slices and covering the entire width of a 20mm CCD when the cylindrical lens was not used. Although this slicer would work well with a larger detector, it had to be masked down in order to accommodate some background signal within the CCD. By doing this, the cylindrical lens had to be removed as it would otherwise concentrate both the spectrum and the background signal on a single narrow strip, making it impossible to separate them during data reduction (see figures 7 and 8). As a result of masking, the original square area of $1.5''$ in the core of the seeing disk is reduced to an equivalent area of $1.5''$ by $0.7''$. Further research may help to improve this situation. It is important to note that atmospheric dispersion may shift the image at the observed wavelength out of the CIS aperture. Although the AAT has an excellent guiding system able to compensate for this, hopefully an atmospheric dispersion corrector could be installed in the near future.

In a preliminary report (Diego *et al.*[14]) we mentioned the expected problem of lack of sufficient lines from the ThAr lamp within the small area of the detector, which would make wavelength calibration almost impossible in some spectral regions. The use of étalons in white light to produce a pattern of emission lines (Edser-Butler bands) regularly spaced at, say, 0.5Å intervals has been reported by Ouellette *et al.*[15]. Such a system was planned for the UHRF but its implementation would have been too complicated as the device needs strong illumination associated with heat which would require a thermostatic environment to minimize spectral shifts of the reference lines. It was fortunate to find that when the ThAr lamp is placed just in front of the slit or slicer, the illumination of the instrument is much stronger and then many faint Th lines appear in the spectrum. This requires careful calibration which then can be used in the future. After this discovery, the Edser-Butler band approach was abandoned.

7. RESULTS

The UHRF has been very active during and immediately after its commissioning period. The results presented here were obtained using the Confocal Image Slicer to demonstrate the relatively high throughput and resolution of the instrument. It must be noted that both UCLES and the UHRF are mounted on a heavy structure originally conceived for a classical coudé spectrograph. The structure was modified by the AAO staff and is currently supported by four air pads which isolate it from mechanical vibrations in the building. Combined with the stable atmosphere in the coudé room, these are important factors contributing to the high quality of the UHRF images.

The evaluation of the instrumental profile of a spectrograph capable of resolving almost anything required very special light sources. For this purpose, a HeNe laser with stabilized frequency was included with the UHRF. This laser provides a line at 6328.16Å which would only be resolved at $\lambda/\Delta\lambda \approx 10^8$ (well beyond the UHRF possibilities). In addition to this, a similar laser delivering a green line (5433.647Å) was borrowed from the Australian CSIRO National Measurement Laboratory and tried on the UHRF in January, 1994. The FWHM of the profiles of both lines indicate a resolution of 990,000.

The first scientific projects included observations of molecular and atomic lines towards ζ Ophiuchi (Crawford *et al.*[16] and Barlow *et al.*[17]). There is also a project to monitor the evolution of the complex line structure at Ca K in β Pictoris (see Crawford *et al.*[18]). In January 1994, the UHRF was used to look at atomic lines towards B stars in Orion and Scorpius. Relevant spectra appear in figures 9 to 14. From these data is is possible to calculate that a star of V≈9.0 would give a signal to noise ratio of 30 in 2.5 hours. This would bring the brightest stars in the Large Magellanic Cloud within reach of the UHRF.

8. CONCLUSIONS

It is very satisfactory to report that the UHRF has met its design specifications and that it has opened a completely unexplored panorama for the study of the interstellar medium. Some of the main disadvantages of the UHRF are due to the limitations imposed by the current CCD detectors. This will change as new large detectors become available and then the full potential of the UHRF can be fulfilled. In particular, we hope to try soon the new BIGMIC photon counting detector, being developed at UCL (Fordham *et al.*[19]). Extending the resolution of a grating spectrograph by increasing the focal length of its camera and reducing the width of the entrance slit proved very successful due in great part to the high throughput delivered by the Confocal Image Slicer. Hopefully this contribution has shown that the technique is simple and relatively cheap, so it is expected that similar facilities will soon be developed elsewhere. The UHRF is now available to the astronomical community and together with UCLES is taking a considerable amount of telescope time, so the advent of a coudé auxiliary telescope may be a natural consequence in the near future.

9. ACKNOWLEDGEMENTS

We are grateful to Peter Gillingham (now at the Keck telescope) for his novel ideas and fruitful discussions. This project received great support and encouragement from Russell Cannon, director of the AAO. Terry Dines, from I.C. Optical Systems produced and assembled the two versions of the Confocal Image Slicer. We are grateful to the Australian CSIRO National Measurement Laboratory for facilitating their stabilized green laser. Commissioning of the UHRF was greatly facilitated by the positive attitudes and high professionalism of the AAO staff. The UHRF was designed, built and commissioned by members of the Optical Science Laboratory at UCL under grant GR/F/23880 from the UK Science and Engineering Research Council, with additional funding from the Anglo-Australian Observatory.

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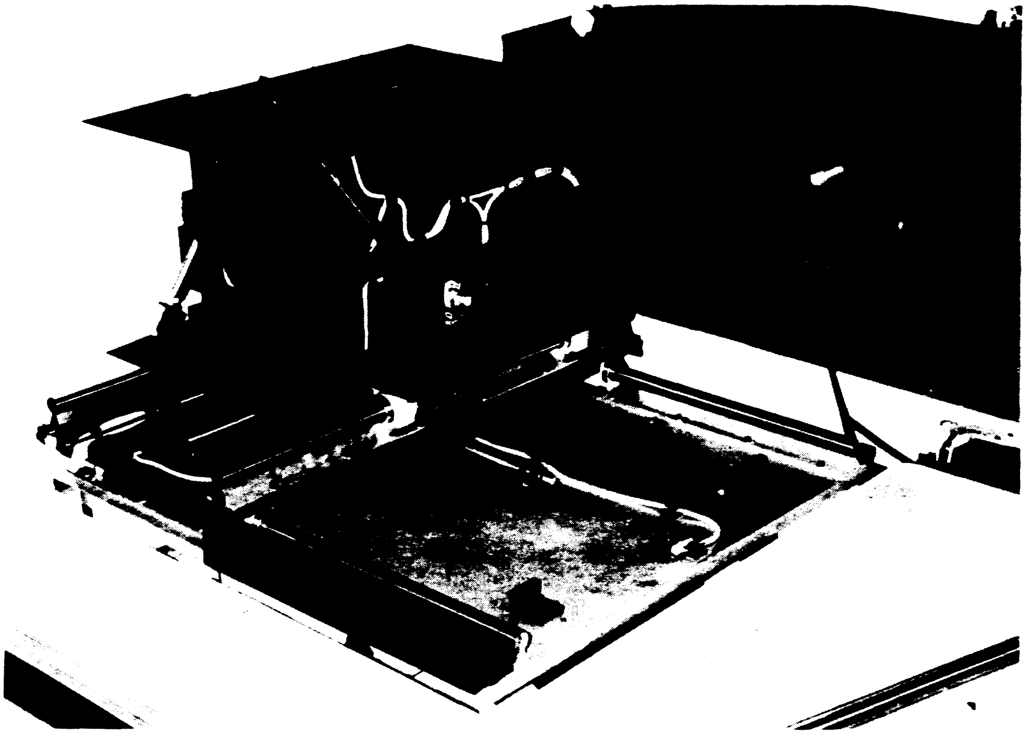


Figure 1. The échelle-collimator unit of the UHRF is installed in front of the UCLES collimator. Light is coming from the left. a) The unit is out of the beam for UCLES operation. b) The unit is in the beam for the UHRF operation. Note the orthogonal linear bearings for placing the unit in and out of the beam and for focusing. Also visible are the Hartmann shutters, wide open.

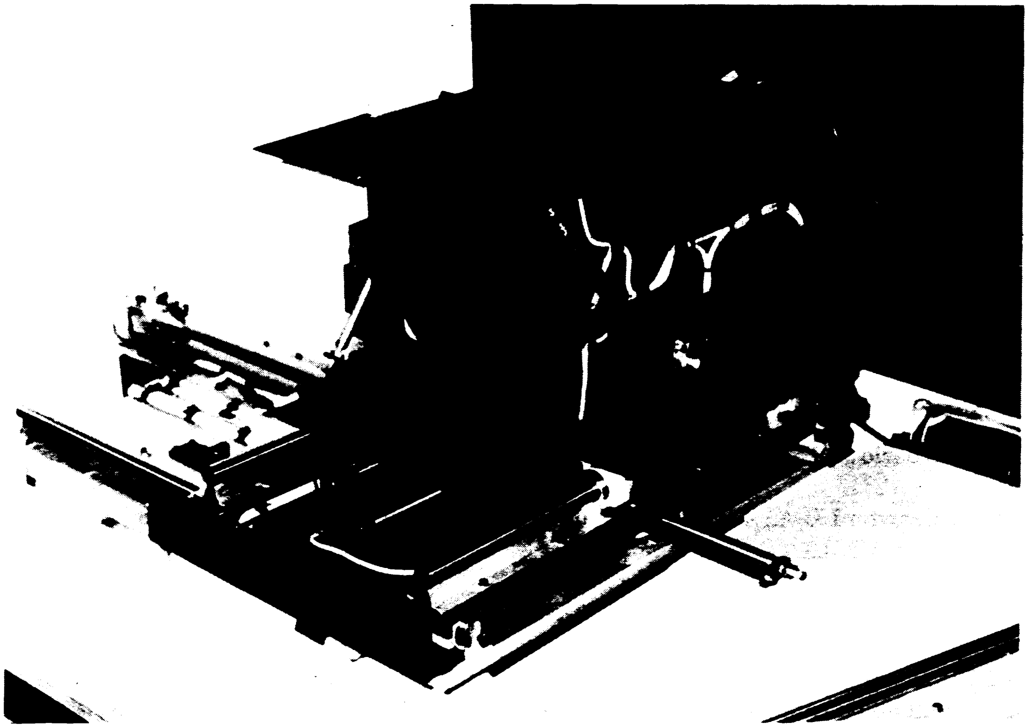
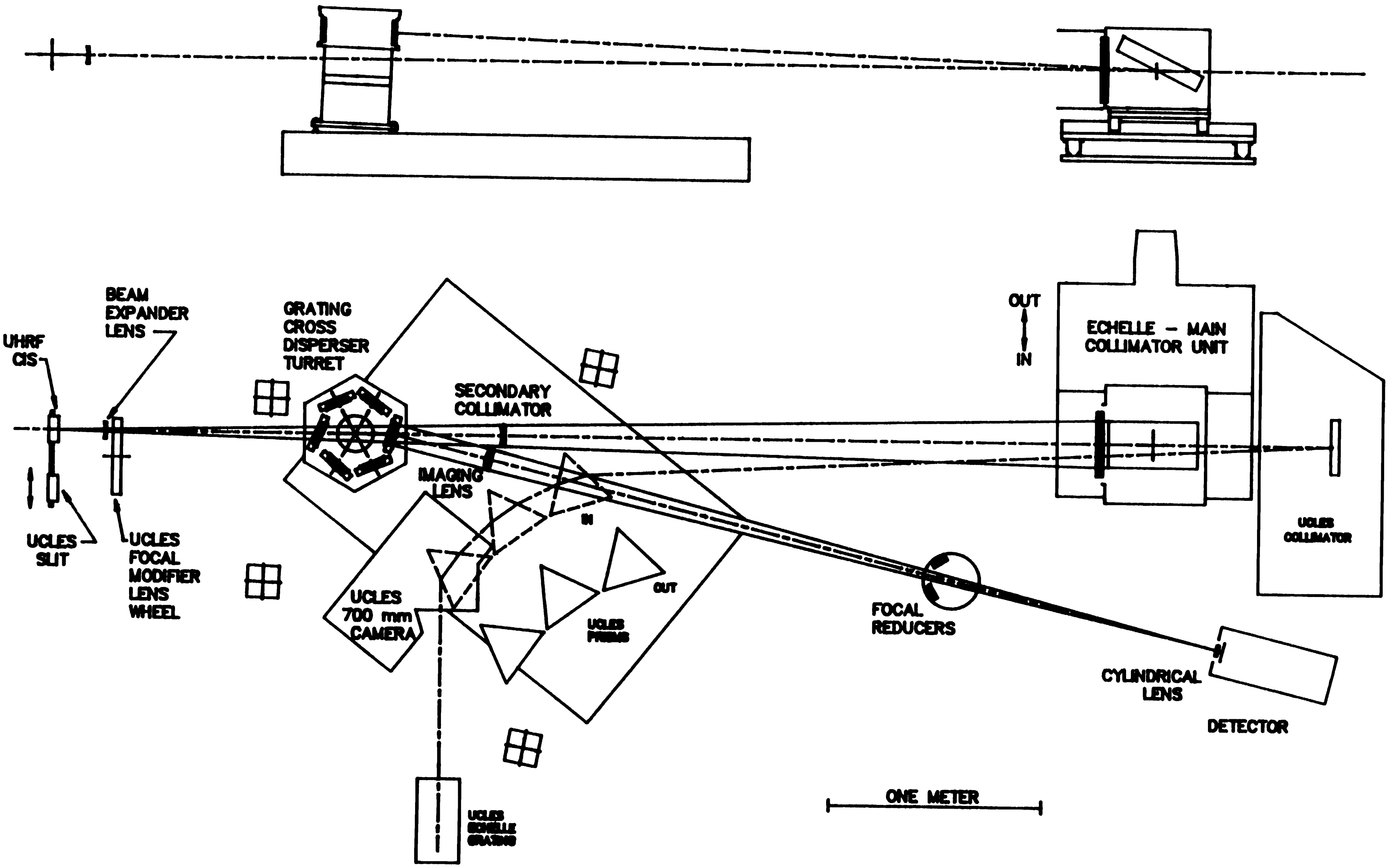


Figure 2. Cross-disperser unit mounted on the optical table which also supports UCLES prisms. At the centre is the turret with the gratings and the mirrors. To the left is the mechanism holding the secondary collimator. The main optical axis goes horizontally from right to left passing just below the turret.

FIGURE 3 : INSTRUMENTAL LAYOUT AT THE A.A.T. COUDE ROOM



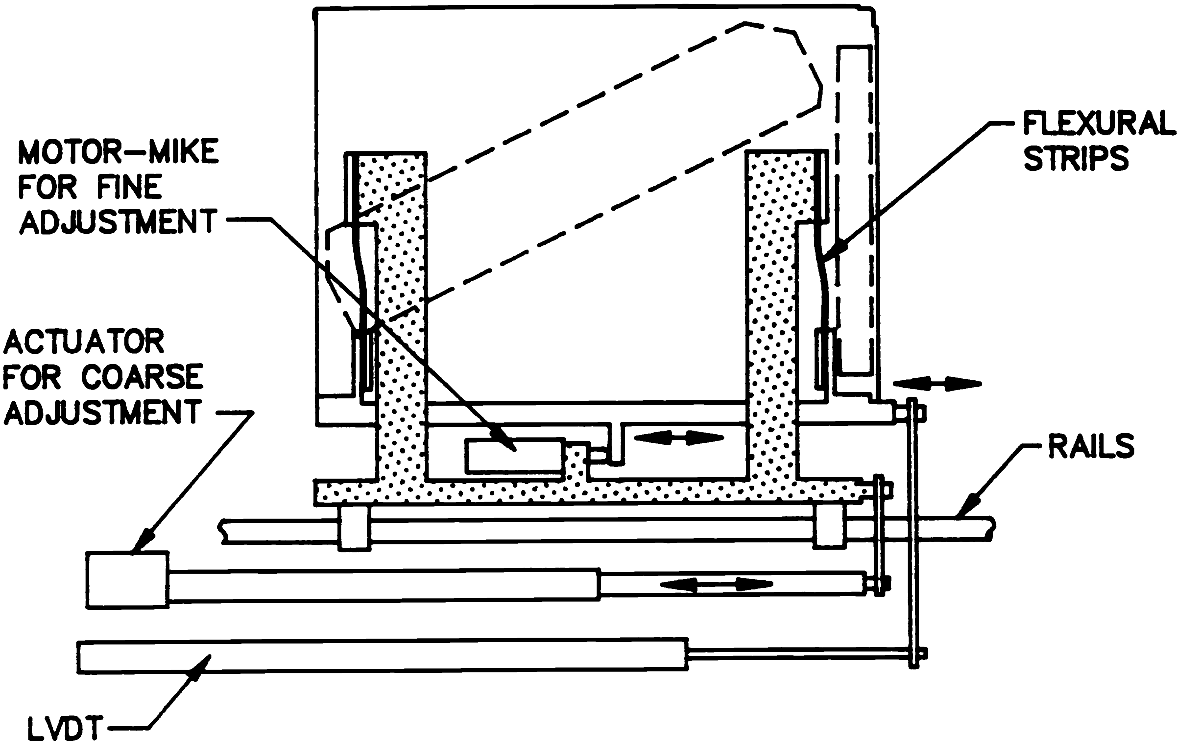


Figure 4. Schematic view of the échelle-collimator unit showing the mechanism to adjust and measure the position for collimation as a function of wavelength.

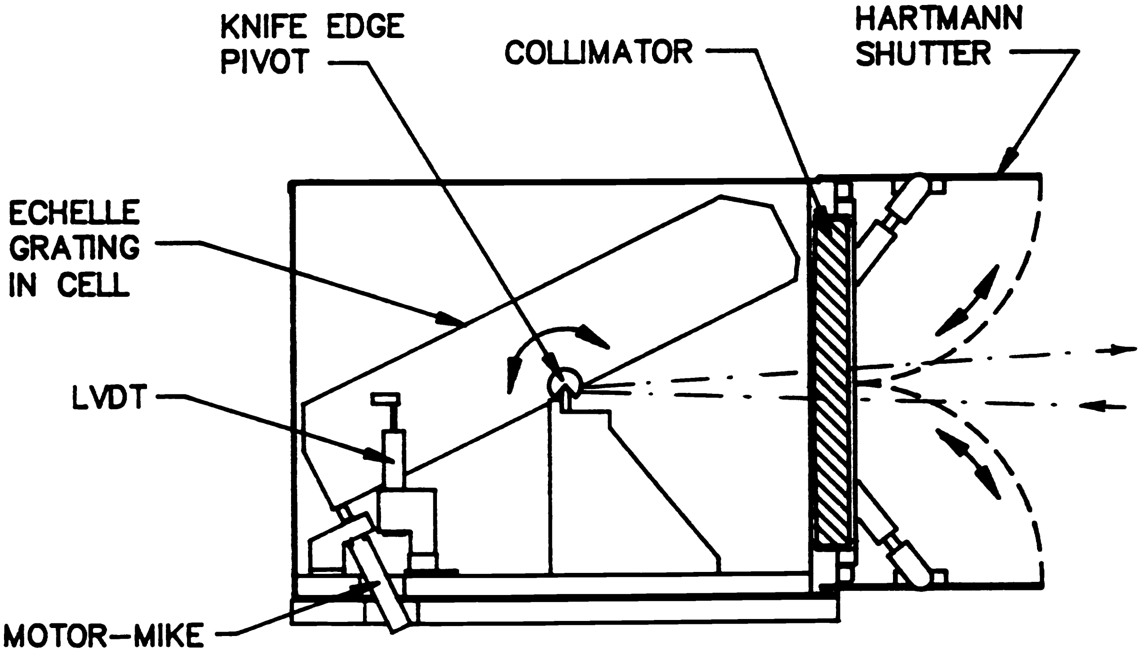


Figure 5. Schematic view of the box containing the échelle grating and the collimator. Note the system used to tilt the grating and also the Hartmann shutters. Compare this with figure 1.

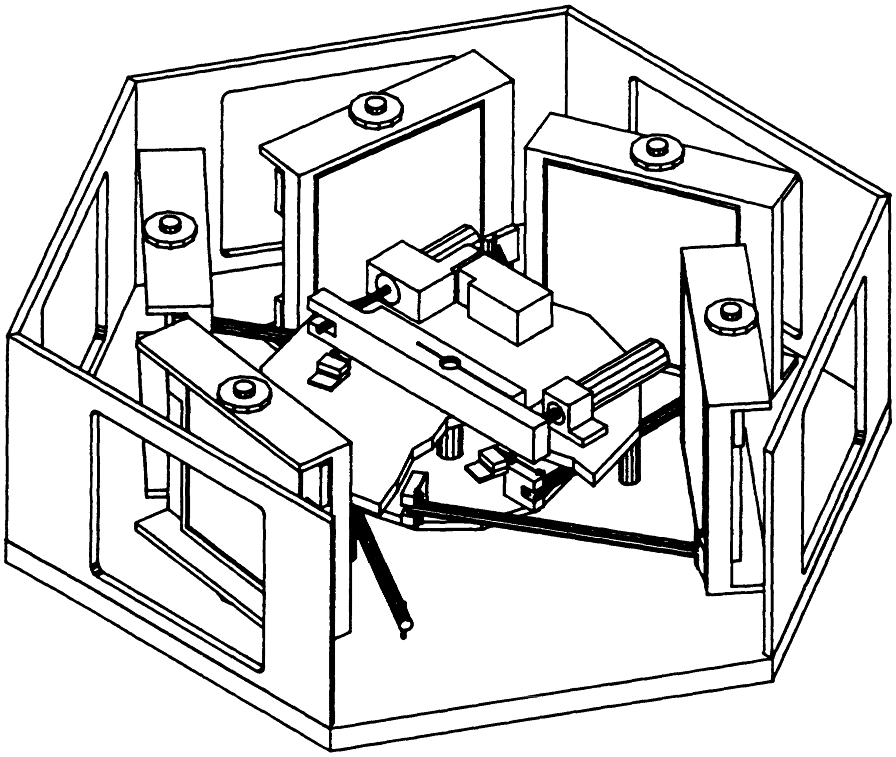


Figure 6. Isometric view of the cross-disperser turret containing the cells for the optics (one has been removed for clarity). Note the motor-mike (left) pushing a lever (centre) against an LVDT (left). The lever is attached to a disk which pushes six rods connected to the cells, respectively. This rotation is used to scan across the échelle orders.

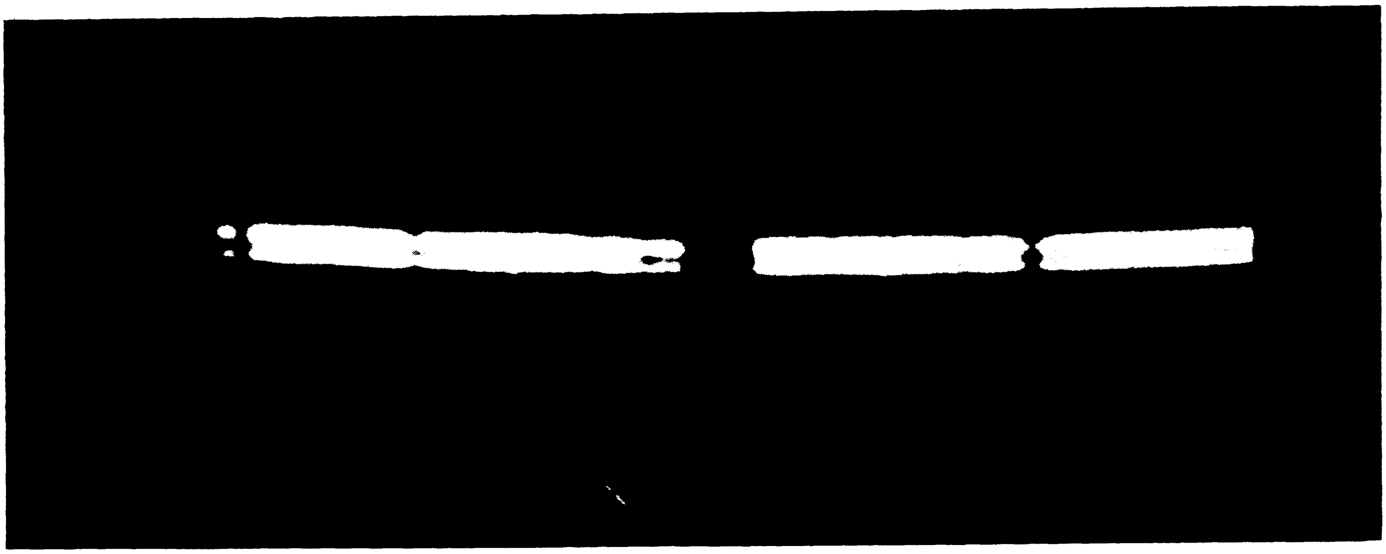


Figure 7. Typical raw spectrum of the UHRF taken with the Confocal Image Slicer and the cylindrical lens. The spectrum appears slightly curved as the picture was taken directly from the TV monitor as it came from the detector. The black line at the centre is the saturated Na D2 line towards ζ Oph. Note also the presence of cosmic ray events.

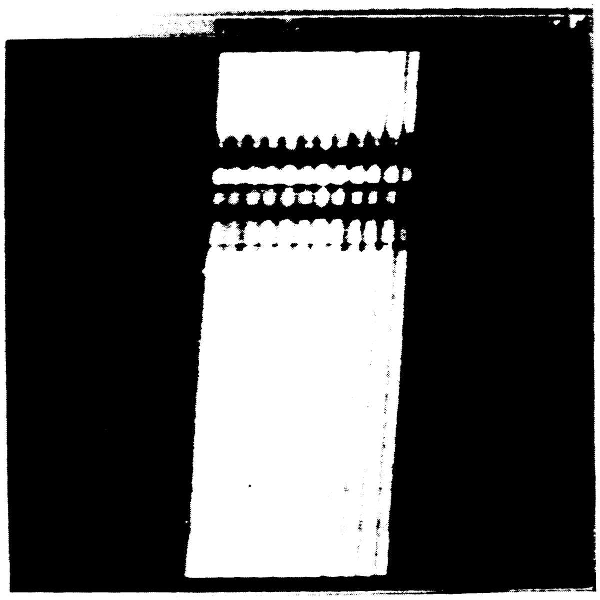


Figure 8. Image of the spectrum of ϵ Orionis in the region of Na D1. The UHRF main dispersion is along the vertical plane. Note the tilt of the spectrum. Each column corresponds to a slice from the Confocal Image Slicer. Several Na lines are projected at different radial velocities. Some of the lines show hyperfine splitting of ≈ 1 km s^{-1}.

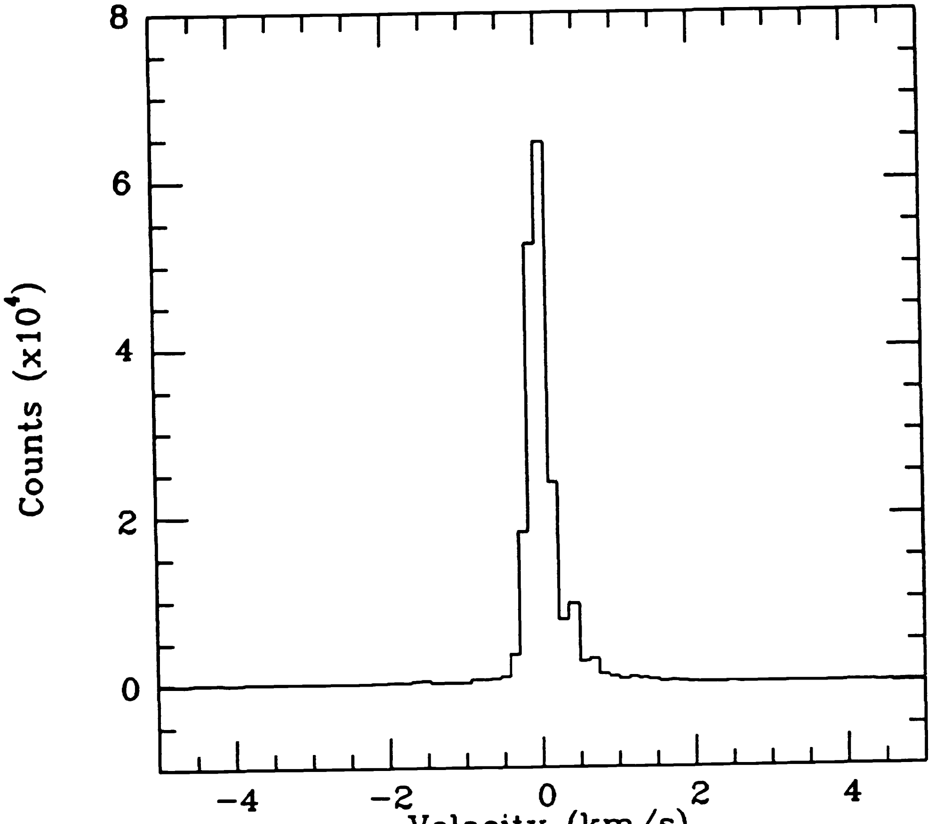


Figure 9. Instrumental profile of the UHRF obtained with the Confocal Image Slicer and a CCD with 19μm pixels. The frequency-stabilized HeNe laser was used as a light source ($\lambda\lambda$6328.16). The measured FWHM is equivalent to a resolution of 990,000.

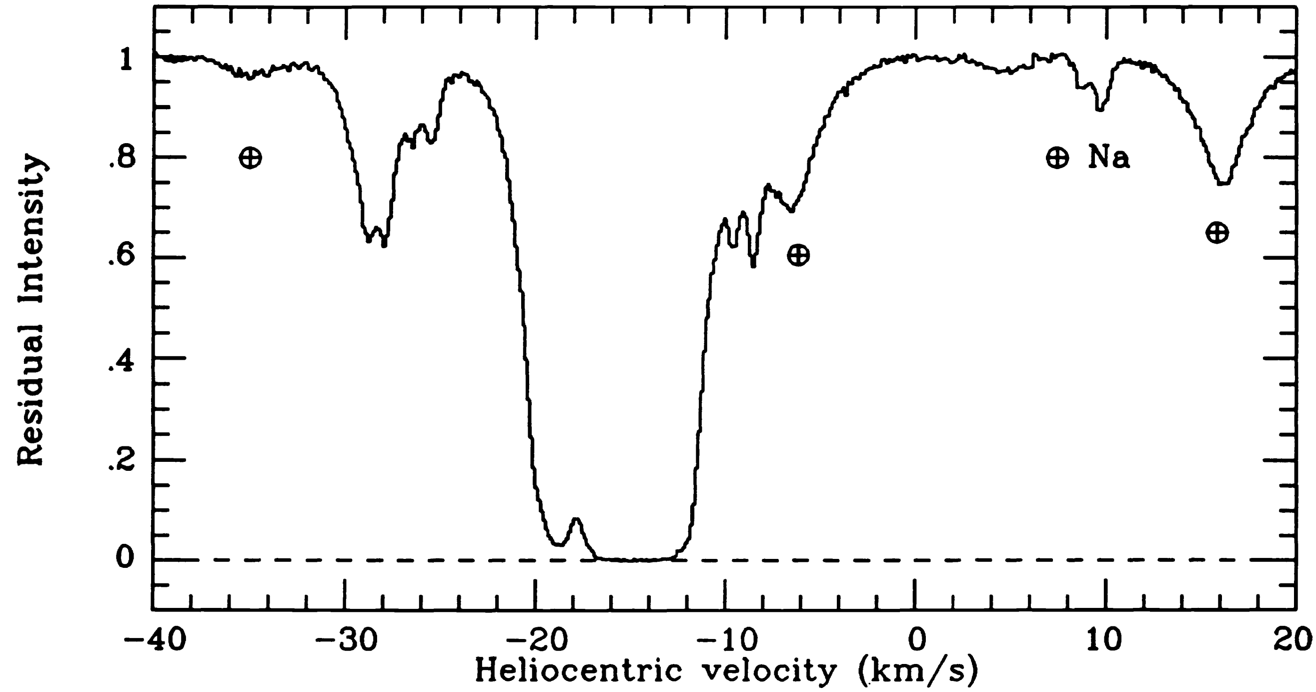


Figure 10. Spectrum of ζ Ophiuchi in the region of Na D2 showing hyperfine structure in several components. Features marked with a cross are telluric, including the Na line at 10 km s^{-1}. (From Barlow *et al.*[17]).

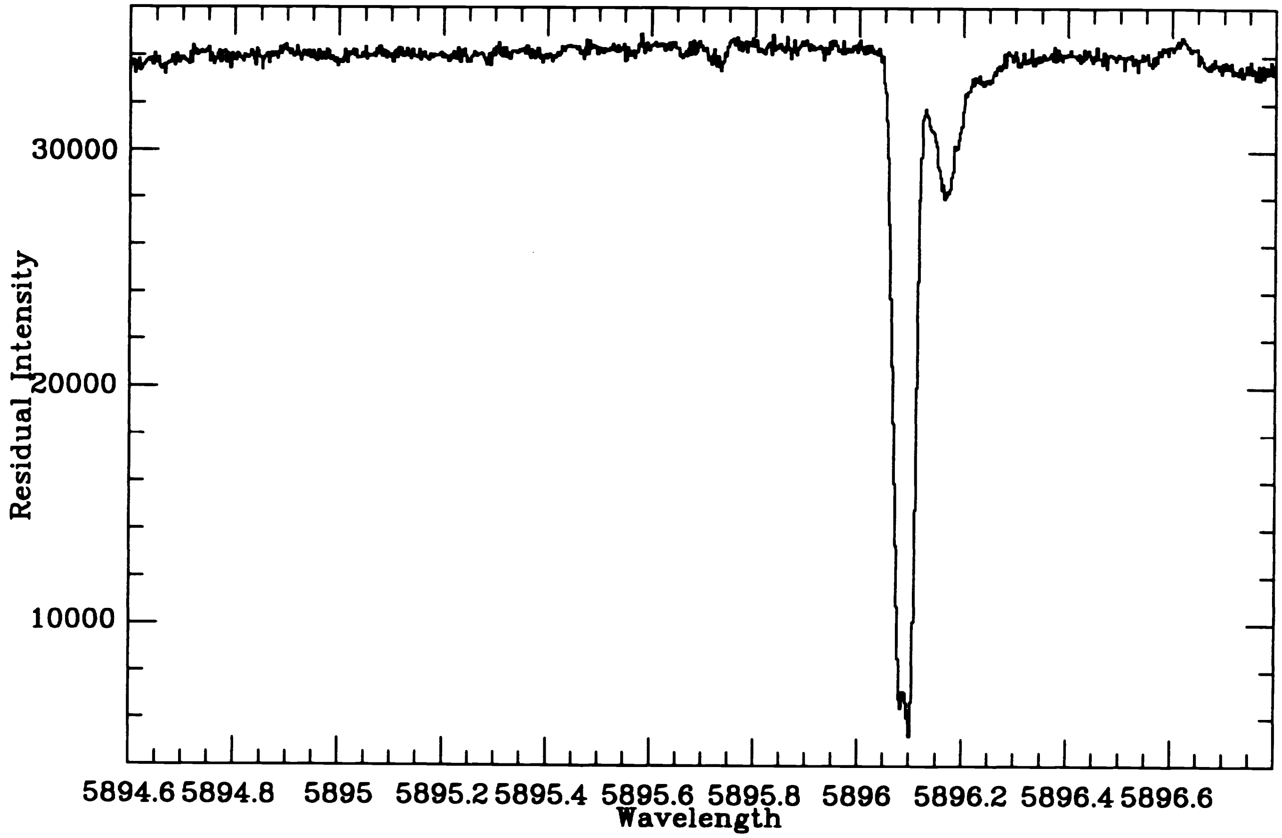


Figure 11. Spectrum of κ Velorum at the Na D1 wavelength. The blue wing has been fully resolved. Note the hyperfine splitting at the bottom of the profile.

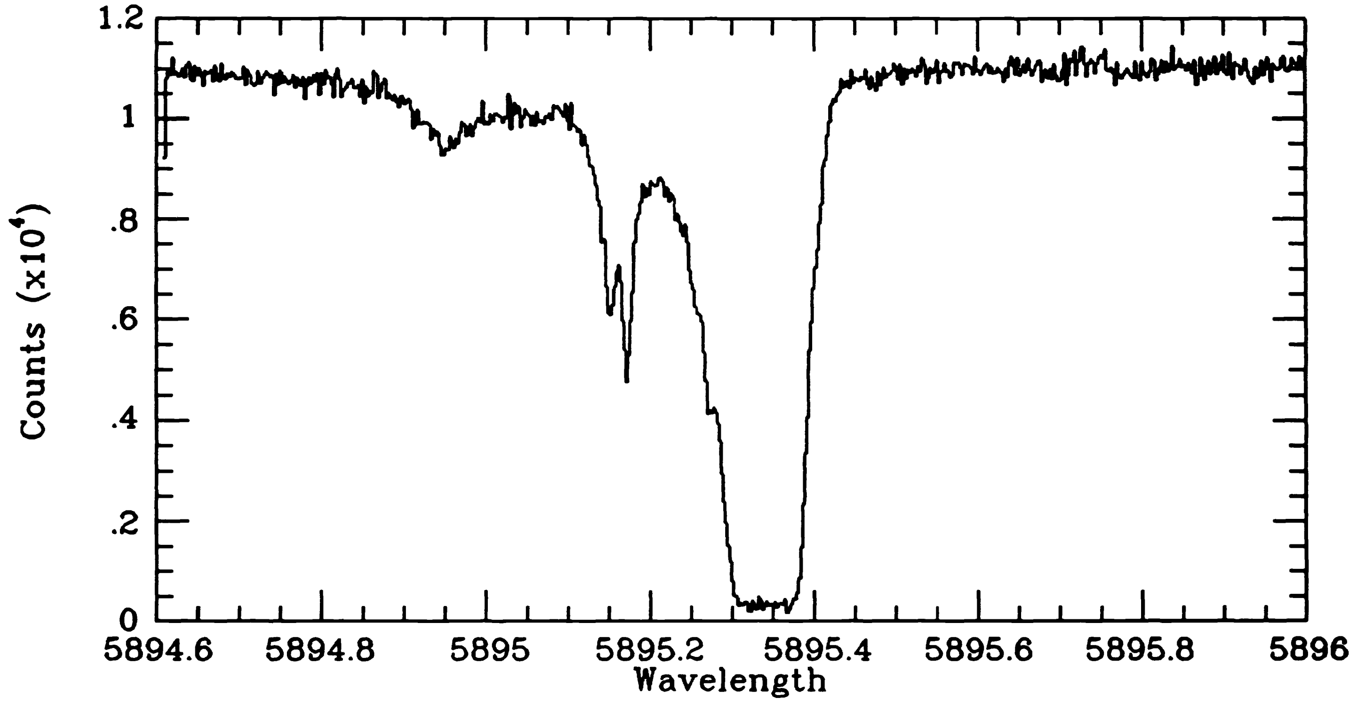


Figure 12. Spectrum of σ Scorpii at the wavelength of Na D1 obtained in January 1994. The main line is completely saturated and helps to evaluate scattered light within the UHRF, which appears at a level of $\approx$ 2.5 percent. Note also the hyperfine splitting in the blue component.

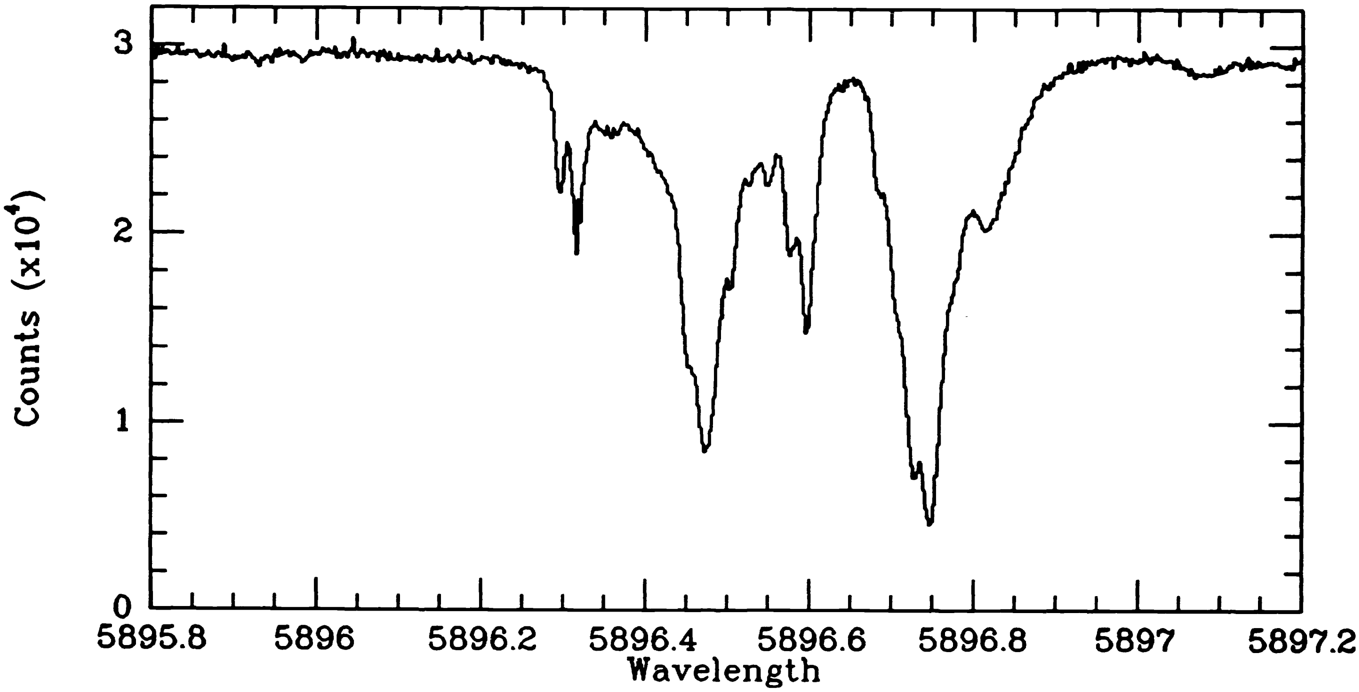


Figure 13. Spectrum of ϵ Orionis obtained also in January 1994. Na D1 shows a complex structure from several clouds with hyperfine splitting evident in most of them. Compare this spectrum with figure 8.

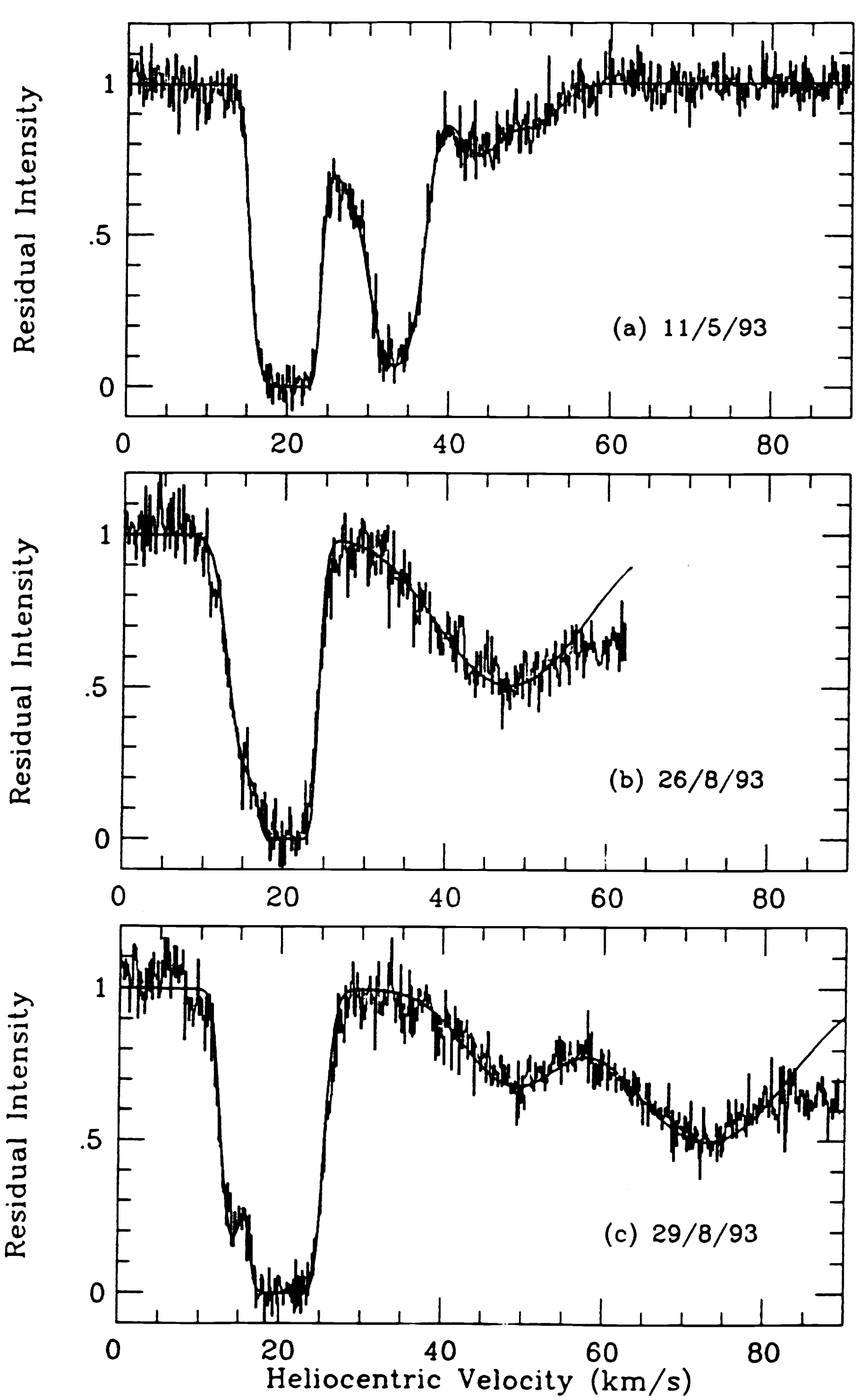


Figure 14. The dynamic nature of the Ca K line ($\lambda\lambda$3933.633) towards β Pictoris (taken from Crawford *et al.*[18]).