Asian Journal of Physics Vol 13, Nos 3 & 4 (2004) 267 - 276

Fiber-fed echelle spectrometer of the 2.34 meter Vainu Bappu Telescope

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The optical design and performance of high resolution fiber-fed echelle spectrometer for the 2.34 meter Vainu Bappu Telescope (VBT) is described. An optical fiber of core 100 μm and length 45 meter is used to link the spectrometer with the telescope. The instrument provides a resolving power of 72,000 (4 Km/s) with a 60 μm slit and provides continuous coverage with gaps for $\lambda < 1$ μm. The spectrum is recorded on a thinned back-illuminated Marconi 2048 $\times$ 4096, 15 μm square pixel, charge coupled device (CCD) detector. The wavelength coverage in a single order varies from roughly 35Åat λ = 4050Å(range 4030Å- 4065Å) to 70Å(range 8465Å- 8535Å).The present overall efficiency of the spectrometer at 6000Åis about 10%. The operation of the spectrometer and object acquisition and guiding at the telescope end is described. Some of the observed spectra from VBT are also illustrated.

1. Introduction

Many stellar programmes like study of stellar activity, elemental abundances, atmospheric motions, mass loss, etc., are planned for the 2.34 meter Vainu Bappu Telescope (VBT), Vainu Bappu Observatory (VBO), Kavalur, India, require high spectral resolutions of about 60,000 (5 Km/s). Thus an efficient high resolution spectrometer has been a long standing need at VBO (that could cover large region of the spectrum extending from 4000 Åto 1 μm in one exposure). The obvious choice that emerged is an echelle grating based spectrometer. Spectrometer gives a high resolution, a large wavelength coverage and a high efficiency simultaneously by using an echelle grating at a large blaze angle (typically θ of 63° to 70°) operated in high diffracted orders. The orders overlap at the focus and they need to be separated by dispersing them in the perpendicular direction by use of a cross dispersing prism (in our case) or a grating. Prisms are preferred owing to their higher throughput efficiency and the fact that they give rise to a more uniform order spacing. The prism dispersion is greater in the blue where the free spectral range of the echelle grating (i.e the difference in wavelength between the centers of the successive orders) is less. The major advantage of this type of format is its suitability to image (or record) the spectrum on a two-dimensional high quantum efficiency detectors, like CCDs.

The conventional 'coude' scheme [1] of bringing the star light to a laboratory based spectrometer for VBT requires about seven reflections which may cause loss of about 10 percent light at each reflection. It was realized that there would be much reduction in loss if light is transmitted by an optical fiber from the prime focus of the telescope directly to the spectrometer slit. To limit the sky light entering the slit as well as allowing the star light fully through a 100 μm diameter fiber corresponding to 2.7 arcsec on the sky, which is slightly bigger than the average seeing image at VBT, is required. There are other advantages as well for using a fiber minimizing the image guiding errors, scrambling image and uniformly illuminating the slit (Optics), etc.

This report summarizes the the optical design and the performance of the fiber fed echelle spectrometer for 2.34 meter VBT, VBO, Kavalur, India. The stellar spectra obtained from VBT echelle spectrometer are presented. These stellar spectra are compared with the spectra obtained from other similar echelle spectrometers.

2. Design and Optical Layout

An Echelle spectrometer like the conventional grating spectrometer essentially consists of a slit, collimator, grating, camera and detector. The additional element is a cross disperser prism or a grating. The fundamental consideration is the maximum spectral resolving power based on the astronomical motivation.

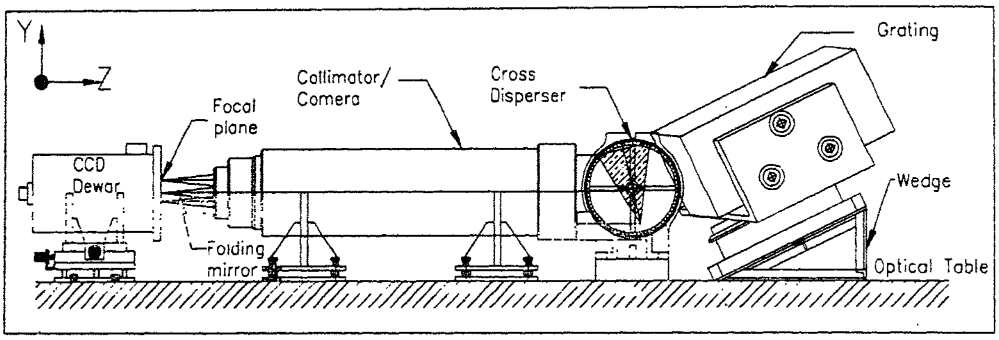

Figure 1: Optomechanical layout of the Spectrometer. F/5 beam emerging from the slit fed into the collimator by a folding mirror. Then the collimated beam passes through the cross disperser (prism) and get pre dispersed and then illuminates the echelle grating. The dispersed beam from the grating again passes through the prism second time and finally comes to focus on to the CCD plane where the spectrum is recorded.

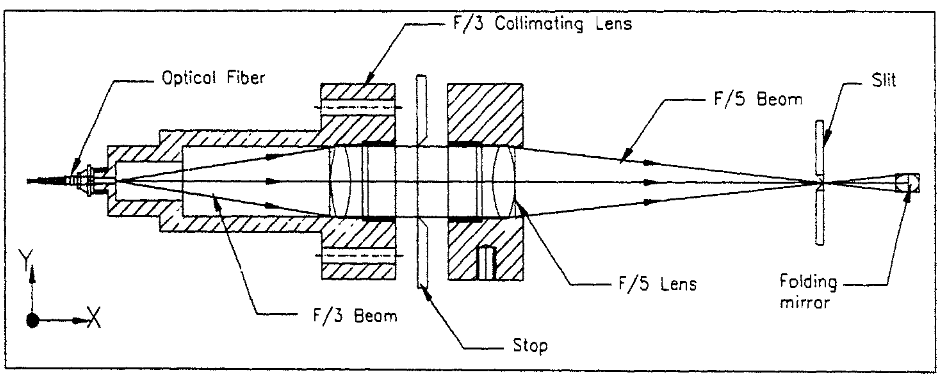

Figure 2: F-Ratio enlarger. F/3 beam from the optical fiber is converted into a collimated beam by the F/3 collimating lens then it is re-converted into F/5 converging beam by another F/5 lens. The slit positioned at the focus of the converging beam. The beam diverging from the slit falls on the folding mirror which redirects the beam into the spectrometer collimator.

In our case we choose it to be about 70,000 (4 Km/s). Once this is fixed other considerations about the echelle grating, the beam size, the camera, collimator focal length, the detector size etc., follow. The questions that are considered here are:

how to fit most of the spectrum in a given detector real estate (i.e., the CCD size).

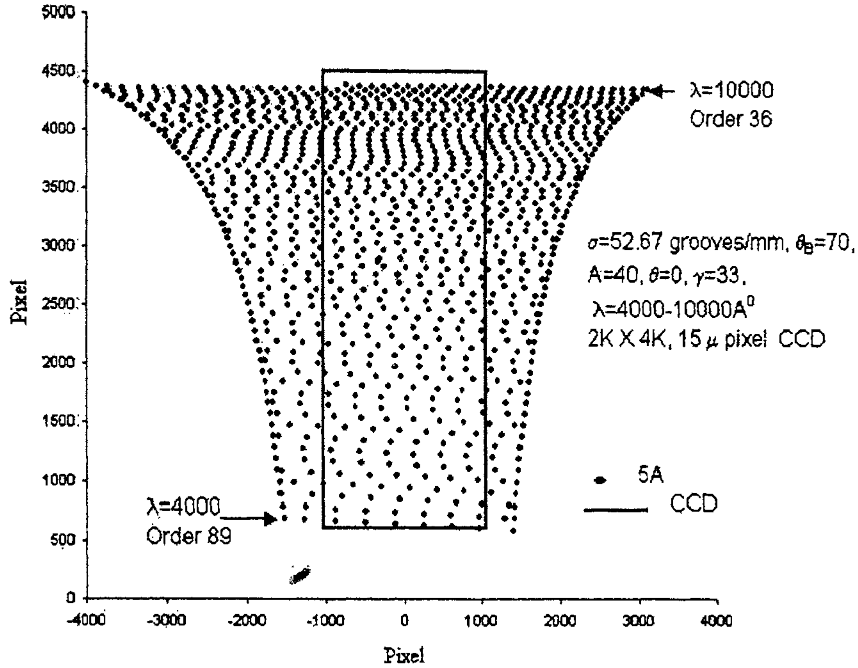

Figure 3: CCD echelle image format resulting from the combined use of echelle grating and Lithium Floride (LF5) cross disperser (prism) used in double pass. Each spot in the format is one wavelength and the separation between the spot is 5Å. Wavelength increases from left to right and from bottom to top. At top $\lambda = 1\ \mu$m (spectral order, m = 36), at the center λ = 5025Å(m = 70) and at the bottom λ = 4000Å(m = 89). The solid rectangle illustrates the CCD chip of 4096 rows by 2048 columns and it covers the spectrum fully in the vertical direction and nearly half in the horizontal direction.

- The extent of the wavelength range (i.e, number of orders).
- Overlaps (free spectral range, number of lines/mm) and order spacing such that the inter-order background is minimal (i.e, cross-disperser).
- The intensity variations along the order as well as across the orders should be smooth and less steep (i.e, broad blaze function) so that nearly same signal to noise could be obtained across an order without saturating one place and unable to register in other place.
- Efficiency should be optimal (i.e, throughput should be high) and scattered light minimal.
- Good sharp lines without tilts and wings (in plane design).
- Stability and repeatability (environmental, mechanical stability, isolation from the telescope, temperature control and dome vibrations etc.).
- Spectral format should be amendable for easy reductions and calibrations.

Easy operations.

Table I
Optical parameters of the Spectrometer

Telescope (VBT)	
Aperture	2340 mm
Focal ratio	$f/3.25$
Mode	Prime
Scale	27 arcsecond/mm
Optical Fiber	
Core	100 μm
Cladding	140 μm
NA	0.22
Length	45 meter
Procured from	Polymicro technologies, USA
Operating wavelength	4,000Å-10,000Å
Collimator-Camera	
Focal ratio	$f/5$
Focal length	755 mm
Field of view	60 mm diameter
No of elements	Six (Triplet, doublet, Field flattener)
Off axis launching angle	0.05°
Working distance (CCD side)	131.5 mm
Field stop position	406 mm away from the last surface of the triplet
Clear aperture	190 mm
Cross disperser	
Material	LF5 glass
Apex angle	40°
Length	188 mm
Base size	126 $\times$165 mm
Echelle Grating	
Groove density	52.67 grooves/mm
Blaze angle	70°
Ruling area	408 $\times$208 mm
Operation mode	Quasi-littrow mode, $\Theta = 1.1°$
Working order	40 to 90
CCD	
Chip Size	2048 $\times$4096 pixels
Pixel Size	15 μm square pixel

We finally preferred all transmitting system for the spectrometer with the optical surfaces with anti-reflection coatings to optimize the throughput rather than reflecting cameras with central obscurations. Following other optimized throughput spectrometers like Sandiford system at McDonald observatory [1], we opted for a Littrow configuration (Collimator also acts as the camera; the input and output beams trace almost the same path). Again to optimize the throughput (maximum efficiency blaze) we preferred to broaden the blaze function by using a finer echelle grating with more number of grooves/mm. The echelle grating selected has 52.67 gr/mm and blazed at 70° (R2.6).

Thus the figure of merit, a product of resolution and angular extent of the slit (in radians) is,

$$R\phi = 2B\frac{\tan\Theta_b}{D}, \tag{1}$$

where R is the resolution of the instrument, ϕ the angular slit width in radian, Θ_b the blaze angle, B the beam size, and D the diameter of the telescope.

The expected resolution of the spectrometer with a slit width of 1 arcsecond with a collimated beam diameter of 151 mm and with an echelle of 70° blaze angle is 72,000. The optical parameters of the spectrometer are tabulated under Table 1.

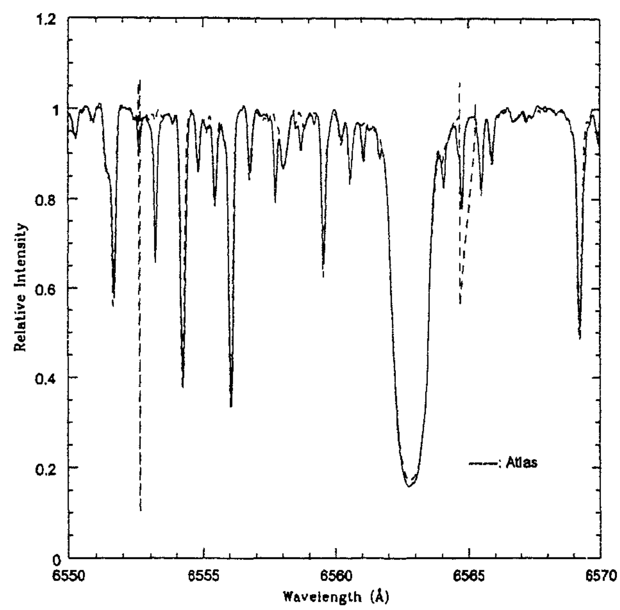

Figure 4: Spectrum of Arcturus obtained with fiber fed echelle spectrometer at VBT superposed on Kit Peak Atlas spectrum.

The opto-mechanical layout of the spectrometer is shown in Figure 1. The star light after hitting the primary mirror comes to a focus as a f/3.25 beam which is fed to a 100 μm core fiber located on the optical axis of the telescope. An image acquisition unit containing an intensified camera displays the stellar image and the fiber position on a monitor in the control room from where guiding is done to keep the star light fed continuously into the fiber during an exposure. The light from calibration lamps - Thorium-Argon for wavelength calibration and Xenon and Tungsten lamps for flat field, is also fed to the fiber through the same unit. The fiber output is collimated and reconverted to an $f/5$ converging beam with a focal ratio enlarger, as shown in Figure 2, that focuses the light on to the slit. The image scale at the slit is 154μm. The fiber output can also be used without the

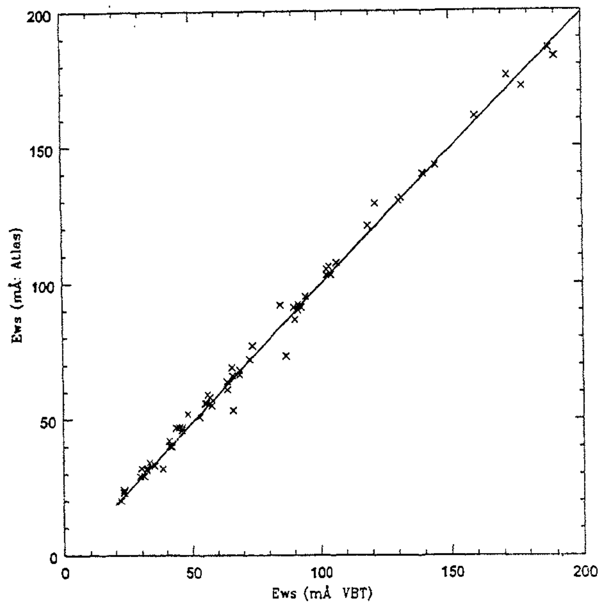

Figure 5: Comparison of equivalent widths in the spectra taken from VBT and Kitt Peak.

slit with a lower resolution for maximum throughput. The light after the slit is reflected into the collimator by a 10 mm folding mirror that sends the beam at an angle of 0.05° to the optical axis of the spectrometer.

The collimator is a six element $f/5$ system designed for a beam size of 151 mm and has a focal length of 755 mm (Optical Science Laboratory, UCL). The first element (also the last element in the double pass mode) corrects for off-axis feeding of the beam. The system further contains a doublet and a triplet, all anti-reflection coated and chromatically corrected to a wavelength range of 4000 Åto 1 μm. The collimator system also acts as a camera.

All the elements in the collimator is rigidly mounted in a single cylindrical tube with a provision to flush them with dry nitrogen. The collimated beam then passes through an LF5 prism of about 165 mm height and an apex angle of 40° which pre-disperses (in the cross dispersion direction) the light and sends it to the echelle grating. The echelle grating is blazed for 70° and is illuminated by the incident beam fully (in both directions). The grating is the single largest grating available and has a size of 408 ×208 mm. The dispersed beam retraces the same path and the prism cross-disperses for a second time (thus ensuring enough order separation) and enters the collimator for a second time. Now the collimator acts as a camera and focuses the dispersed spectrum on to a CCD chip. The emergent beam is again slightly off-axis and avoids the reflecting mirror that puts the beam in. The camera has a corrected field of about 60 mm diameter in the focal plane. The spectrum is recorded on a 2048 ×4096 pixels CCD camera exclusively built for the spectrometer. The CCD dewar is mounted on a stage with a provision to move in X, Y, Z directions. The focus is obtained by moving the dewar along the direction of the optical axis of the collimator.All the optical components are mounted on a 8 feet × 4 feet size Milles Griot vibration isolation table.

The whole mechanical assembly is placed in an environmentally (temperature, humidity) con-

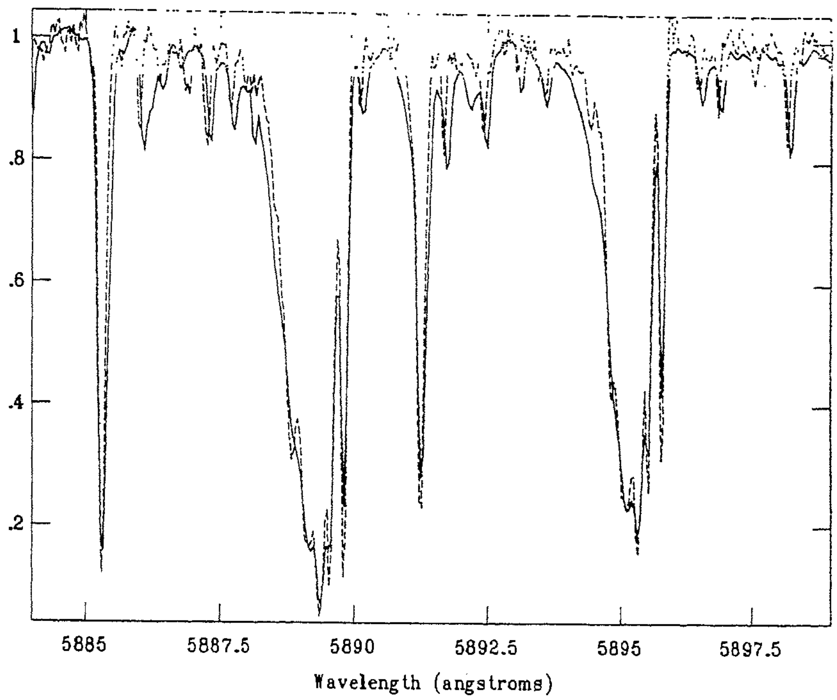

Figure 6: Comparison of the spectra of Hydrogen deficient R CrB star, V854 Cen obtained with McDonald observatory 107-inch coude echelle spectrometer with resolution 60,000 in February 1999 (full line) with the spectrum obtained by VBT fiber-fed echelle spectrometer on 13 Jan 2004 in Na ID line region.

trolled dark room - coude laboratory. The CCD is a back illuminated, thinned Marconi chip with square pixels of 15 μm size and is placed in a LN2 cooled dewar. The controller and the associated electronics, and the dewar have all been built in Indian Institute of Astrophysics laboratories. The slit size of 60 μm covers about four pixels on the CCD. The area of the two dimensional spectrum format in the focal plane of the camera as shown in Figure 3. In this format each horizontal strip is a spectral order (free spectral range) and each spectral order is separated by the cross disperser. The separation between the orders varies from 40 pixels (at 8000 A0) to 80 pixels (at 4000Å). Each spot in a row is a wavelength and separation between the spot is 5Å. Only 5Åseparated wavelengths are shown in Figure 3 because of the clarity, however, the resolution of the spectra varies from 0.05Åat 4000Åto 0.09Åat 8000Å. The present CCD chip (solid rectangle) covers almost half of the spectrum in a single exposure. Entire region of the spectrum can be covered by either moving the grating or CCD dewar.

It was realized early that a separate foundation might be required which is isolated from the rest of the telescope building and dome, for the coude laboratory. Thus four pillars have been incorporated in the building in the coude area exclusively for placing the spectrometer. The vibrational free table is placed on these independent foundations to isolate it from the building vibrations.

3. Operations

All the operations of star acquisition, control of various lamp movements etc., are done from the telescope control room remotely through a PC. The grating and prism movements could also be accomplished remotely through PC commands (encoder displays). The CCD stage movements also can be controlled remotely.

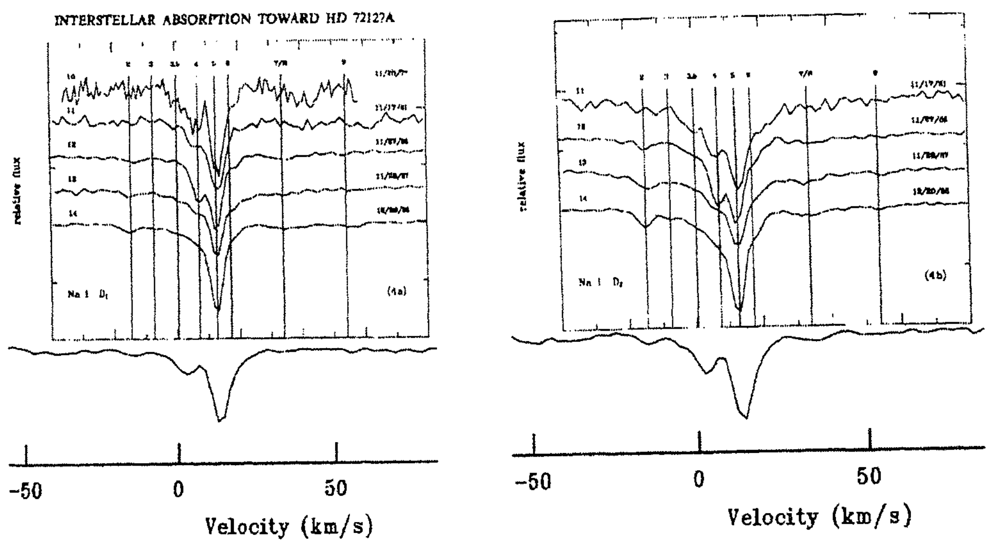

Figure 7: (a) Variations of interstellar Na ID1 line towards HD72127A VBT spectrum is shown in the bottom. (b) Variations of interstellar Na ID2 line towards HD72127A VBT spectrum is shown in the bottom.

Presently the spectrometer operates in two modes with a 60 micron slit (full resolution of 72,000) and without the slit (full fiber at 27,000 resolution) although there is a provision to change the slit width. However there will be loss of light on the slit jaws whenever the slit is used till an image slicer is built for the system.

A 1024 $\times$1024 pixels of 24 μm size CCD system is also available at the VBT which could be used for programmes that do not require a large range in wavelength. This system has a higher quantum efficiency in the red and shorter readout time of 40 seconds per image. There would be slight loss of resolution because of the bigger pixel size.

4. Observations

Some of the stellar spectra that have been obtained recently are illustrated with some comparisons with the observations obtained with other spectrometers. The Figure 4 shows the spectrum of the star α-Boo (Arcturus) in the Hα region obtained with VBT at 72,000 resolution (full line) compared with the spectrum displayed in 'Visible and near-Infrared Atlas of the Arcturus Spectrum' obtained at Kitt Peak [2] at 120,000 resolution. Note the line to line matching and also the depth of the strong Hα line, centered at 6563Å, in both spectra match very well illustrating the high quality of the spectrum without any scattered light in the VBT spectrometer. Figure 5 shows the comparison of equivalent widths in the spectra to be an agreement within a standard deviation of less than 2 milli-angstrom.

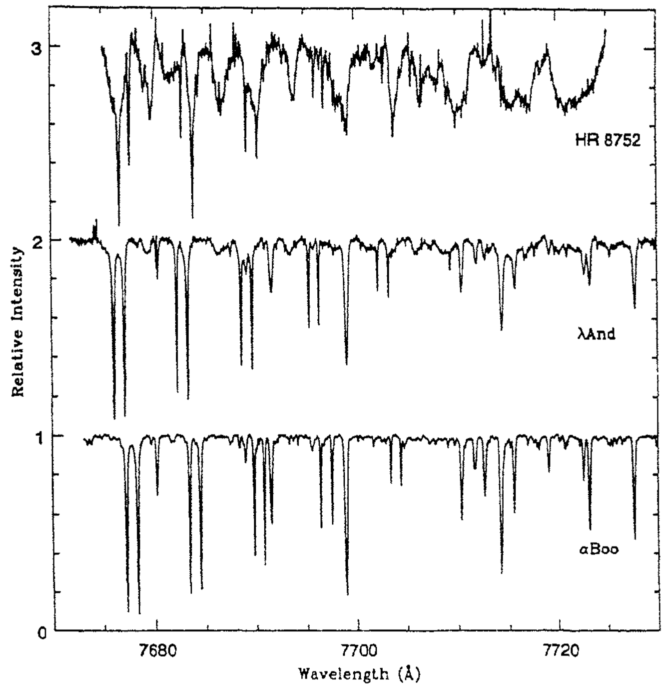

Figure 8: Spectra of three stars in the region of KI, λ 7699 with VBT echelle spectrometer. The spectra taken due to terrestrial O_2; the width of stellar line changes in the three objects.

The spectrum illustrated in Figure 6 is of the hydrogen deficient star V854 Cen that has been obtained with VBT echelle (dashed line) compared with the spectrum obtained with 107 inch telescope, McDonald observatory, in 1999 at a resolution of 60,000 (full line) in the Na ID line region. The spectra are matched to the interstellar components. Note the narrowness of the interstellar lines and terrestrial water vapour lines in VBT spectrum compared to McDonald spectrum due to higher spectral resolution. However the central intensity of the stellar line blend matches in both spectra remarkably.

The Figures 7a and 7b illustrate variations of interstellar Na ID line components (interstellar clouds) in the direction of the star HD72127A. Note that several components (shown as vertical lines) [3] match in the VBT spectrum and others both in velocity and equivalent widths for several components except for the one at velocity +2.8 km/s - in VBT spectrum in both D1 and D2 lines. It illustrates the capability of VBT echelle to study some of the problems in inter-stellar medium. Figure 8 illustrates another spectra observed from VBT.

The above examples illustrate the quality and potential of the instrument which is expected to be used extensively with VBT.

5. Summary

The fiber fed echelle spectrometer for 2.34meter telescope at Vainu Bappu Observatory has been built successfully and commissioned recently. The spectrometer is linked with the telescope by optical fiber of 100 μm core size. This spectrometer utilizes echelle grating with cross dispersing prism, providing spectral resolution of 72,000 with a 60 μm slit width. The two dimensional spectrum extends from 4,000 Åto 10,000 Å, and is recorded on a CCD of 2K ×4K of 15 μm pixel. The star acquisition and guiding is accomplished by an imaging unit located at the $f/3.25$ prime focus of the telescope, which also includes the lamps for wavelength and flat fielding calibrations. All the spectrometer operations, both at the prime focus and spectrograph laboratory, are remotely done from the telescope control room. It is planned to use an image slicer to improve the throughput.

Acknowledgments: We would like to thank several colleagues and friends who either participated or offered valuable advice and helped us one way or other in the realizations of this major project. In particular we would like to thank Ramanath Cowsik, A. V. Raveendran, Unnikrishnan Nair, A. K. Saxena for various kinds of help. Gajendra Pandey, Eswar Reddy and Aruna Goswami for help with observations and reductions. Help from G. Raghupathi and Y. K Raja Iyengar in procurement of components is appreciated. We would like to offer particular appreciation to Richard Bingham of University College London who built the excellent collimator system and improvised the original design. Thanks are also due to David Lambert, Phillip McQueen and especially Jim McCarthy of University of Texas at Austin who supplied the original design of Sandiford collimator, for their support and encouragement. NKR would like to acknowledge very useful discussions he had with Steve Vogt of Lick Observatory. NKR would like to thank Indo (CSIR)-US (NSF) exchange of scientists programme which enabled his visit to University of Texas and Lick Observatory while the instrument was being planned.

References

1 McCarthy J K, Sandiford B A, Boyd D, Booth J, *Publ. Astron. Soc. Pac.*, 105 (1993), 881.

2. Hinkle K, Wallace L, Valenti J, Harmer D, *ASP series on "Visible and Near-Infrared Atlas of the Arcturus Spectrum 3727-9300 Å"*, (2000), Kitt Peak National Observatory, Astron. Soc. of Pacific, San-francisco.

3. Hobbs L M, Ferler R, Welty D E, Wallerstein K, *Astrophys. J.*, 378 (1991), 586.

Received : July 01, 2004 *Revised : October 03 ,2004* *Accepted : October 17, 2004*