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High Resolution Stellar Spectroscopy with VBT Echelle Spectrometer

N. Kameswara Rao, S. Sriram, K. Jayakumar & F. Gabriel
Indian Institute of Astrophysics, Bangalore 560 034, India.

Abstract. The optical design and performance of the recently commissioned fiber fed echelle spectrometer of 2.34 meter Vainu Bappu Telescope are described. The use of it for stellar spectroscopic studies is discussed.

Key words. High resolution spectroscopy.

1. Introduction

An efficient high resolution spectrometer has been a long standing need at Vainu Bappu Observatory (that could cover a large region of the spectrum extending from 4000 Å to 1 μm in one exposure) for stellar spectroscopic programmes. The obvious choice that emerged is an echelle grating based spectrometer. The environmental conditions at VBO dictated the efficiency optimization to wavelengths longward of 4000 Å. The final choice was a spectrometer that has transmitting optics configured to operate in Littrow mode that provides a high resolution and a large wavelength coverage simultaneously by using an echelle grating at a large blaze angle (θ of 70°). The order overlap at the focus is separated by dispersing them in the perpendicular direction by the use of a cross dispersing prism. 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 two-dimensional high quantum efficiency detectors, like CCD.

The conventional 'coude' scheme of bringing the star light to a laboratory based spectrometer for VBT requires seven reflections which may cause loss of about 10 per cent light at each reflection. It was realized that there would be much less light loss if transmitted by an optical fiber from the prime focus of the telescope directly to the spectrometer slit. The diameter of the fiber that satisfies the requirement of minimizing the sky light entering the slit while allowing most of the star light, is about 100 μm which corresponds to 2.7 arcsec at the prime focus. This size is slightly larger than the average seeing disc at VBT. There are other advantages as well for using a fiber to link the spectrometer to the telescope like minimizing the image guiding errors, image scrambling thus uniformly illuminating the slit (optics), etc. Thus the final choice was the use of a 45 metre long optical fiber to link the prime focus to the spectrograph slit. In the following account we describe the configuration of the echelle spectrometer. A more detailed account can be found in Rao *et al.* (2005).

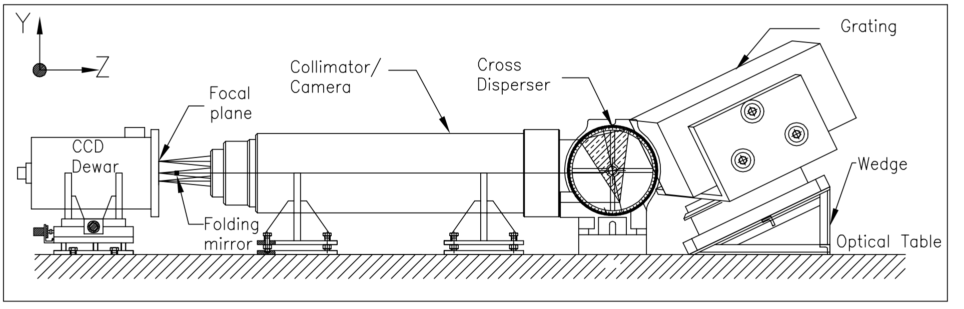

Figure 1. Opto-mechanical layout of the spectrometer. F/5 beam emerging from the slit is fed into the collimator by a folding mirror. The collimated beam then passes through the cross disperser (prism) and gets predispersed and illuminates the echelle grating. The dispersed beam from the grating again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

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.

In our case we chose it to be about 70,000 (4 km s^{-1}). 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).
- 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 the same signal to noise could be obtained across an order without saturating in 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.

We finally preferred the all transmitting system for the spectrometer with the optical surfaces anti-reflection coated to optimize the throughput rather than reflecting cameras with central obscurations. Following other optimized throughput spectrometers like Sandiford at McDonald Observatory (McCarthy *et al.* 1993), we opted for Littrow configuration (*i.e.*, the collimator also acts as a camera; the input and output beams trace almost the same path). Again to have less steep light distribution along the orders we preferred to broaden the blaze function by using an echelle grating with more number of grooves/mm. The echelle grating selected has 52.67 gr/mm and blazed at 70° (R2.6).

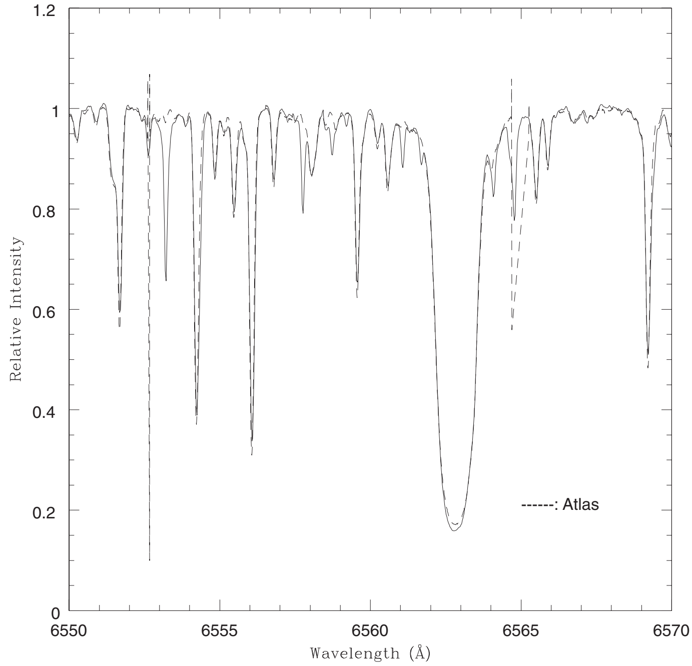

Figure 2. Spectrum of Arcturus obtained with fiber fed echelle spectrometer at VBT superposed on Kit Peak Atlas spectrum.

The expected resolution of the spectrometer with a slit width of 57 μm and a collimated beam diameter of 151 mm is 72,000.

The star light after hitting the primary mirror which comes to a focus as an f/3.25 beam, 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. 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 converted to an $f/5$ converging beam that focuses on to the slit. The image size at the slit is 154 μm. The fiber output can also be used without the 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. 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 Å to 1 μm.

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 illuminated by the incident beam fully. The grating is the single

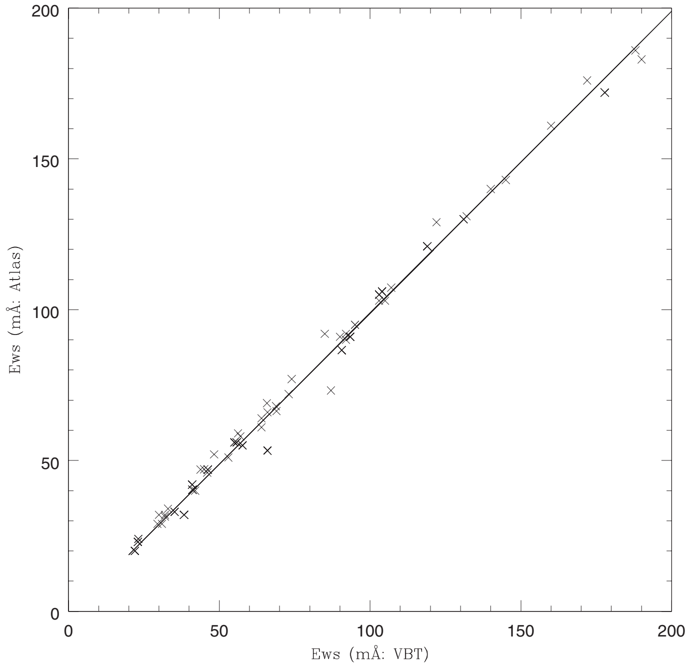

Figure 3. Comparison of equivalent widths in the spectra taken from VBT and Kitt Peak.

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 is a back illuminated, thinned Marconi chip with square pixels of 15 μm size and is placed in an LN2 cooled dewar. The controller and the associated electronics, and the dewar have all been built in the Indian Institute of Astrophysics laboratories. The slit size of 60 μm covers about four pixels on the CCD. The present CCD chip almost covers half of the area of the two dimensional spectrum format in the focal plane of the camera. The desired wavelength region is recorded either by moving the grating or CCD dewar. All the optical components are mounted on a Milles Griot vibration free table of size 8 × 4 feet. The opto-mechanical layout of the spectrometer is shown in Fig. 1. The CCD dewar is mounted on a stage with a provision to move in X–Y and Z directions, the direction of the optical axis of the collimator. The whole mechanical assembly is placed in an environmentally (temperature, humidity) controlled dark room – Coude laboratory.

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.

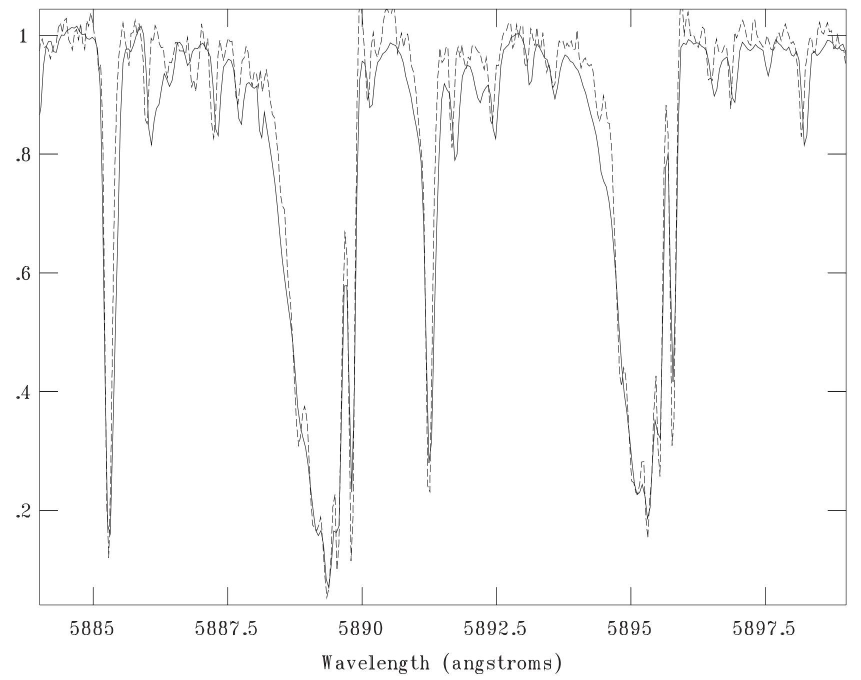

Figure 4. Comparison of the spectra of hydrogen deficient R CrB star, V854 Cen obtained with McDonald Observatory 107-inch coude echelle spectrometer with resolution 60,000 in February 1999 (full line) with the spectrum obtained by VBT fiber-fed echelle spectrometer on 13 Jan 2004 in Na ID line region.

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.

Presently the spectrometer operates in two modes with a 60 micron slit (resolution of 72,000) and without the slit (full fiber at 27,000 resolution) although there is a provision to change the slit width. By narrowing the slit we even obtained more than 100,000 resolution for HR 3117. 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. Presently two other CCD systems are also available to be used with the spectrometer for programmes that do not require large wavelength coverage.

A 1024 $\times$ 1024 pixels of 24 μm size CCD system with a read out of 30s and a Pixcellent CCD system with 2048 $\times$ 2048 of 13.5 μm square pixels with the readout time of about 60s. Both the systems have higher quantum efficiency in the red and cover about the same wavelength range. For recording fast time varying spectroscopic phenomena these systems would be more suitable.

3. Some observational studies

In the last few months the spectrometer has been extensively used in the studies of stellar elemental abundances (Rao & Reddy 2005). The quality of the spectra obtained

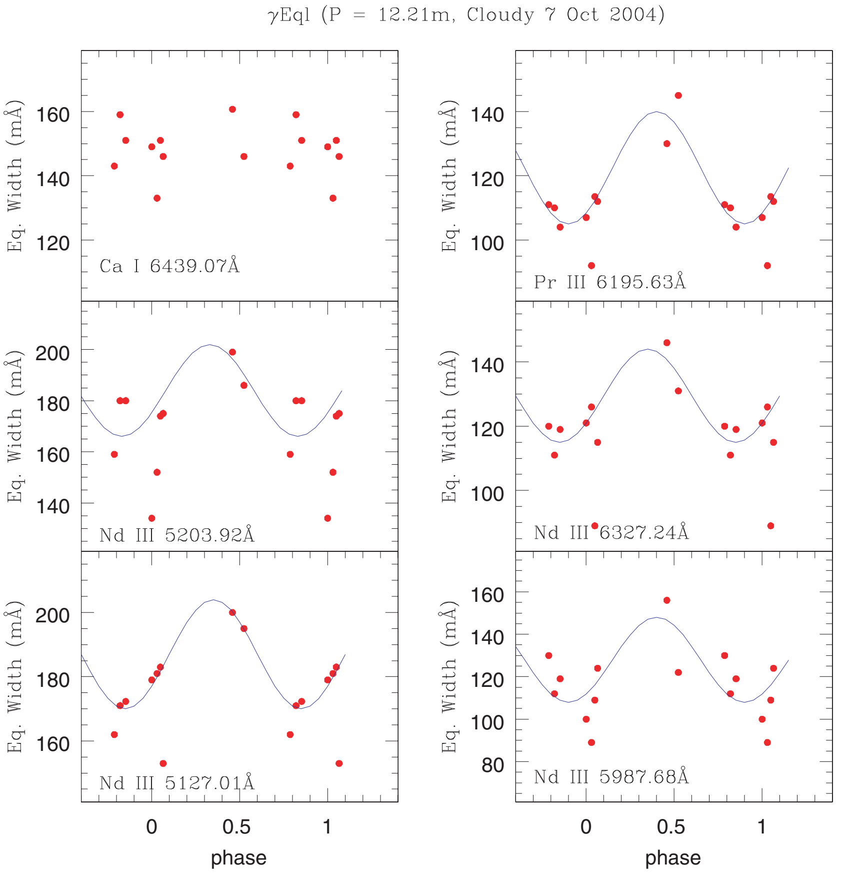

Figure 5. Variations of equivalent widths with period in γ eql. Variations are strong in rare earth lines where as Ca I lines do not show such variations.

can be illustrated from a comparison of Arcturus spectrum obtained with VBT and Kitt Peak Atlas (Hinkle *et al.* 2000). The Fig. 2 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 'Visible and near-Infrared Atlas of the Arcturus spectrum' obtained at Kitt Peak at 120,000 resolution. Note the line to line matching and also the depth of the strong Hα line, centered at 6563 Å, in both spectra match very well illustrating the high quality of the spectrum without any scattered light in the VBT spectrometer. Figure 3 shows the comparison of equivalent widths in the spectra to be an agreement within a standard deviation of less than 2 mÅ.

The spectrum illustrated in Fig. 4 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.

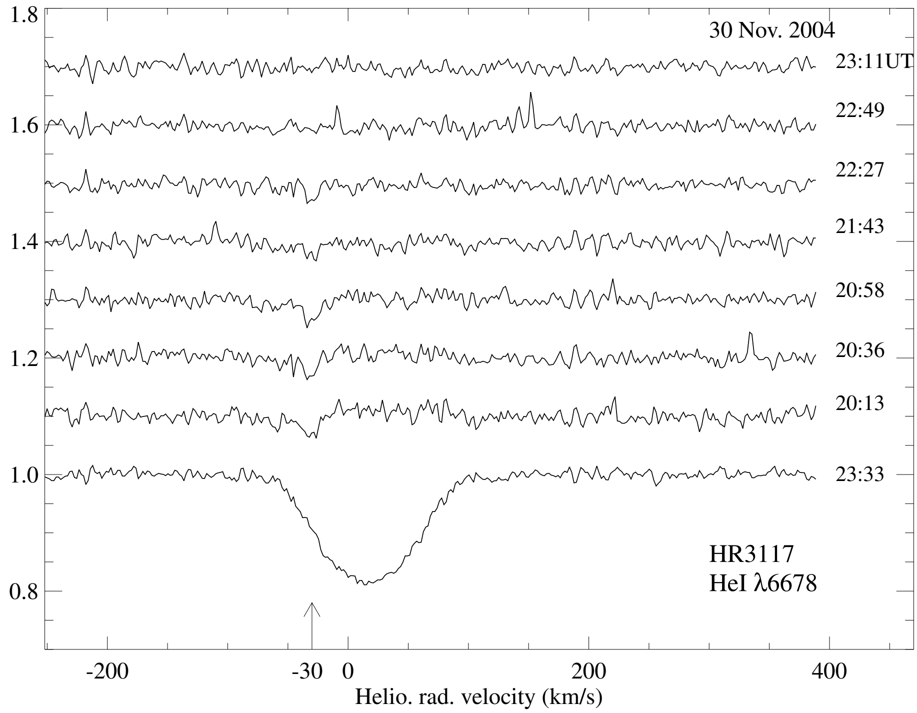

Figure 6. He I λ 6678 line and its variations with time in HR 3117. The divided profiles are arranged in increasing time sequence starting from the bottom. Note the extra absorption component at radial velocity $-29\,\mathrm{km\,s^{-1}}$ that disappears with time.

In the context of the present workshop where variability is the central theme the following examples would illustrate the present capability of the instrument. The roAp star HR 1217 has been observed with a time resolution of 1 min at a spectral resolution of 28,000. The variation in the equivalent widths of a few selected lines is illustrated in the period of 12.2 min. Such variations are already well known in the star. The observation have been obtained using 1K $\times$ 1K EEV CCD camera. More interesting are the observations of the suspected β Cephei star HR 3117 (χ Car). The star is supposed to show light variations with a period of 2 hours 25 minutes (Elst 1979). We have obtained spectra almost every 20 min on 30 November 2004 for a period of $3\frac{1}{2}$ hours continuously. The spectral resolution achieved is about 65,000 and the S/N ranged from about 108 to 180. During this period interesting changes have been seen in the He I 6678 Å line. As shown in the Fig. 6, the broad He I line extends from $-68\,\mathrm{km\,s^{-1}}$ to $108\,\mathrm{km\,s^{-1}}$ at the base. The profile shows changes mainly on the blue side becoming from an asymmetrical line to a more symmetrical line. These changes are at 3 to 4 per cent level in relative intensity. The changes are better illustrated by dividing each profile with the last profile in the sequence (and relatively more symmetrical) and the resultant profiles are arranged in a time sequence along with the dividing profile in Fig. 6. It is clear that a narrow (relatively) absorption component that was present initially at radial velocity of $-30\,\mathrm{km\,s^{-1}}$ (the stellar velocity is given as $19.4\,\mathrm{km\,s^{-1}}$) slowly disappears in about 2 h 30 min. The equivalent width initially is 12 mÅ. Since the component already exists in our initial spectra and disappears in

$2\frac{1}{2}$ hours suggests the phenomenon, if periodic, would have a period much longer than the canonical light period. (Handler (private communication) says it is not considered as a β Cehei star any more because of lack of detectable light variations in Hipparchus measurements.) The star has been classified as peculiar by Hiltner *et al.* (1969), a B3 Si star, because of silicon line strengths. The helium lines have been studied by Leone & Lanzafame (1997) and Leone & Catanzaro (1998). Both these sets of authors obtain normal abundance of helium. Leone & Catanzro (1998) determine abundances of other elements that are close to the values of main sequence B stars (including Si). Their spectra obtained on four nights in 1995 at a resolution of 13,000 showed no evidence of spectral variability. They even conclude that HR 3117 is not a peculiar star as reported in general catalogue of Ap and Am stars. Our present observations obtained at much higher resolution do show changes in He I lines. Additional observations are being obtained.

The above account describes the present capabilities of the spectrometer. Further developments in improving the throughput and more importantly improving the accuracy of radial velocity measurements are planned.

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