A Proposal for an Echelle spectropolarimeter for the 2-m Hanle Chandra Telescope [1][2]

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INTRODUCTION

Origin of the proposal

The proposal traces its origin to a collaborative international programme under the Indo-French Centre for the Promotion of Advanced Research (IFCPAR) entitled "Dynamics of solar and stellar interiors asteroseismology and activity", (in which the PI is also a co-investigator). Recently astronomers at the Laboratory for Astrophysics of the Observatory Midi Pyrenees, Toulouse, France, have developed a spectro-polarimeter called ESPaDOnS (Echelle Spectro-Polarimeteric Device for Observation of Stars), which is installed at the Canadian- French telescope in Hawaii (Donati et. al. 2004). An identical spectro-polarimeter is currently being assembled for the 2-m Bernard Lyot telescope atop Pic du Midi in France. The French astronomers have offered to provide full technical support, including the supply of the drawings of the above spectro-polarimeter and also to supervise the construction of another instrument. This offer was discussed in great detail when Professor Claude Catala from the Paris Observatory, Meudon, who has participated in the development of ESPaDOnS, visited IIA in 2003. It was found that the proposed instrument could be easily interfaced with the 2-m Himalayan Chandra telescope (HCT) at Hanle, and thereby would fulfill the much needed requirement for high resolution spectroscopy with the HCT.

Definition of the problem

The Himalayan Chandra Telescope at Hanle is currently operational with the first phase-instruments which support low-resolution spectroscopy, optical and near-infrared imaging. With large number of clear nights and sub-arcsec seeing this optical telescope is a valuable tool for carrying out a large number of important astronomical studies. In the last three years many valuable observations have been made and the results are published in leading research journals (see http://www.iiap.ernet.in/iao/publications.html for more details). A very large number of scientific programs which are being carried out at the Indian Institute of Astrophysics (IIA) require high spectral resolution. The VBT echelle spectrometer is used heavily. Unfortunately, the Kavalur site faces two annual monsoons, and hence objects which are accessible in June-December cannot be observed from the Vainu Bappu Observatory (VBO). The need for a high resolution facility with the 2-m HCT has been emphasized by many astronomers. We propose a high resolution spectro-polarimeter which can also be used as an efficient spectrometer. The chosen configuration would yield a spectral resolving power of 50,000, complete spectral coverage in a single CCD frame and very high light efficiency due to the usage of an image slicer. In polarimetric mode, the wavelength dependence of linear and circular polarization can be made at the same high resolution of 50,000. This high precision instrument would cater to the observational requirement of a large number of front-line astronomical problems.

Scientific Objectives

We list a few representative fields in which astronomers of IIA are already active and when the instrument would be put to use immediately after its commissioning.

(a) Stellar compositional studies

The chemical composition of stars occupying different regions of HR diagram is one of the basic ingredients for the construction and testing of theories of stellar evolution. A young star reflects the composition of the interstellar medium (ISM) out of which it is born, but a highly evolved object bears the signature of nuclear processing and mixing that it has undergone in the course of its evolution.

Elements like C,N,O participate in nuclear reactions and therefore their abundances and isotopic abundance fractions are good indicators of the evolutionary status of the star. Abundances of heavy neutron capture elements are also very good diagnostics of the various evolutionary processes occurring in stars of different mass range. However most of these elements present themselves as very weak features.

To derive the chemical composition, one requires the strengths of clean unblended spectral lines for each element of interest. Accurate line strength measurements of weak lines require a resolution R of $\sim$ 50,000 or better.

The line components resulting from isotopes of an element are generally separated by a small fraction of an Ansgstrom. The measurement of isotopic abundance fraction also requires very high resolution spectra.

There are a large number of scientists at IIA who have been working on the studies chemical composition studies of different classes of stars, like Post-AGB stars, RV Tau stars, R CrB and other groups of hydrogen deficient stars, PPNe, metal-poor stars, Chromospherically active stars like T Tauri and RS CVn stars. A very large number of papers ($\geq$ 200) on the chemical composition of stars have been published by IIA astronomers in international journals recently. In fact, within the country, it is IIA that has the largest group of astronomers using spectroscopic techniques, especially high resolution.

The scientific team mentioned in 500 also contains the names of the persons very keen to use this facility for their scientific programs.

(b) Search for binary companions and extra-solar planets

For different families of stars such as Pre-Main-Sequence stars, Post-AGB stars etc the presence of companions seen to have played very important roles in defining their evolutionary status. Some of the chemical peculiarities exhibited by post-AGB stars and RV Tau stars can be better understood in the framework of circumbinary environments. The list of known post-AGB stars with binary companions is growing (Van Winckel 2003). Binary companion for PMS star HD 34700 was detected by Arellano Ferro and Giridhar (2003). Hence the search of low mass companions is considered a very important area where both the long-term as well as short-term monitoring yields very important results.

Detection of planets of Jupiter-size around other solar-type stars demands extremely precise radial velocity measures (of the orders of tens of ms^{-1}. A dedicated instrument giving a complete spectral coverage from 370 to 900nm in a single CCD frame is necessary to meet the required precision. It can significantly increase the detections of such systems. It should be noted that instruments like HARPS (High Accuracy Radial Velocity Search (cf. Queloz and Mayor 2001; Pepe, Mayor and Ruprecht 2002), SARG (Spettarografo Alta Risoluzione Galileo (cf. Gratton et al. 2002) and FEROS (Fiber fed Extended Range Optical Spectrograph (cf. Kaufer and Pasquini 1998) mounted on 1.5 to 2-m class telescopes have made significant contributions to this field. CORALIE and ELODIE (Baranne 1997) have made significant contributions to the detection of a large number of planets with short-period orbits (P$\sim$ 20 days). Significant effort has gone in the detection of planets. Measurement of the $^6Li/^7Li$ isotopic ratio in planet harbouring stars is an excellent tool to test different theories of giant planet formation. Reddy et al. (2002) have carried out a search of ^{6}Li in a sample of metal-rich stars.

(c) Studies of mass-loss and extended envelopes around evolved stars.

Stars lose considerable amount of mass at their Red Giant Branch (RGB) and at Asymptotic Giant Branch (AGB) evolutionary stage. Massive stars like Wolf-Rayet stars also lose considerable amount of mass in the course of their evolution. Mass-loss rates are important parameters involved in stellar evolutionary calculations. One uses circumstellar components in the profiles of resonance lines to estimate mass-loss rate. These components are generally very weak. Hence a high resolution spectrograph giving clean profiles is necessary to calculate the mass-loss rate.

Very significant contributions to the understanding of R CrB and other hydrogen deficient stars through the studies of their light fadings, pulsations and moss-loss have been made by N.K.Rao and his collaborators using high resolution spectroscopy. (see for example Rao et al. 2004, 1997, 1993; Goswami et al. 1997; Pandey et al. 2004, 2001).

The field of Proto-Planetary Nebulae, and AGB stars has been enriched by Parthasarathy (see for example Parthasarathy et el. 1993; Gauba and Parthasarathy, 2004). Mass-loss estimates for a few post-AGB stars are presented in Reddy and Parthasarathy (1996).

Using high resolution spectra, molecular C_2 and CN lines formed in AGB remnants have been detected in the optical spectra of a few post-AGB stars. These features are used in deriving outflow velocities, rotational temperatures and column densities in the AGB remnant. These molecules are new tracers of AGB remnants and are formed in the regions relatively nearer to the star than those detected from CO and IR observations. By comparing the results from different molecules with different excitation conditions one can study the AGB ejected material as a function of distance and make inferences on the evolutionary status of the star on AGB (Bakker et al 1995).

(d) Metal-poor field stars

The chemical history of the early Galaxy can only be understood through the study of ultra metal-poor objects. Survey of high proper-motion stars have led to the discovery of many metal-poor stars with unusual compositions. A well-known example is the metal-poor star CS 22892-052 . This star is carbon-rich but is overabundant in r-process elements. The abundances of 20 n-capture elements have been derived for it. The observed Th/Eu ratio gives an age estimate of 15.2 $\pm$ 3.7 Gyr for CS 22892-052 which has [Fe/H] of -3.1 (Sneden et al. 1996). Similarly, detection of U II line in CS 31082-001 by Cayrel et al. (2001) has led to an even more accurate age estimate of 12.5 $\pm$ 3.0 Gyr for this star. The detection of stars with [Fe/H] < -3 in different parts of our Galaxy would have strong impact on our understanding of star formation in early stages of galactic evolution. Giridhar et al. (2001) have found carbon enrichment in metal-poor stars CS 22877-1 and CS 22166-16. Takeda, Y., Parthasarathy, M. et al. (2001), Sneden and Parthsarathy (1983) have made very important contribution to this field.

(e) Doppler imaging of spotted stars

Doppler imaging technique (DPI) is an indirect elaborate computational technique to invert a series of high-resolution spectral line profile into an image of stellar surface (Donati et. al. 1997). The development and refinement of this indirect stellar imaging technique over two decades has made DPI one of the most reliable tools to estimate spatial distribution of the temperature and chemical abundances over the stellar surface. It requires high-resolution ($\frac{\lambda}{\Delta\lambda} \geq 30000$) and high signal-to-noise ratio($\frac{S}{N} \geq$200) spectra with a good phase coverage. This method is being employed to reconstruct star-spot patterns on the stellar surface and monitor them over long periods of time. Stars like RS CVn binaries with their known surface activities could be used to explore the possibility of their surface features showing regularity similar to the sun-spot butterfly diagram (Vogt et al. 1999). Raveendran, Mekkaden and Padmakar Singh Parihar have done photometric studies of RS CVn stars (see for example, Mekkaden and Raveendran 1998; Raveendran and Mohin, 1995) and have attempted modelling of the surface features using broad-band observations. With a high resolution spectrometer, they would be able to carry out very comprehensive studies of these stars. Such investigations are important to understand the nature and origin of magnetic activities in the stars as well as the Sun (Donati et al. 2003).

(f) Star-spots and activity

Star-spots, similar to sunspots, are a common occurrence in active stars and provide a measure of the dynamo effects through which the magnetic field is generated. In recent years, many stellar systems have been observed through Doppler imaging. Most of them have high-latitude/and or polar spots, while a significant fraction of others have spots covering the rotational poles. In addition, all of them are rapid rotators. Using a high resolution echelle spectro-polarimeter (like that of the MuSiCoS spectrograph, an earlier version of ESPaDOnS) and cross-correlation techniques such as least-squares deconvolution, one can detect stellar magnetic fields through the Zeeman signatures they generate in the shape and polarization state of spectral line profiles. Zeeman-Doppler imaging works efficiently for fast rotators, for which circular polarization signatures of individual unipolar magnetic regions are associated with different Doppler velocities and thus no longer mutually cancel as in conventional polarimetric methods. This method has been successfully used to obtain direct detection (i.e. from spectro-polarimetric data) of magnetic fields in cool stars other than the Sun. For instance, using Doppler imaging techniques a gigantic cool star-spot (about 10,000 times the area of the largest sunspot group) was found on the active K0 giant HD 12545 (Strassmeier 1999).

(h) The polarimetric studies of Hanle effect in spectral lines

The spectro-polarimetric studies of Hanle effect in strong lines of alkali elements (Ca II H & K, Mg II doublet, Na D_1 & D_2, Sr I 4607 $\AA$, He I D_3 etc.), as well as molecules of MgH, C_2, CN, CH, and NH_3, represent very interesting and new areas of research. The Stokes polarimetry in the above mentioned and other features (in optical and near IR) can tell us more about the weak turbulent magnetic field ($B \approx 10 - -200G$) in stellar atmospheres. Notice that in the case of Hanle effect, unlike Zeeman effect, the Stokes parameters do not cancel out due to surface averaging, even in spherically symmetric stars. The kind of objects one can choose for such studies are both early type stars with or without winds, and late type supergiants (which are established to be non-magnetic through Zeeman-Doppler imaging or Zeeman polarimetry). The idea is to measure the magnetic intensification caused by atmospheric turbulence. The measurement of weak magnetic fields provides an important data for stellar evolution studies. The equipment required is an optical and near IR spectro-polarimeter.

(i) Strong magnetic fields in chemically peculiar stars

The Ap stars fall in this class of stars with the magnetic fields of a few KG. It is necessary to observe the circular and linear polarisation due to the Zeeman effect in many lines to be able to carry out the mapping of the field structures . The equipment required is again a spectro-polarimeter and the Zeeman-Doppler imaging/ analysis software. With suitable modelling it is possible to understand the field strength distribution, geometry etc (Bagnulo et al. 2001).

(j) Magnetic fields in RS CVn stars

The study of magnetic fields in cool active stars (Zeeman - Doppler imaging) is mandatory to understand their activity, and to enable us to see our Sun in an evolutionary context.

The magnetic fields so far found (e.g. RS CVn systems) are sufficiently intricate that the circular polarisation signal (sensitive to the vector properties of the magnetic field) they induce in a spectral line is tiny. Co-addition of the signals from many lines permit major reductions in the threshold for detection and the limiting magnitude for observations and greatly facilitates mapping of the field structure (Donati 1999). Stellar activity in RS CVn binaries has been studied by Padmakar Singh Parihar and Pandey (1999), Padmakar Singh Parihar, Drake and Pandey (2000) using long-term photometry. Spectro-polarimetric studies of these objects is contemplated to give detailed information on their magnetic fields.

(k) Classical, Recurrent and Symbiotic Novae

Novae, which are interacting binary star systems, consists of a Roche-lobe filling secondary on or near-main sequence star, losing hydrogen-rich material through the inner-Lagrangian point onto an accretion disc surrounding the white dwarf primary. The mass losing secondary in some recurrent novae and symbiotic novae is either a late giant or a Mira. A nova eruption is triggered by the thermonuclear runaway on the surface of the accreting, degenerate white dwarf primary. Nova systems serve as valuable astrophysical laboratories in the studies of physics of accretion onto compact, evolved objects, thermonuclear runaways on semi-degenerate surface which give insight into nuclear reaction networks, and line formation and transfer processes in moving atmospheres.

A nova outburst is accompanied by the ejection of the accreted material, at velocities ≥ 300 kms^{-1}. A study of the temporal evolution of the spectrum from the ejected material is very useful in deriving the physical conditions in the envelope and their evolution (e.g. Anupama et al. 1992; Austin et al. 1993; Kamath et al. 1997; Shore et al. 2003; Cassatella et al. 2004). The exploration of the shape of the nova ejecta provides an insight into the physical processes during a nova outburst. It is thought that mass loss in novae deviates from spherical symmetry due to the effects(s) of binary motion and/or the rotating white dwarf. Hydrodynamic simulations of the shaping of the nova ejecta (Llyod et al. 1997; Porter et al. 1998; Gill & O'Brien 1999) indicate that the temporal variation of a nova wind, which blows continuously following the outburst, plays an important role in determining the final shape of the ejecta. Analyses of the emission line profiles of many novae in outburst also suggest the existence of non-spherical structures in the ejecta (e.g. Prabhu & Anupama 1987; Martin 1989; Shore et al. 2003) . The line profile, however, can be deformed and complicated by optical depth effects, making it somewhat difficult to derive the asymmetric properties, particularly during the early stages of the nova. To study the asymmetric properties of the nova ejecta, spectro-polarimetry is a very useful method, as not only can one obtain information on the asymmetry itself from linear polarization, but it also permits separation between the line and continuum components, which also enables estimation of the foreground interstellar polarization. A few novae have also shown variable intrinsic polarization. The proposed mechanisms of the intrinsic polarization in the outburst phase can be roughly divided into two kinds of light scattering: Thomson scattering (due to free electrons) or Mie scattering (due to dust grains). Generally, the former mechanism dominates in the early phases of a nova outburst, and during all phases of non-dusty novae. In dusty novae, Mie scattering dominates, during the dust formation phase. The information on the wavelength dependence of continuum polarization obtained by spectro-polarimetric observations is hence of great benefit in distinguishing the origin of the polarization.

The spectrophotometric observations of novae V1974 Cyg (Bjorkman et al. 1994) and V1494 Aql (Kawabata et al. 2001) have confirmed the presence of an asymmetric geometry for the nova ejecta, as also indicated by the emission line profiles. Intrinsic polarization has been detected in the recurrent nova U Sco (Ikeda 2000) and nova V4444 Sgr (Kawabata et al. 2000). However, the fraction of novae which have spectro-polarimetric information is very low. In the recent past, though, with the availability of improved telescopes and instruments, this fraction is slowly increasing. There clearly is a need for more spectro-polarimetric observations of novae, given the amount information such data can give in the understanding of the nova phenomenon.

Technical Specifications

To be able to cater to the needs of the scientific programs mentioned above, the instrument must meet the following technical requirements.

1. Resolving power of at least 50,000. Most scientific program mentioned in the sections 2 and 3 require such a resolution. It is not possible to get a clean narrow instrumental profile at a lower resolution. Chemical composition studies require measurement of the line strength of weak stellar lines. At lower resolution, the lines are highly blended, hence accurate line strengths cannot be measured. Lines of important radioactive elements like Th II, U II, which are most important tools for getting accurate age estimates, cannot be detected at lower resolutions.

   This resolution is mandatory to yield sufficient spatial resolution for Doppler and Zeeman-Doppler imaging of rapid rotators, and thus increase the sensitivity of the observations to small-scale magnetic structures.

2. Large continuous spectral coverage. The instrument must yield a complete coverage of the optical domain, from 370 to 900 nm, in a single exposure, in order to maximise the multiplex gain for most of the stellar physics programmes listed above.

3. Possibility of recording two interleaved spectra. The instrument should be able to record at the same time, the spectrum of a faint object along with that of the adja-

cent sky. Alternatively, it should provide the possibility to interleave the spectrum of an object and that of a spectral calibration lamp (e.g. Th/Ar lamp) for precise measurements of radial velocity variations. In polarimetric mode, this would allow one to measure simultaneously both the orthogonal components of a given polarisation state on the detector.

4. Highest possible throughput. One should aim at a peak total throughput of 20 % (atmosphere, telescope and detector included), which is possible with modern detectors and spectrometer designs (dual -pupil mounting, fully dioptric camera), to be able to detect objects of mag 11-12.

Proposed Optical Design

In the last two decades many new tools have become available to the spectrograph designers, such as ray tracing codes, optimization algorithms, finite-element analysis, new glasses, better grating performance, high-efficiency coatings and modern detector formats. These new tools have made it possible to consider innovative approaches to spectrograph designs, including white-pupil designs, refractive or catadioptric cameras. In conventional spectrograph designs with a single collimator used in one pass, two integrations are needed to obtain the full free spectral coverage. The overall efficiency of the telescope+spectrograph+detector seldom exceeded 8-10%. Beranne in 1972 introduced a concept for spectrograph design which eliminates the vignetting and aberrations found in some conventional spectrographs. Since the pupil at the grating is re-imaged onto the camera pupil, the required camera entrance aperture is smaller and aberrations are controlled better. It is accomplished with the help of additional collimator (mirror). The additional optical element does increase the cost but the reduction in losses due to vignetting (which could be as much as 30% in a conventional design), provide a significant advantage. The light losses due to additional refections could be minimised by the use of high efficiency refective coatings. The Baranne's white-pupil design has been adopted in the UV-VISUAL Echelle spectrograph (UVES) for ESO's Very Large Telescope (See Delabre 1993, D'Odorico et al 2000) and also for the High Resolution Spectrograph (HRS) on the Hobby-Eberly Telescope. The instrument configuration has been described in Tull (1998).

The optical configuration of the proposed spectrograph is inspired by FEROS, a well-known bench mounted fibre fed spectrograph, used at the European Southern Observatory (ESO) 1.52-m telescope. The spectrograph design uses the white-pupil configuration introduced by Baranne in 1988. In the white-pupil design, the disperser (an echelle grating here) is re-imaged onto the camera. The dispersed rays from the grating are sent to collimator again and an intermediate spectrum is formed at the focus of the collimator consisting of overlapping orders. A small flat mirror near the intermediate spectrum sends back the monochromatic beams towards a transfer collimator. Since the folding mirror is at the focus of the transfer collimator, the latter forms a white pupil in the parallel light. This pupil is the white image of the grating but reduced to a smaller diameter so that one does not require unreasonably large camera aperture, thus avoiding vignetting at the camera. The narrow flat mirror for the folding of the beam is located near the intermediate focus of the two collimators and acts as an effective baffle for the stray-light produced by the echelle grating.

Proposed optical configuration of the spectrograph

We envisage the use of two identical off-axis collimators with focal ratio of f/11 and of 680 mm diameter. Normally, these mirrors are cut from the common parent parabolic mirror. The beam size of the spectrograph is chosen as 180 mm. The we intend using echelle grating (R2) with 79 lines per mm and with a ruled surface of 200 X 400 mm. The cross-disperser would be a 55^o prism with a base length of 235 mm and a height of 220 mm. The prism would be used in the minimum deviation condition for the central wavelength of spectrograph which is 462.3 nm in order 49. The two dimensional echelle spectrum would be imaged by a fully dioptric f/2 camera onto the detector. The chosen camera is optimized for the extended wavelength range 350-900nm. It has a focal length of 400 mm, a field diameter of 69 mm and a clear aperture of 220 mm. Due to the use of UV transmitting glasses and broadband anti-reflection coating a total transmission efficiency greater than 85% could be reached over the full wavelength range. The field lens of the camera would act as the entrance window of the CCD system. The detector chosen is a 2048 X 4096 back illuminated 15 μ pixel CCD by EEV. It has low readout noise and relatively high quantum efficiency over wavelength range of 350 to 900 nm.

The chosen fibres would have a core diameter of 100μm and are fed by micro-lenses on the telescope side. Two apertures with 0.22 mm diameter corresponding to 2.5 arcsec in the f/9 focal plane of the 2.01m HCT telescope are imaged onto 90% of the fibres input end diameter, resulting in an effective f/4.6 feed which is well suited to minimise focal-ratio-degradation (FRD) effect on the fibre link. The micro-lens is a rod lens with radius of curvature of 0.7 mm and a length of 2.0 mm. It is directly glued with the flat surface of the fibre entrance surface. The micro-lens and the fibre are mechanically mounted in a modified SMA 906 connector. The polished fibre exits are left blank and are re-imaged by the F/N-system which converts the f/4.6 fibre beams to f/11 beam accepted by the spectrograph. The F/N system produces images of the fibre enlarged to 240 μm at the intermediate focus. The image slicer is kept at this intermediate focus.

The image slicer of FEROS is a modified Bowen-Walraven design which simultaneously slices the two beams emerging from the object and sky fibres with minimum of defocussing introduced by the optical path differences (OPD) inside the slicer. This slicer halves the width of the image of the two fibres in the direction of dispersion and generates a rectangular image of width 120 μm and height 520 μm. This leads to better resolution and increased S/N in the detector plane.

The FEROS when used with the ESO 1.52 m telescope gave complete wavelength coverage in the region 370-860 nm in 40 orders with overlapping wavelengths in successive orders. Since there is no need to move any of its optical components, it ensures better mechanical stability and hence better precision in velocity measurements.

The instrument reached the expected limited mag 12 with a signal to noise ratio S/N of 100 with 2 frames of 1 hr integration. It can be used to study objects up to 16th mag, if the S/N ratio requirement is lowered to about 10.

The 2 fibres can be used for recording the star and arc spectrum simultaneously on the same CCD frame. This allows one to overcome the effect of residual motions of the spectrograph during the night and during the exposure. For a radial velocity standard τ Ceti the radial velocity has been measured for 130 epochs and the radial velocity is derived with an accuracy of $\pm$ 21ms^{-1} . Alternately, the second fibre can be used to record the night sky spectrum. This allows the subtraction of night-sky emission lines, which are strong contaminants in the spectra of faint stars. This would also help observations during bright moon and twilight conditions.

The only change from the FEROS design we have planned is that the camera would have a larger pupil size (180 mm) in accordance with the size of HCT primary, which should enable us to collect stellar light through a 2.5" circular aperture (with no increase in detector size nor decrease in spectral domain and resolution). The performance of HESP should therefore be very similar to that of FEROS, i.e. full spectral coverage from 370 to 900 nm (orders 25 to 61) at 50,000 spectral resolution and with 20% peak efficiency at 500 nm (and 6 % throughout on both spectral domain edges).

Optical configuration of the polarimeter

The stellar/calibration light is collected at the Cassegrain focus through a 220 μ circular pinhole at the center of the inclined mirror atop the polarimeter. Two triplets with respective focal lengths of 55 and 25 mm, working at infinite conjugate ratio and separated by an air equivalent optical path of 80 mm ensure that fibres are fed at a beam aperture of f/4.6. Hence the output beams at fibre level are telecentric (pupil at infinity) and hence the Wollaston prism receives a parallel beam. The two beams produced by the Wollaston prism are imaged on to the two fibres of the fiber link that feature a separation of 110μ. The deviation that the Wollaston produces for each beam is 0.126 deg at 500 nm.

In the polarimeter unit, we plan to use a combination of a Wollaston prism with three Fresnel rhombs (one fixed quarter wave rhomb located between two rotating half wave

Table 1: High resolution spectrographs

Spectrograph	Spectral coverage (nm)	Spectral orders	Resolution	Throughput (Sp+Det)	Observing limit 1hr, 100 S/N	Radial Vel Acc. m/s
2DCoude	340-1000	-	60000	15[1]	11.0 (2.7m)	-
ELODIE	385-680	67	42000	4.2	9.7 (1.93m)	20
MUSICOS	380-880	2x46	35000	-	7.0 (2.0m)	100
FOCES	360-940	70	40600	-	11.0 (2.2m)	18
FEROS	356-920	39	48000	27	12.5[2] (1.5m)	30
SARG	370-900	-	164000	13.2	16.0 [3](3.6m)	5.0
ESPaDOnS	370-1000	-	50000	20.0[1]	14.0 (3.6m)	-
PEPSI	450-1000	-	300000	26.0[1]	20.4 [4](2x8.4m)	-

(1) Including telescope (2) 2 hours exposure, (3) R=86000 and S/N $\sim$15 (4) R=120000 and S/N$\sim$10

Fresnel rhombs) . These rhombs are made highly achromatic by adding a layer of magnesium fluoride (of calibrated thickness) on one of the two total internal reflecting surfaces. These devices are free of fringing pattern compared to the conventional crystalline plate such as those generated by the super-achromatic Halle waveplates (Semel 2003). We propose to use the low OH H treated Ceram-Optec fibres (with .100/110 μm core /cladding diameters) which provide close to optimal transmission through out the whole spectral domain of interest. By rotating both half-wave rhombs with respect to the fixed quarter-wave rhomb and the Wollaston prism one can make either a circular or linear polarisation measurement of the stellar light. It is possible to exchange the role of both the beams within the instrument to minimise spurious polarisation signatures.

Review of status of Research and Development in the subject

International status:

The white-pupil arrangement has been adopted in many spectrographs that are currently in use in various observatories around the world. By minimising the light losses at the camera, the throughput of the spectrograph is increased considerably. Secondly, the scattered light within the spectrograph which adversely affects the line strength measurement of weak lines is minimised. This design, together with the image slicer can enable the instrument to detect objects 1-2 mag. fainter compared to instruments of a different design for the same telescope aperture.

ELODIE designed to give a resolution of 42,000 with a 1.9-m telescope could reach m_V of 9.7 giving S/N of 100 in one hour integration time. FOCES (Fiber Optics Cassegrain

Echelle Spectrograph cf Pfeiffer et al. 1998) with a resolution of 40,000 mounted on a 2.2-m telescope reached m_V of 11.2 for the same integration time and S/N ratio. The 2D Coudé described by Tull et al. (1995) giving a resolution of 60,000 with a 2.7-m telescope reaches m_V of 11.2 for the same integration time and S/N ratio.

National Status

The 2.3-m Vainu Bappu Telescope at the Vainu Bappu Observatory, Kavalur is equipped with a fibre-fed echelle spectrometer. It is based upon Sandiford Echelle Spectrometer design of the 2.1-m telescope of McDonald Observatory (McCarthy et. al. 1993). Commissioned in 2004, this spectrometer is being used extensively during the bright moon period. The instrument has been performing well in conformity with the specifications of its design.

Two proposers of the present project (Sunetra Giridhar and S. Sriram) were members of the VBT echelle spectrometer team. This instrument is described in Rao et al. (2004). However, the good observing season for Kavalur is restricted between January and May and hence the objects that are in favourable positions during June - December cannot be observed. The Kavalur site also suffers from high humidity which restricts the usage of the cooled CCD camera and haze formation in the sky is very common. Hence a need for a complimentary high resolution facility has always been felt.

Furthermore, the proposed instrument has the additional option of polarimetry. It uses white-pupil concept which avoids vignetting and other aberrations and minimises light-losses. Also, the design includes an image slicer which would increase the light efficiency of the instrument by a factor of 3. The Hanle site is known to have larger number of clear nights and much better seeing conditions than Kavalur. However, the present back end instrumentation at the HCT consist only of a low resolution spectrometer/imager HFOSC (Hanle, Faint Object Spectrometer). The 2-m HCT does not have a high resolution spectroscopic facility, though its necessity has been strongly felt. The proposed instrument would not only boost the on going high resolution spectroscopy programme, but also allow astronomers to undertake new programmes requiring high precision measurements.

Importance of the proposed project in the context of the current status

Owing to the very large and continuous wavelength coverage and high total throughput for which the proposed spectrograph is designed, HESP will be competitive in overall information acquisition (within a factor of about two) with the high resolution cross-dispersed spectrographs being built for 8-m class telescopes. Though the latter may reach fainter magnitudes, many of them have a smaller spectral coverage (eg. HIRES of KECK Telescope described in Vogt 1994) and no order overlap. The white pupil configuration, combined with an image slicer and a double optical fibre, enabling users to record star/sky or star/arc spectrum, makes it a unique instrument capable of catering to the needs of a wide class of astronomical programmes. It should be noted that many scientific programmes that have been mentioned in section 1 are ideally suited for the bright-moon period of moderately sized 2-m class telescopes. These programs primarily require extended runs (not necessarily fainter magnitudes) that cannot be obtained on 8-m class telescopes. Hence in outcome, this instrument will compete favourably with spectrographs on larger telescopes for such programmes.

HESP, would also compare well with the best spectro-polarimeters in the world. Its design promises a wider spectral coverage and better throughput than many spectro-polarimeters in use presently. To mention a few, neither Semel's visitor instrument on the UCL, nor MuSiCoS spectro-polarimeter on the 2-m Bernard Lyot Telescope on Pic du Midi give this wide spectral coverage, resolution and throughput. To the best of our knowledge, no high resolution echelle spectro-polarimeter is being planned for any of the 8 to 10-m class telescope in the near future. Hence HESP would play a significant role in carrying out many interesting astronomical programmes.

Review of the expertise available with proposed investigating group

The team of proposers contains scientists with considerable experience in high resolution spectroscopy and in the study of stellar activities. The team has scientists who have carried out high resolution spectroscopy of different classes of stars and have covered a range of topics in stellar physics. To mention a few examples, chemical composition studies for RV Tau stars, SRD variables, post-AGB stars, metal-poor stars, R CrB stars and Cepheids to study their evolutionary history and also that of ISM is carried out by Sunetra Giridhar. She has also participated in the testing procedures of the high resolution spectrograph at VBO, Kavalur. She has made use of the high resolution spectra obtained from McDonald Observatory, Apache Center Observatory, Cerro Tololo and Kitt Peak National observatory.

A.V. Raveendran has carried out polarimetric studies of variable stars including RS CVn stars, Mira variables and RV Tau type stars (See for example Raveendran 2002, 1999). He has been engaged in the design and construction of a dual-beam photo- polarimeter for VBO, Kavalur. With this polarimeter, linear polarisation can be measured simultaneously in three spectral bands. Thee bands are isolated using dichroic filters and for light detection three photo-multipliers tubes operated in pulse counting mode are employed. He has been serving as the Chairman of telescope time allottment committee for VBO for the last seven years.

B.Eswar Reddy has carved a niche for himself in the field of chemical compositions of stars. Apart from his earlier work on PPNe and post-AGB and Li-rich stars, he has been studying a large sample of G-K stars to define the metallicity trends in thin and thick disk components of our Galaxy. More recently he has also made contribution in the field of R CrB and RV Tauri stars.

The team also contains Mr S. Sriram (an optics engineer) whose dedicated efforts have gone a long way in the commissioning of fibre-fed high resolution spectrograph for 2.3-m telescope at VBO Kavalur. He has also participated in testing and alignment of the 1-m telescope using the Shack-Hartmann wavefront sensor. He is currently providing support towards instrumentation to the ultraviolet astronomy program of the Institute.

Padmakar Singh Parihar has actively participated in the testing stages of the 2-m HCT telescope and its backend instruments. He has developed software for automatic estimation of extinction, and taken part in the modeling of tracking and pointing of HCT. As a support astronomer for HCT he has participated in the testing of HFOSC, CCD Camera. His scientific interests include studies of magnetic activity of RS CVn binaries, Pre-Main Sequence stars like weak-lined T Tauri stars, HAe/Be stars and photometric monitoring of GRBs. He has submitted a proposal to carryout an imaging and slitless spectroscopic survey of the fields near prime asteroseismology targets of COROT space mission to identify magnetically active stars to be observed under the COROT Additional Science Program.

Full details of the expertise of the co-investigators are given in their curriculum vitae (along with their list of publications), which are enclosed.

In addition to the team of investigators discussed above, the project will be supported by a Science Team consisting of astronomers like T.P. Prabhu and G.C.Anupama, D.K. Sahu , development team led by R. Srinivasan and infrastructural team containing B.C.Bhatt who have played a key role in the commissioning of the 2-m HCT and its present backend instruments. They will provide technical advice and guidance to the programme. In particular, their expertise would be available in the design of the instrument interface with HCT. The location of the Coudé laboratory and routing of the optical fibre has to be done without affecting the existing facilities.

The science team also consists of Prof. S.S. Hasan and K.N.Nagendra who have been working on activity on the sun and other stars, study of magnetic fields and spectral line formation. They will provide support in defining new scientific programmes and also subsequently participate in the analysis of the data obtained using HESP.

Work Plan

Organization of work elements

1. Procurement of basic components

We need to procure dioptric f/2 camera, grating, collimators, cross-dispersers, optical fibres, accessories for micro-lens coupling, detectors etc. For some of the components like camera even most reputed companies require 18 months to manufacture. None of the items are available off the shelf.

2. Preparation of a dust-free Coudé Laboratory at Hanle

The proposed instrument with its optical table, shock absorbing support, optical accessories, detector, and thermal enclosure would weigh about 2 tons. A suitable place has been identified on the ground floor of the HCT telescope building that is isolated from the rest of the building. The present power generating system of the HCT using solar panels would not be able to take the additional load of the spectro-polarimeter lab with air conditioning and other accessories. Hence an additional power generating unit need to be procured. The air conditioner must give a fixed temperature notwithstanding a large range in temperature (-26^{o}C to +20^{o}C) encountered at the Hanle site. Routing of the air duct should be kept such that the creation of the temperature gradient in the atmosphere is avoided. The additional structure should not cause degradation of the seeing conditions.

3. Development of the telescope interface

This part of the instrument requires very high mechanical accuracy. This unit houses the polarimeter, calibration lamps, filters etc and at the output end, fibre connectors are provided. The size of this unit including the mounting flanges and the location of the focal point has been very carefully considered in consultation with the support team of HCT. This unit also contains the autoguider which is fed by a 10^o entrance titled mirror with a centered pinhole. It contains a MaxCam camera with two stage thermoelectric cooling which maintains cold fingure at -55^o. One can guide on star upto V mag of 18 with exposures of 1s.

4. Layout of the routing of the optical fibre

It is very important that the starlight is transmitted to the slit of the spectrometer with minimum light losses. We have chosen a fibre giving 95% efficiency upto 60 m length of the cable. The transmission efficiency of the light by the fibre depends much less on the length of the fibre. It is the bending of the fiber that need to be avoided. It is very important to route the fibre cable such as to avoid bending of the fibre at all positions of the telescope. A concept drawing of the fibre routing is in preparation.

5. Integration of the various component controls of the instrument with the HCT control system

A technical team comprising of mechanical, electrical and software Engineers need to make dedicated effort to develop a spectrograph operation unit which should be integrated with the existing telescope control system. The instrument control software similar to that existing on ESPaDOnS would be implemented on Instrument Workstation. This will contain observational software. It will interact with PCs which would control all the opto-mechanical part of the instrument and the guiding camera. The detector control software which would control the scientific camera would running on the second PC. These three computers should be connected with each other and with HCT control via Local Area Network.

Time schedule of activities giving milestones

First Year

In the first year we would be engaged in procuring optical components and preparation of the Coudé laboratory at the HCT. Software will be developed for the integration of different component controls with the HCT operational system.

Second Year

In the second year, the spectro-polarimeter would go through one stage of testing and alignment at Toulouse, France in which both the Indian and French teams would participate.

Third Year

In third year the instrument would be tested at IOA Hanle. In addition to optical alignments and testing of various components the integration of the instrument controls with the telescope control system need to be carried out. A quick analysis of trial data using calibration sources need to be carried to verify that the instrument components are performing according to the subscribed values. Next standard stars of known fluxes need to be observed to measure the throughput of the system. We need to ensure also the mechanical stability of the system. We need to use the stars of known polarization to estimate the smallest amount of polarization that can be measured.

Suggested plan of action for the utilisation of research outcome expected from the project

The instrument will enable astronomers all over India to deal with large number of scientific programmess. In addition to the programmes by a given individual or group, it will be possible to participate in multi-site campaigns where observations in time series are important. Since there are not many observatories at the longitude of Hanle, the observations obtained from Hanle would nicely fill the gap. The results would be published in leading astronomical journals.

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References

Anupama, G.C., Duerbeck, H.W., Prabhu, T.P. et al. 1992, A&A, 263, 87

Austin et al. 1996, AJ, 111, 869

Arellano Ferro,A. & Giridhar, S. 2003, A&A, 408L, 29A

Bakker, E.J., Lamers,H.J.G.,Waters, L. B. F. M.; Schoenmaker, T. 1995, Ap&SS,224, 335

Bagnulo, S.,Wade,G.A.,Donati,J.F.,2001,A&A, 369,889

Barrane, A., Queloz,D., Mayor,M, and 7 coauthors 1996, A&ASS 119, 373 Barrane, A. 1988 in ESO Conference on VLT and their Instrumentation.
Eds.Ulrich,M.H.
Bjorkman, K.S., Johansen, K.A., Nordsieck, K.H. et al. 1994, ApJ, 425, 247
Cayrel, R., Hill,V., Beers, T., and 13 coauthors, 2001 Nature, 409. 691
Cassatella, A., Lamers, H.J.G.L.M., Rossi, C. et al. 2004, A&A, 470, 571
D'Odorico, S. et al, 2002, Proc. SPIE, Vol 4005, 121
Delabre, B., 1993, ESO-Very Large Telescope, UVES Prel. Report, ESO Doc No VLT-TRE-ESO-13200-0272
Donati, J-F., 1999, MNRAS, 302,457
Donati, J-F., Catala,C., Landstreet,J.D., 2004, EdP-Sciences, Conf. Ser, Eds, Combe,F., Barret, D., et al
Donati, J-F., Cameron,A.C., Petit,P., et al. 2003, MNRAS, 345, 1145
Donati, J-F., Semel, M., Carter,B.D., Rees,D.E., Cameron,A.C., 1997, MNRAS,291,658
Gauba G. & Parthasarathy, M., 2004, A&A, 417,201
Gill, C.D., O'Brien, T.J. 1999, MNRAS, 307, 677
Giridhar,S. & Goswami, A. 2002, BASI, 30,501
Giridhar,S., Lambert,D.L., Gonzalez,G., Pandey,G. 2001, PASP, 113,519
Giridhar,S., Lambert,D.L., Gonzalez,G., 2000, ApJ, 531,521
Giridhar,S., Lambert,D.L., Gonzalez,G., 2000, PASP,112,1159
Giridhar,S., Lambert,D.L., Gonzalez,G., 1998, ApJ, 509,366
Goswami,A., Rao,N.K., Lambert,D.L., Gonzalez,G., PASP, 109, 796
Gratton,R., Bonanno,G., and 10 coauthors 2002 in proc. Ist Eddington Workshop. (ESTA, SP-485, Eds Favata,F., Roxburgh,I.W. and Galadi-Enriquez,D.)
Ikeda, Y., Kawabata, K.S., Akitaya, H. 2000, A&A 355, 256
Kamath, U.S., Anupama, G.C., Ashok, N.M. et al. 1997, AJ, 114, 2671
Kaufer,A., Wolf,B., Anderson,J., & Pasquini,L., 1997, The Messenger 89, 1
Kawabata, K.S., Akitaya, H., Hirakata, N., et al. 2001, ApJ 552, 782
Kawabata, K.S., Hirata, R., Ikeda, Y., et al. 2000, ApJ, 540, 429
Llyod, H.M., O'Brien, T.J., Bode, M.F., 1997, MNRAS, 284, 137
Martin, P.G. 1989, in Classical Novae, ed. M.F. Bode & A. Evans (New York: Wiley), 73
McCarthy, J.K., Sandiford, B.A., Boyd, D., Booth, J., 1993, PASP, 105, 881
Mekkaden, M.V., Raveendran, A.V. 1998, A&A, 338, 1031
Pfieffer,M.J., Frank,C., Baumüller,D., Fuhrmann,K., Gehren,T., 1998, A&ASS,130,381
Pepe,F, Mayor,M., Ruprecht ,G., 2002, The Messenger, 110, 9

Padmakar S. Parihar, Drake,S.A. and Pandey,S.K. 2001, MNRAS, 314,733
Padmakar S. Parihar, and Pandey,S.K. 1999, A&AS, 138,203
Pandey,G., Rao,N.K., Lambert,D.L., Jeffery,C.S., Asplund,M., 2001,MNRAS, 324,937
Pandey,G., Lambert,D.L., Rao,N.K., Gustafsson,B., Ryde,N., Yong,D.
2001, MNRAS, 353,143
Parthasarathy, M., Garcia-Lario, Pottasch,P. and 5 coauthors 1993, A&A, 267,19
Porter, J.M., O'Brien, T.J., Bode, M.F. 1998, MNRAS, 296, 943
Prabhu, T.P., Anupama, G.C. 1987, JApA, 8, 369
Raveendran, A.V., Mohin,S., 1995, A&A, 301, 788
Raveendran, A.V., 2002, MNRAS, 336, 992
Raveendran, A.V., 1999, MNRAS, 303, 595
Rao, N.K., Reddy,B.E., Lambert,D.L., 2004, MNRAS, 355, 855
Rao, N.K., Lambert,D.L., 1997, MNRAS, 284, 489
Rao, N.K., Lambert,D.L., 1993, AJ, 105,1915
Rao, N.K., Sriram,S., Gabriel,F., Prasad,B.R., Samson, J.P.A., Jayakumar,
K., Srinivasan, R., Mahesh, P.K., Giridhar,S. 2004 to Appear in Asian Journal of Physics
Reddy, B.E., Parthasarathy, M. 1996, AJ, 112, 2053
Reddy, B.E., Lambert,D.L., Laws,C., Gonzalez,G. 2002, MNRAS, 335, 1005
Reddy, B.E., Tomkin,J., Lambert,D.L., Allende Prieto,C., 2003, MNRAS, 340, 304
Reddy, B.E., Parthasarathy,M., Gonzalez,G., Bakkers,E.J., 1997, A&A, 328,331
Semel, M., Donati,J-F, Rees,D.E., 1993, A&A, 278,231
Semel, M., 2003, A&A, 401, 1
Shore, S.N., Schwarz, G., Bond, H.E. et al. 2003, AJ, 125, 1507
Sneden, C. & Parthasarathy, M., 1983, ApJ, 267, 757
Sneden,C., McWillams,A., Preston,G.W., Cowan,J.J., Burris, D.L., Armosky,B.J.
1996, ApJ, 467, 819
Strassmeier,K.G., 1999, A&AS, 140,29
Takeda,Y., Parthasarathy,M. and 10 coauthors 2001, PASJ, 54, 765
Tull,R.G., MacQueen,P.J., Sneden,C. & Lambert,D.L., 1995, PASP, 107,251
Tull, R. G. 1998, Proc. SPIE, 3355, 387
Queloz,D., Mayor,M., Weber,L. and 7 coauthors 2000, A&A, 354,99
Van Winckel, H. 2003, ARAA&A, 41,391
Vogt, S.S., et al. 1994, in Proc. SPIE Conf. 2198,
Eds. Crawford, D.L. and Craine, E.R.
Vogt, S.S., Hatzes, A.P., Misch, A.A., Kurster, M., 1999, ApJS, 121, 547