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Multiwavelength observations of Be stars

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Abstract. Several Be stars are reported to exhibit rapid variations ranging from a few tens of minutes to days, in their photospheric absorption lines as well as the emission lines from their circumstellar matter. While periodic variabilities may occur due to either rotational modulation of surface inhomogeneities or non-radial pulsations or both, it is the transients or aperiodic variabilities which cause even more concern because of lack of viable explanations. In order to understand their cause it is important to see if there exists a causal relationship between high energy activity and the optical line transients. We have recently participated in an international multiwavelength monitoring program on the Be star λ Eridani (HR 1679; B2IVne). This coordinated campaign involved ground-based optical spectroscopic observations, X-ray observations from ROSAT and ASCA satellites and ultraviolet observations from IUE satellite and Voyager 2 spacecraft. We present here results from this campaign and indicate future plans which include Doppler imaging of stellar surfaces using high S/N spectroscopy on moderate size telescopes.

Key words : Be stars : λ Eri-multiwavelength observations-Doppler imaging

1. Introduction

Be stars (Kitchin 1982) are non-supergiant B stars with emission episodes signifying massloss (10^{-11} - 10^{-9} $M_{\odot}$). Their rotational velocities (~ 200-400 km/s) are distinctly higher than those of the normal B stars (≤ 200 km/s) reaching near-breakup values. Be stars are brighter than normal B stars of the same spectral type by about 1 magnitude. It is not very clear as to their evolutionary status vis-a-vis the normal B stars. It has been conjectured that the Be stars represent post-ZAMS (but not post mainsequence) B stars with statistically higher rotational velocities (with the B stars having a normal distribution of velocities) and during their evolution on the mainsequence phase they tend to gain in angular momentum due to the redistribution of mass inside the cores of such stars. This scenario is based on the big assumption that the stars rotate like rigid bodies. Whatever be their evolutionary status, these stars are episodically undergoing considerable massloss leading to the formation of circumstellar discs (CD) which is known as "Be Phenomenon". The cause of this massloss is not yet known. Rotation at near critical velocities was suggested by Struve (1931) and all went well till the high S/N spectroscopy during the 80's revealed variabilities which could not be reconciled with the rotational hypothesis. While the rotation must definitely contribute its might to the massloss episodes (Balona 1991) it is now clear that it requires a supportive/alternative mechanism. Non-radial pulsations (NRP, Smith 1977) can be a viable process by which massloss can occur but there is so far no evidence for this.

The CD reveals in UV and optical observations a complex structure characterized by both moderately (T ~ T_{eff}) and highly ionized (T ~ 50000 K) plasmas (Smith et al. 1991). These envelopes are variable on time scales of hours to prolonged envelope formation and dissipation episodes lasting a month to years. The geometrical and spatial structure of these envelopes is not clearly known. Longterm, systematic multiwavelength spectroscopic data on lines characteristic of near-photospheric region, the envelope itself, and the hot, highly ionized stellar wind. Suitable stars are single, viewed nearly equator-on and having a history of rapidly developing minor emission episodes. Such stars allow simultaneous study of different physical parameters (Smith et al. 1991).

The observed variabilities in their spectral lines are of two types : (i) periodic variabilities with periods longer than a day or close to a day; and (ii) aperiodic variabilities of time scales of about a few minutes and longer. While the periodic variabilities when confirmed should be related to rotational modulation (RM) of surface inhomogeneities (Struve 1931; Balona 1991) or NRP (Smith 1977) or both, it is the aperiodic, transient-like variabilities which pose even bigger problem (Kambe et al. 1993). These aperiodic variabilities are conjectured to be due to localised high magnetic fields. Transients in the HeI line, for instance, suggest small-scale magnetic flaring processes similar to the flares observed in Sun, T Tauri stars and several magnetically active cool stars (Smith 1989). The production of such magnetic fields in these early type stars is now a very important theoretical problem in astrophysics. On the observational front there is a need to establish the existence of one or more periodic modes of variabilities in these stars. A single period with corresponding photometric variation would point to the importance of effects due to RM. On the other hand, multiple periods with no significant variation in the light flux would confirm the role of NRP.

One decisive step towards a better understanding of these stars is to start a systematic program on Doppler imaging of the stellar surface (Kurster 1993 and the references therein) to find out the relative roles of RM and NRP. Further, multiwavelength observations in optical, infrared and high energy regions like UV or X-ray would give us clues on the mechanisms responsible for such transient behaviour as is found in some of these stars. We have recently participated in an international campaign on simultaneous optical, UV, and X-ray observations on the Be star λ Eri using ground-based and satellite/spacecraft-based observations with Myron Smith as the Principal Investigator (Smith et al. 1996). This was only the second such attempt on the Be stars; the first being a campaign on γ Cas (Slettebak and Smith 1978; Peters 1982).

2. Non-radial pulsations vs rotational modulation

One of the biggest impediments to the current research on Be stars is the lack of reliable rotation periods. There should be more systematic observations required to determine the periods with high accuracies. Then it is possible to delineate between the NRP which manifest themselves in multiple periodicities and small (≤ 0.02 mag) photometric variability and the RM which shows up in a single period variation with large (≥ 0.05 mag) photometric variability. The inhomogeneities which are the root cause of the variabilities could be star spots or some spoke-like structures connecting the stellar surface and circumstellar matter corotating with the star (Vogt and Penrod 1983). The spokes represent hypothetical jet-like streams of massloss triggered by magnetic fields. Not only these models are highly imaginative but they also demand a few additional complications like associated large photometric variabilities and localised strong magnetic fields like in the Sun. The NRP, on the other hand, implies velocity inhomogeneities on the surface of the star which can manifest themselves as running features on the spectral lines. This mechanism predicts no significant photometric changes. It is also possible that two or more modes are preferentially excited and hence the mechanism predicts multiple periods. However, these periods are a good fraction of the rotation periods and a systematic survey with high S/N (≥ 200) spectrographs with a large number of profile observations during a few periods of rotation would be able to tell one mechanism from the other.

3. Multiwavelength observations on Be stars : A case study of λ Eridani

The aperiodic variability observed in a few Be stars suggets localised strong magnetic fields (Smith 1989; Smith et al. 1991). Smith et al. (1993) have observed in the B2IVne star λ Eri a flare-like activity (with $L_x \sim 10^{31}$ ergs/s, i.e., 6 times the value in the quiescent state in a duration of more than 13 hrs at photon energies ≥ 0.7 keV) in the X-rays using the PSPC onboard the ROSAT satellite (Feb. 1991). While it is possible that λ Eri may not represent a typical Be star, it is also possible that the observation of such a strong transient in X-ray flux could be a common occurrence in this star. Further, and more importantly, one should find out if there exists a associated transient behaviour in the optical and UV regions. With these aims a unique international campaign was organised by Myron Smith during Feb-Mar 1995. The spectroscopy group at PRL participated in this campaign chipping in with Hα emission line observations made during 26-28 Feb 1995 at Mt. Abu using a Central-Aperture Scanning Fabry-Perot Spectrometer (CASFPS) at the Cassegrain focus of the 1.2m infrared telescope. The X-ray observations were made by the ROSAT and ASCA satellites. The UV observations were made by IUE (perhaps some of its last observations before it was out-commissioned) and the famous spacecraft Voyager 2. There were optical observations from McMath observatory at Kitt Peak, USA for obtaining the HeI and the Hα lines. Adequate time coverage on the optical observations was thus ensured before and after the ROSAT and ASCA observations.

The ROSAT high resolution imager (HRI, 0.6-5 keV) observations *indicated* a mild enhancement in the flux. Interestingly enough there was an associated enhancement in the HeI and Hα lines as well as in the UV absorption lines in CIII (Voyager) and CIV (IUE). Enhanced V wing emission in the Hα profiles observed from Mt. Abu and Kitt Peak could be caused by an enhanced supply of Lyman continuum photon flux from the star, ionizing additional atoms in the CD. The CD atoms would then recombine and produce additional Hα radiation. The additonal flux of Lyman continuum can be caused by a dense plasma slab of $T \sim 50000K$ above the surface of the star. It is not very clear whether or not the X-ray enhancement could have had a role in all these effects observed in the optical and UV regions, as it changed on a much more rapid timescales than the changes in the lower wavelengths (Smith et al 1997).

The Voyager 2 UV Spectrometer (UVS) light curves during February 27-28 showed a kind of "ringing" with fluctuations of time periods 1-2 hrs having amplitudes decreasing from high energy towards the lower energy in the range λλ 900-1500 Å. This happened after the slight enhancement in the x-ray flux and the Mt. Abu optical observations. While the far UV ringing may not have a direct context to the other observations, it is important to look for such a phenomenon in the optical region which can be done using moderate/small telescopes (Smith et al. 1997).

4. Conclusion : Doppler imaging of stellar surfaces

Rotational broadening contributes predominantly to the width of the spectal lines from a rapidly rotating star ($V_{rot} \geq 100$ km/s). For such a star one can imagine that each longitudinal strip of its surface, in the direction perpendicular to the line of sight, represents a definite portion in the observed spectral line profile. Likewise, the star can be divided into several longitudinal strips,

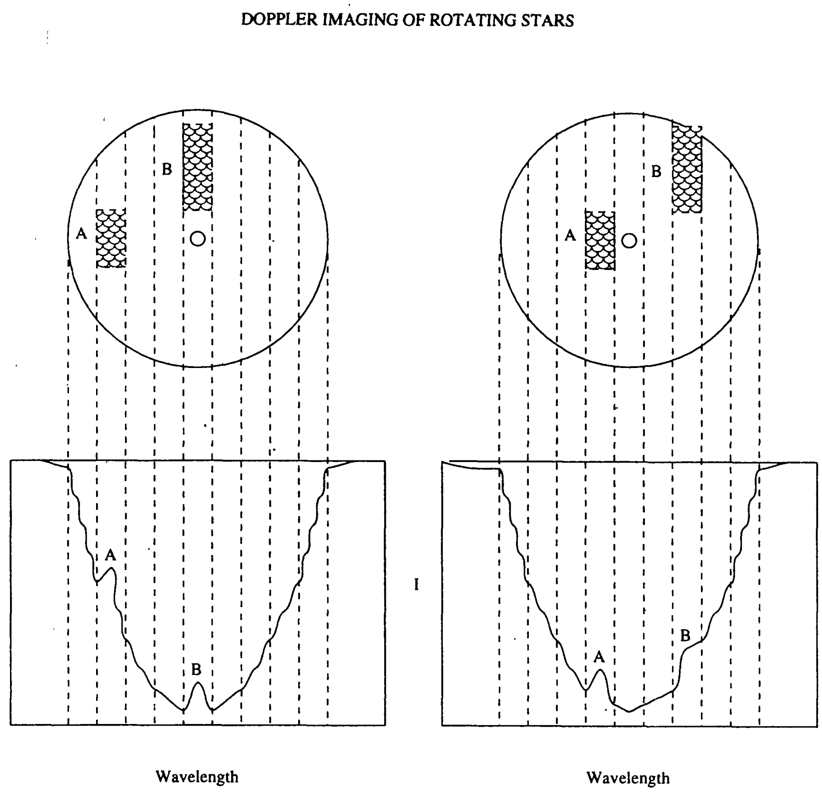

Figure 1. Doppler imaging schematic. As the star rotates at two different times of observation t_1 (left) and t_2 (right), we can see that the bumps caused by the inhomogeneities A and B appearing at different parts of the line profile. It is then possible to work out the inversion problem to map these inhomogeneities back on to the surface of the star, if they persist longer than the observing time.

each one representing a definite portion in the line profile. Now as the star rotates, there will be a change with time in the position of a particular point on the star (Fig. 1). Therefore, the inhomogeneities that may be present on the surface of the star would leave their signatures on the line profiles observed sequentially during one period of rotation (Fig. 1) This way of mapping the inhomogeneities on the surface of the star is known as the Doppler Imaging (Vogt and Penrod 1983; Vogt et al. 1987; Kurster 1993). This technique is obviously an inversion technique and hence it has its beauty and charm as well as pitfalls. One essential requirement, nevertheless, is the availability of spectroscopic data at very high S/N ratio (≥200). With the present day technology it is possible to achieve these high S/N ratios at reasonable integration times using moderate size telescopes (~ 1m) at spectral resolutions of ~ 10^4.

The classical Be star γ Cas was observed at Mt. Abu Infrared Observatory's 1.2m telescope using the CASFPS having a resolving power of 9×10^3 (~ 0.7 Å at the Hα 6563 Å line) with a S/N of 50 (at the peak of the profile) achieved at an integration time of 1 sec at each spectral element (Fig.2). Thus S/N ratios of 200 can be achieved with integration times of 16

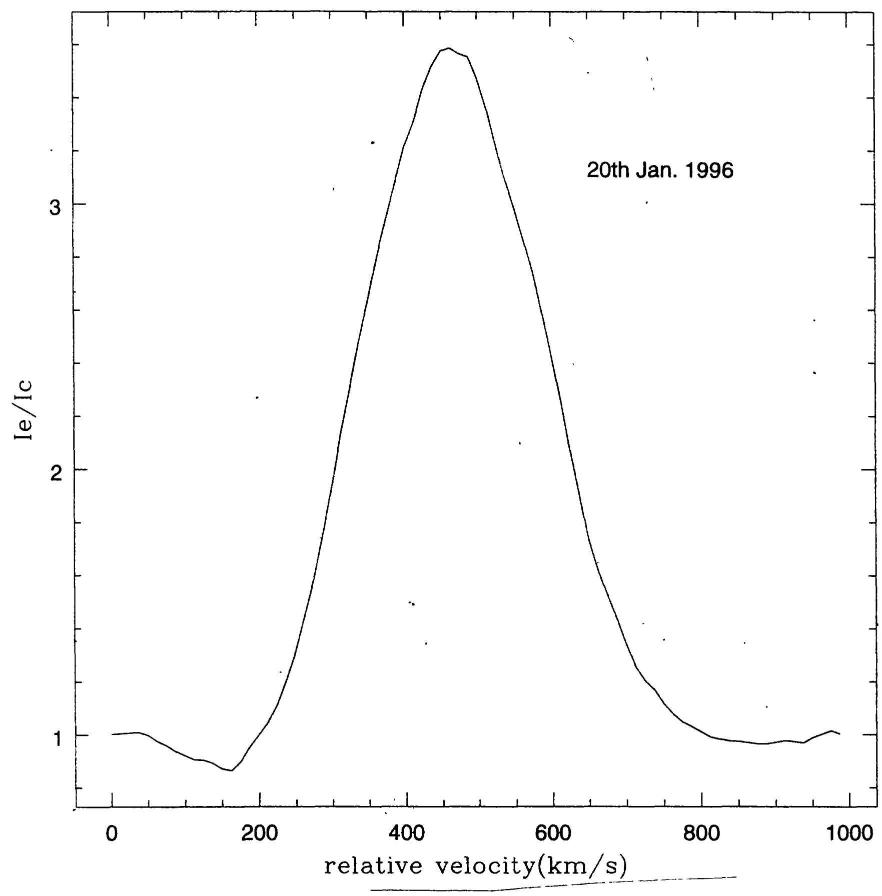

Figure 2. Hα line profile in γ Cas observed using the CASFPS at Mt. Abu 1.2 m telescope. Integration time at each spectral element was 1s. Total number of spectral elements was 90. The S/N at the peak of the profile is ~ 50.

sec per spectral element. For 100 such elements this would mean a total integration time of around 30 mts. Variabilities of timescales greater than 30 mts can thus be identified and mapped on the surface of the star. These figures could be comparable for an Echelle Spectrograph. The CASFPS suffers from the drawback of not being able to observe absorption lines. Therefore at PRL we are building a grating spectrograph with a resolution of 0.7Å at the Hα line. The system has a fibre-fed f/13 Cassegrain beam and currently uses a thermo-electrically cooled CCD camera. Bright stars can be studied using this system. Future plans include building an Echelle Spectrograph with 2000 × 2000 CCD array cooled by liquid Nitrogen. A photometer also has been built to observe simultaneous photometric variations. This instrument can be mounted on a 14" telescope attached to the main 1.2m telescope at Mt. Abu. Simultaneous observations at different wavelengths and using different techniques such as IR photometry and optical polarimetry at different sites is very important. So a coordinated program can be chalked out within our country to study a few stars in a very systematic manner.

We are attempting to make the Doppler imaging models to incorporate not only possible temperature variations on the surface but also some of the dominant modes of the NRP leading to surface velocity field variations and then compare with observed profiles. A realistic model should incorporate the rotational effects also (Aerts and Waelkens 1993), and hence the oblateness of the star needs to be considered.

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