SHOCK PHENOMENA IN β CEPHEI STARS

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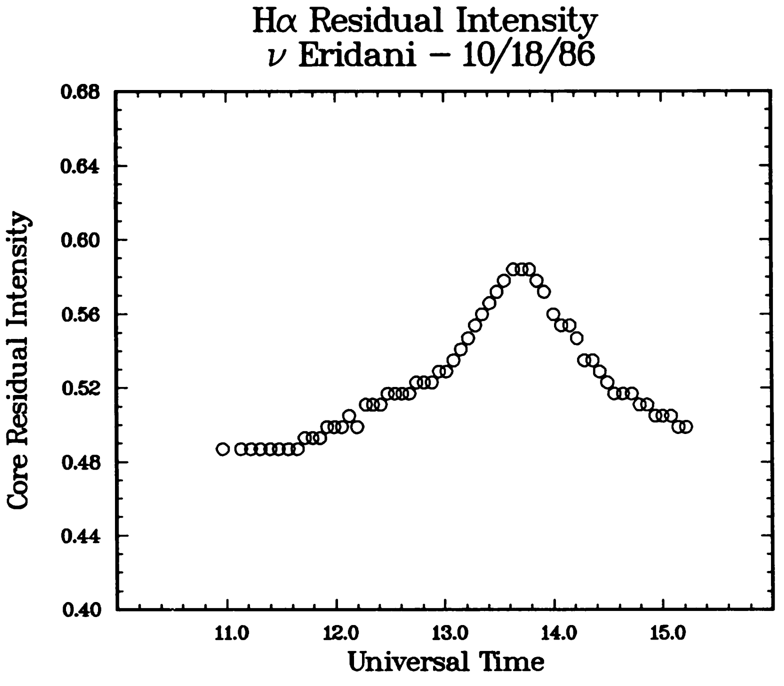
ABSTRACT. In this paper, we present new observations of β Cephei stars made with the CFHT coudé Reticon. Spectral sequences of the extreme star BW Vulpeculae show large velocity and line profile changes in Hα and in the C II doublet ($\lambda\lambda$6578,6582) over 0.04 of a cycle, during three different cycles on three different nights. In fact, there are two such phases of line doubling where the velocities are nearly discontinuous before and after the so-called velocity "stillstand" (near maximum light). Also, the line doubling phases coincide with pronounced peaks in the Hα core residual intensity. The most straightforward interpretation of these observations is that there are two shock waves, separated by about 50 minutes, which generate double absorption components. For ν Eridani and γ Pegasi, there are no discernible changes in the Hα profiles, despite rather regular velocity variations. This argues against the shock-wave interpretation for "classical" β Cephei stars.

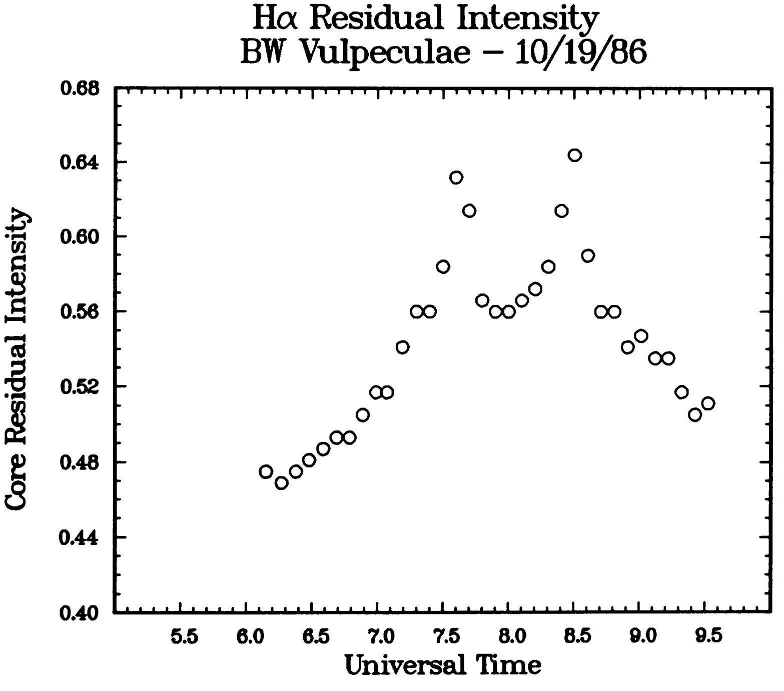
1. INTRODUCTION AND OBSERVATIONS

The importance of rapid and complex line profile variations in the short-period variable β Cephei stars has long been recognized. Recent studies of these objects with new detectors include those by Goldberg, Walker and Odgers (1976) and Young, Furenlid and Snowden (1981) of BW Vulpeculae; by Smith and McCall (1978) and Le Contel and Morel (1982) of γ Pegasi; and by Smith (1983) of ν Eridani. The study reported by Young *et al.* concerned the behaviour of Hα and C II $\lambda\lambda$6578,6582, while the other studies concentrated on Si III λ4567. The extreme star BW Vulpeculae is of particular interest because it is observed to have the largest variability of light, radial velocity and line profiles among members of the β Cephei class.

It has been suggested that all β Cephei stars have moving shells which arise from atmospheric shocks associated with non-linear radial pulsation (Smith 1983). The original hypothesis was made by Odgers (1955), based on observations of BW Vul. The presence of a shock wave is deduced from the appearance of an extended "shell" feature to

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 169–174.





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the red or blue of the photospheric profile, which appears and disappears on a time scale of less than 0.1 of a period. In the spectra of BW Vul, line doubling and a prominent "stillstand" on the descending branch of the radial velocity curve can be seen; these effects are attributed to the movement of an ejected shell above the deeper photospheric layer. Thus, the velocity stillstand apparently corresponds to a brief period of rest for the lower photosphere before the upper layer is once more impulsively ejected. It has been shown that the line profiles can be generated by strong shock waves associated with radial pulsation (Campos and Smith 1980). However, some investigators (*cf.* Young *et al.* 1981; Le Contel and Morel 1982) have expressed concern that an interpretation of the line profile variations based solely on Doppler displacements of the spectral wing features is naive, because of radiative transfer effects which should be taken into account. Nonetheless, radial velocity variations of 50 km sec^{-1} or more, such as are found in BW Vul and ν Eri imply that shock velocities should be present. Propagating shocks in stellar atmospheres usually produce line doubling and emission in the Balmer lines, such as in Mira variables, RR Lyrae stars, W Virginis stars and RV Tauri stars (Gillet 1988). At least, we would expect the residual intensity of the Hα core to be filled in by emission during shock phases. Therefore, we have obtained more time-resolved spectra of BW Vulpeculae and a few classical β Cephei stars at Hα.

The spectroscopic observations were made with the CFHT f/8.2 coudé spectrograph and 1872-element Reticon on the nights of October 17-21, 1986. The 830 groove mm^{-1} grating was used to deliver a linear reciprocal dispersion of 4.83 Å mm^{-1}. Each Reticon pixel accepted 72 mÅ, and the entire array comprised a bandpass of 135 Å. We followed BW Vul through three cycles on three different nights. On U.T. October 18, we obtained 13 spectra over 0.70 cycle with a time resolution of 12 minutes. The signal-to-noise ratios varied from 250-160. During that same night, we observed ν Eri over 1.02 cycles, obtaining 59 spectra exposed 4 minutes apart to get S/N ratios varying from 560-380. The following night, we obtained a series of 34 spectra of BW Vul over 0.70 cycle with a time resolution of 6 minutes. This time, the signal-to-noise ratios varied from 150-75. Finally, on U.T. October 21, we obtained 32 spectra of BW Vul over 0.66 cycle, again with a time resolution of 6 minutes. Since the star was at a slightly higher air mass, the achieved signal-to-noise was lower, varying from 100 to 40. In addition, γ Peg was observed over 0.30 cycle, during which time we obtained 12 spectra spaced 6 minutes apart, with signal-to-noise ratios between 650 and 400. Heliocentric radial velocities in the stellar rest frame were derived for Hα and for both lines in the C II doublet $\lambda\lambda$6578,6582 of each spectrum. The largest internal velocity errors at Hα were of order $\pm$4.5 km sec^{-1}. However, the mean errors were smaller, corresponding to about 3 km sec^{-1} in BW Vul and about 1 km sec^{-1} in ν Eri and in γ Peg.

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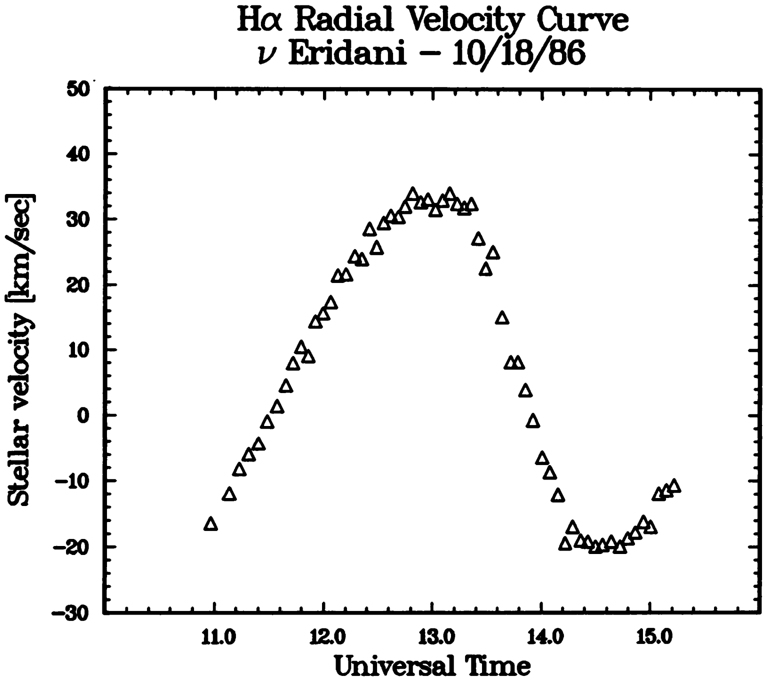

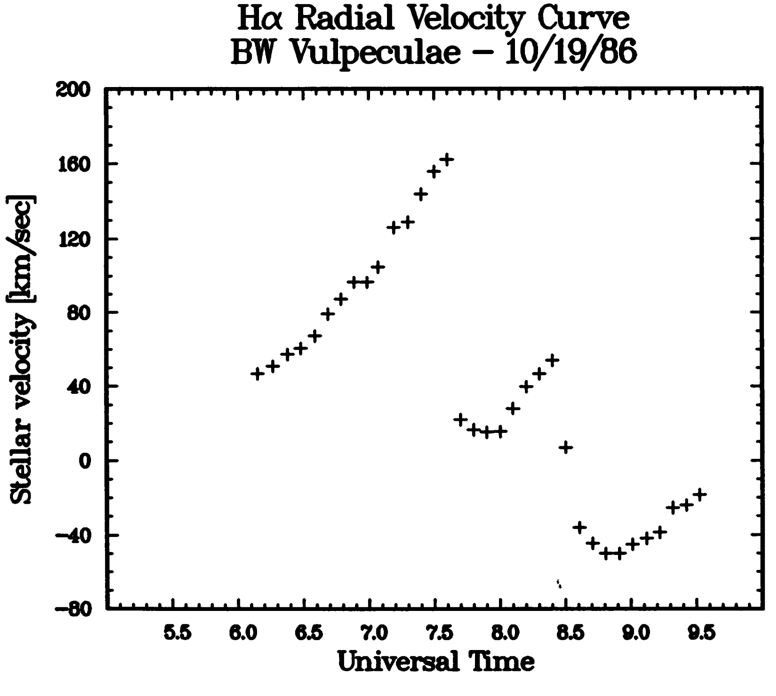

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2. SUMMARY OF RESULTS

From these new high-resolution spectra, we conclude that the line profile changes and radial velocity curves for BW Vulpeculae are consistent with a double-shock model. The shell components are clearly visible, and there is line doubling and asymmetry in the Hα profiles before and after the velocity "stillstand" which is associated with maximum light. The similarity of the profiles, during two phases of nearly discontinuous velocity change 50 minutes apart, leads us to the hypothesis that the same shock-wave mechanism produces both phases of line doubling. The velocity variations through the stillstand phases are consistent with rapid upward acceleration, deceleration and infall toward maximum compression, implying that the "stillstand" is actually a recovery from a shock acceleration. The core residual intensity of Hα exhibits pronounced peaks during the phases of largest velocity variation, implying that there is filling in by emission at these phases. The most straightforward interpretation of these observations is that there are two shock waves, separated by about 50 minutes, which generate photoionizing precursors and double absorption components.

The radial velocity curve of ν Eridani is skewed, implying some kind of impulsive atmospheric motion; however, the velocity variations are not discontinuous at any time through the cycle, suggesting that the perturbations are not sufficient to generate shock waves. Also, the Hα core residual intensity peaks at phase 0.13, relative to maximum radial velocity, which is near maximum compression; this is consistent with an increase in the intensity of the source function as a result of atmospheric contraction. Thus, although a shock wave model for ν Eri cannot be ruled out, we find the evidence for it unconvincing. In γ Peg we see no evidence for shock activity, since there is no significant change in the Hα or C II profiles during the moving-shell phases. It seems that only the largest-amplitude pulsators (*e.g.,* BW Vul) show clear evidence for shock pulsation. In fact, since BW Vul is the only β Cephei star to display two velocity discontinuities, we surmise that the double-shock mechanism only applies to BW Vul.

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DISCUSSION

FURENLID I'd like to make two comments. First, it is hard to discover shocks in Hα in hot stars, where hydrogen is almost completely ionized. Second, the two episodes of highest residual flux may have their origin in emission from pressure induced recombination.

CROWE We were discussing these points before the session, and I do not necessarily disagree with the view expressed by Dr. Furenlid. (We need to find an explanation for why "classical" β Cephei stars show little or no evidence for shock waves at Hα. I will be looking forward to seeing Dr. Furenlid's et al. recent work in print).

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