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Chapter 6

A Connection Between V/R and Polarization in Be Stars

with
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ABSTRACT

It has been suggested that the quasi-cyclic V/R variability observed in the emission line profiles of many Be stars is caused by a precessing one-armed density wave in the circumstellar disk. It seems likely that the changing aspect of such a non-axisymmetric density pattern might also lead to a related variation of the continuum polarization. We have searched for such an effect in two well-studied Be shell stars, ζ Tau and 48 Lib, based on data compiled from several groups of observers from 1984 to 1998. Using a Monte Carlo radiation transfer code to calculate the polarization due to electron scattering in Be disks in the presence of one-armed density perturbations, we have been able to find specific modes that are consistent with the observed V/R line profile variations together with the suspected polarization cycles. Although the notorious long and short term deviations from strict periodicity present in Be stars make it impossible to rigorously demonstrate this connection, we can nevertheless say that theoretical calculations based on the one-armed density wave hypothesis are not directly at odds with the polarization observations.
1. Introduction

Be stars are rapidly rotating non-supergiant B-type stars whose spectra have, or had at some time, one or more Balmer lines in emission. In the overall context of stellar structure and evolution, the subject of Be stars is important for its close association with rapid rotation, whose effects are poorly understood. One of the mysteries of the Be phenomenon is that the emission, which originates from an equatorially flattened circumstellar envelope or disk (Quirrenbach et al. 1997), can come and go episodically on time scales of days to decades. This has yet to be explained as a predictable consequence of stellar evolution theory, although many contributing factors have been discussed, including disk formation conditions, rapid rotation, radiation-driven winds, nonradial pulsation, flarelike magnetic activity, and binary interaction. Slettebak (1988) has written a comprehensive review which is highly recommended for the unfamiliar reader.

The Balmer line emission produced by the rotating circumstellar disks of Be stars is double-peaked when viewed at high inclinations (close to edge-on). Interestingly, the ratio of violet to red peak intensity $V/R$ of many Be stars sometimes shows nearly cyclic variations on time scales of several years (Dachs 1987). A promising explanation for this variability is a slowly precessing one-armed ($m = 1$) density wave in a Keplerian equatorial disk, orbiting around the star (Okazaki 1991; Papaloizou, Savonije, & Henrichs 1992). The Keplerian orbital motion of the gas in the disk carries gas elements through this more slowly moving density structure. The overdense region produces excess emission in the double-peaked Balmer line profiles at a wavelength corresponding to its projected line-of-sight velocity, while the underdense region (on the opposite side of the disk) produces an emission deficit on the opposite side of line center. As the density wave precesses around the star, the emission excess and deficit oscillate about line center, producing cyclic $V/R$ variations at the precession frequency of the density wave.

In addition to line emission, Be stars also show intrinsic linear polarization. This polarization arises from electron scattering of starlight in the disk. Although electron scattering is wavelength independent, the polarization develops a wavelength dependence due to attenuation by neutral hydrogen (Coyne & Kruszewski 1969). If a uniform disk is seen along its polar axis, it looks circular and there is no net polarization, because the polarization from every region is exactly cancelled by that from another region $90^\circ$ away in azimuth. As the inclination of the polar axis to the line of sight increases, the disk isophotes become elliptical. This decreases the cancellation, leading to a net polarization with a position angle parallel to the projection of the rotation axis onto the plane of the sky.

The density wave proposed to cause the (rather large) spectroscopic $V/R$ variations described above breaks the axisymmetry of the disk. In the single scattering limit, the polarization $P$ is linear in the density $\rho$ (Brown & McLean 1977), so one naively expects large polarization variations $\delta P/P \sim \delta \rho/\rho$ with corresponding position angle variations that are correlated with $V/R$. However, the polarization change $\delta P$ is given by a volume
integral of the density perturbation \( \delta \rho \). For a one-armed mode, \( \delta \rho / \rho \propto \exp(im\phi) \) with \( m = 1 \). This produces a high density arm, but on the opposite side there is a corresponding low density region — the density perturbation is antisymmetric under reflection through the plane perpendicular to the arm. Consequently the polarization volume integral vanishes because the integration kernel is symmetric under reflection (see Eq. 31 of Brown, Carlaw, & Cassinelli 1989). This implies that in the single scattering limit there is no net change in the polarization in the presence of one-armed density waves. Nonetheless there are second order effects that occur because Be star disks are optically thick to electron scattering (see Wood, Bjorkman, & Bjorkman 1997). In particular, multiple scattering and attenuation effects produce small changes in the polarization as the density wave precesses around the star.

We chose \( \zeta \) Tau (B3 IVe-shell, \( v \sin i = 220 \) km s\(^{-1}\)) and 48 Lib (B3:IV:e-shell, \( v \sin i = 400 \) km s\(^{-1}\)) as test objects because they have been continuously monitored by spectroscopy and polarimetry for many years and have shown hints of roughly periodic variations in polarization on time scales similar to those of the \( V/R \) variations (Okazaki 1997). We combined our polarization measurements of these two stars covering the past 14 years (Bjorkman et al. 1998; McDavid 1999) and also assembled corresponding \( V/R \) measurements of the H\( \alpha \) emission line from the literature. Private communications from colleagues helped to fill gaps in the record.

2. \( \zeta \) Tau

The upper panel of Figure 1 shows the observed \( B \)-band polarization, averaged over quarter-year intervals. According to Poeckert, Bastien, & Landstreet (1979) the interstellar polarization is negligible, so no correction was applied. The position angle of the polarization was constant. The values of \( V/R \) plotted logarithmically in the lower panel are quarterly averages of data gathered from Slettebak, Collins, & Truax (1992), Guo et al. (1995), Hanuschik et al. (1996), and Kaye & Gies (1997).

Based on the work of Guo et al. (1995) and Hanuschik et al. (1996), the most recent episode of cyclic \( V/R \) variations began about 1990 and was preceded by a time of little or no activity. This is illustrated by the horizontal line at \( \log(V/R) = 0 \) from 1984 through 1990 in the lower panel of Figure 1. It appears that the polarization was rising linearly during that period of time, as shown by the sloping straight line through the open circles in the upper panel. This initial slope was removed to give the flattened polarization data (filled circles).

Both the flattened polarization and \( V/R \) were searched for periodicity using the periodogram method of Scargle (1982). The confidence level (probability that a periodogram peak with power signal-to-noise ratio \( z \) at one given frequency out of \( N \) independent frequencies being searched is real) is \( p_0 = [1 - \exp(-z)]^N \). No periodicity in the polarization was detected at the 99% confidence level, but the most prominent signal (34% confidence) occurs at a period of \( T = 2.3 \) yr. The strongest peak in the \( V/R \)
periodogram (61% confidence) was found at $T = 7.2$ yr.

Using these periods as starting points for nonlinear least squares fitting to sine waves, we obtained a polarization period of 2.2 yr and a $V/R$ period of 5.3 yr, which are overplotted in Figure 1. A simplistic interpretation is that the polarization follows a double wave, making two cycles for every one cycle of $V/R$. To estimate the quantities necessary to generate a model we assumed a polarization period of 2.2 yr and a $V/R$ period of 4.4 yr, with a phase relationship such that extrema of $V/R$ correspond to polarization minima.

The simplest one-armed density perturbation of a Be disk is the kidney-shaped mode shown in Figure 2, where the grayscale image shows the density perturbation pattern within 10 stellar radii. The unperturbed disk is assumed to be inviscid and the eigenfunctions of the density perturbation were calculated according to the model of Okazaki (1977). Both the sense of rotation of the disk and the sense of precession of the density perturbation are clockwise in this illustration (prograde precession). Sample Hα line profiles are shown for various azimuthal viewing angles $\phi$ (phase angles of the observed moving pattern), labeled around the perimeter of the disk. The line profiles, normalized to the peak intensity of the unperturbed profile, are computed for $i = 82^\circ$ and $(\rho_1/\rho_0)_{\text{max}} = 0.95$, where $i$ is the inclination angle and $(\rho_1/\rho_0)_{\text{max}}$ is the maximum value of the local density perturbation.
The upper panel of Figure 3 shows the Monte Carlo calculation of the polarization that would be observed as a function of $\phi$, for a sample of disk inclinations near the value $i = 82^\circ$ adopted by Wood, Bjorkman, & Bjorkman (1997) for $\zeta$ Tau. The behavior of $V/R$ according to the model line profiles is shown in the lower panel. These results are in good qualitative agreement with the observations in Figure 1.

Fig. 2.— The kidney-shaped density perturbation and the variability of the H$\alpha$ emission line profile of $\zeta$ Tau.

According the the upper panel of Figure 3, for our chosen inclination of $i = 82^\circ$, there are polarization maxima at $\phi = 0^\circ$ and $\phi = 180^\circ$, when the perturbed region is parallel to the line of sight. Physically, the electron scattering polarization saturates (no longer rising linearly with density) in the overdense region, so its contribution to increasing the polarization is less than the contribution of the underdense region to decreasing the polarization. Thus the polarization perturbation is negative (i.e., parallel to the location of the arm). This produces a polarization variation with two minima at phases $\phi = 90^\circ$ & $\phi = 270^\circ$ and maxima at phases $\phi = 0^\circ$ & $\phi = 180^\circ$. However, at large inclination when one is looking through the disk, attenuation by the overdense region becomes important and removes the maximum at $\phi = 0^\circ$. Thus the polarization curve for $i = 89^\circ$ has only a single maximum at $\phi = 180^\circ$.
Quarterly averages of the $B$-band polarization after removing the interstellar component found by Poeckert, Bastien, & Landstreet (1979) are presented in the upper panel of Figure 4. The intrinsic position angle was constant. The quarterly $V/R$ data plotted in the lower panel are from Hanuschik et al. (1995) and the archives of Ritter Observatory.

Scargle periodogram analysis yielded no periodicity in the polarization at the 99% confidence level, but the highest peak (42% confidence) in the power spectrum occurs at $T = 4.4$ yr. A periodicity in $V/R$ appears with 99% confidence at $T = 13.5$ yr.

With these periods as initial input, nonlinear least squares fitting to sine waves gave a polarization period of 4.2 yr and a $V/R$ period of 11.0 yr, shown overplotted in Figure 4. As in the case of $\zeta$ Tau, there appears to be evidence for a double wave. For the purpose of constructing a model we adopted a polarization period of 4.2 yr and a $V/R$ period of 8.4 yr (c.f. Hanuschik et al. 1995), but for 48 Lib the phasing is such that extrema of $V/R$ correspond to polarization maxima rather than minima.

To produce the phase shift of the $V/R$ maxima relative to the polarization maxima observed for the disk of 48 Lib, we employed the leading, one-armed spiral density wave shown in Figure 5, where the grayscale image represents the density perturbation.

Fig. 3.— The model polarization and $V/R$ for $\zeta$ Tau.

3. 48 Lib
pattern within 10 stellar radii. To produce a spiral density wave, we assumed that the unperturbed disk is a viscous decretion disk with Shakura-Sunyaev (1973) viscosity parameter $\alpha = 0.1$. In this figure both the sense of rotation of the disk and the sense of precession of the density perturbation are clockwise (prograde precession of a leading spiral). The phased line profiles, normalized to the peak intensity of the unperturbed profile, are computed for $i = 87^\circ$ (consistent with $v \sin i = 400 \, \text{km s}^{-1}$) and $(\rho_1/\rho_0)_{\max} = 0.50$.

![Graph showing observed B-band polarization and $V/R$ of 48 Lib.](image)

**Fig. 4.**—The observed $B$-band polarization and $V/R$ of 48 Lib.

The Monte Carlo results for polarization due to the spiral mode are presented in the upper panel of Figure 6. The variation of $V/R$ based on the model line profiles is shown in the lower panel. These results are an acceptable match to the observations in Figure 4.

Physically, it is simpler in this case to account for the polarization minima rather than for the maxima. The dip at $\phi = 150^\circ$ may be understood as dilution of the polarized light from electron scattering in the disk by direct unpolarized light from the star shining through the underdense side of the perturbation. The other dip, at $\phi = 330^\circ$, might be expected because of the extinction of polarized light in the overdense side, so that unpolarized light from the parts of the star not so heavily occulted by the disk would alter the balance toward lower net polarization.
Fig. 5.— The spiral-shaped density perturbation and the variability of the Hα emission line profile of 48 Lib.

4. Conclusion

We do not claim to have formally detected periodicities in the polarization of the program stars, but given the well known fact that Be stars are only quasi-periodic, this is not at all surprising. We can conclude, at very least, that the polarization observations are not at odds with theoretical models based on the one-armed density wave hypothesis, and therefore that the hypothesis has passed the observational test for two specific stars. Our results are consistent with those of Ignace (2000), who showed analytically that polarization variations on the order of 15% of the mean value may be produced by density patterns similar to those considered here.

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Fig. 6.— The model polarization and $V/R$ for 48 Lib.

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