POLARIZATION MEASUREMENTS ACROSS THE BALMER LINES OF Be AND SHELL STARS

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Abstract. We have made linear polarization measurements of several Be and shell stars across the Hα and Hβ lines, all of the stars exhibiting polarization in the continuum, the emphasis here being on measurements made of ζ Tau, 48 Per, φ Per, and γ Cas. Three types of results ensue: some stars show no significant change of polarization across the Balmer features (e.g., 48 Per, X Per); some stars show a reduced polarization across the features (e.g., γ Cas, ζ Tau) indicating the presence of intrinsic polarization; some stars show a change in the degree of polarization but with a marked rotation of the direction of vibration (e.g., φ Per, 48 Lib) which can be attributed to a combination of non-aligned intrinsic (circumstellar) and interstellar polarizations. Interpretations of these results are discussed, and we demonstrate the potential power of line profile polarimetry/photometry as an important new method for separating intrinsic and interstellar polarization effects, thus enabling polarization observations to be used as a constraint on models of Be stars.

1. Introduction

Perhaps the most distinctive feature of the spectra of early-type emission line stars is the appearance of the Balmer series of hydrogen in emission. Although much effort has been devoted to the study of the detailed shape and photometric variations of these lines, their intrinsic polarimetric properties have only recently received attention. Following a preliminary investigation reported to the IAU colloquium on photopolarimetry in 1972 (Clarke and McLean, 1974a), a reduced polarization was discovered at the center of the Hβ emission feature in γ Cas (Clarke and McLean, 1974b) and a similar effect found in ζ Tau. This latter result confirmed unpublished measurements of lower spectral resolution made by Serkowski (quoted in Zellner and Serkowski, 1972). Observations at Hα were first reported by Coyne (1974) for ζ Tau; and, more recently, measurements of this and other stars have been obtained with higher spectral resolution by Poeckert (1975). Polarization changes have also been detected across Hγ in both γ Cas and ζ Tau (Hayes and Illing, 1974; Hayes, 1975, respectively).

Broadband measurements indicate that the wavelength dependence of the intrinsic continuum polarization of shell stars is caused by electron scattering, modified by various wideband absorption and emission processes, deep in the circumstellar envelope (Coyne and Kruszewski, 1969; Capps *et al.*, 1973). The basic observed polarization/wavelength curves for Be and shell stars, however, show a variety of forms, indicating that interstellar effects contaminate the intrinsic polarizations in some cases, putting immediate model fitting out of the question. One of the current hypotheses for explaining the observed polarization changes across the lower Balmer lines, at least to some degree, is that of a dilution of the continuum polarization by addition of unpolarized emission line flux from a higher level of the shell. If this idea

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is correct, it has important bearing on separating the obscuring interstellar polarization from the intrinsic effects. No net polarization of the line radiation implies that the region of line formation to the observer is very optically thin for electron scattering. A scattering optical depth $\tau_s \sim 0.12$ (independent of λ) was found applicable to a model of the continuum polarization of ζ Tau (Capps *et al.*, 1973). Therefore, to escape significant polarization, the bulk of the emission must effectively arise in a region with τ_s several times smaller. Whether or not this situation occurs may well depend on the observer's aspect angle. Thus, some intrinsic differences might be expected in line profile effects from star to star and perhaps among different lines in the same star.

In this paper we discuss a variety of new measurements at Hα and Hβ which illustrate most of the observed and intrinsic effects so far encountered in line profile polarimetry of Be stars. We also present briefly methods for separating circumstellar and interstellar effects by line profile observations and by statistical studies of the polarization of non-Be stars in the same region of sky as the Be star.

2. Observations

All of the measurements discussed in this paper were obtained with the dual-channel wavelength scanning polarimeter described by Clarke and McLean (1975a). The observations were made at the Lowell Observatory, Arizona, using either the 79-cm (31-in.) telescope or the 183-cm (72-in.) Perkins telescope (operated jointly by the Ohio State and Ohio Wesleyan Universities and the Lowell Observatory). Line profile scans of Hα and Hβ are obtained by tilt-scanning narrow-band interference filters (Clarke *et al.*, 1975). For most of the measurements given here, passbands (FWHM) of 8.5 Å at Hα and 12 Å at Hβ were employed. A few measurements have been made at Hβ with a passband of 2.3 Å. Since the width of the Hα emission line at the half-maximum intensity point is ~8–9 Å in many Be stars, then the observed Hα profiles are strongly broadened by the instrumental profile, while at Hβ even less spectral detail is obtained. The chosen passbands represent a compromise necessary to retain viable integration times for the polarimetry.

In Figure 1 the observed normalized line profiles, the degree of linear polarization p (in percent), and the position angle (azimuth), θ, of the direction of vibration in equatorial coordinates are plotted for the Hα region of the four major program stars ζ Tau, 48 Per, ϕ Per, and γ Cas. Horizontal error bars, suppressed in the θ diagrams, indicate the uncertainty in the wavelength setting of the filter. A similar diagram for the Hβ region is shown in Figure 2. For ζ Tau, Hβ line profile polarimetry was obtained with a 2.3 Å filter in addition to the 12 Å filter measurements. Therefore, in Figure 2(a), the horizontal error bars represent the filter passband plus wavelength setting error. Different symbols are used for observations taken on separate nights except when those observations are virtually identical both in and out of the lines. It is immediately apparent that the observed changes of polarization across Hα and Hβ differ considerably for these four stars.

With the exception of 48 Per, there is a decrease in the degree of linear polarization p toward the line center, relative to the nearby red and blue continua, for each of

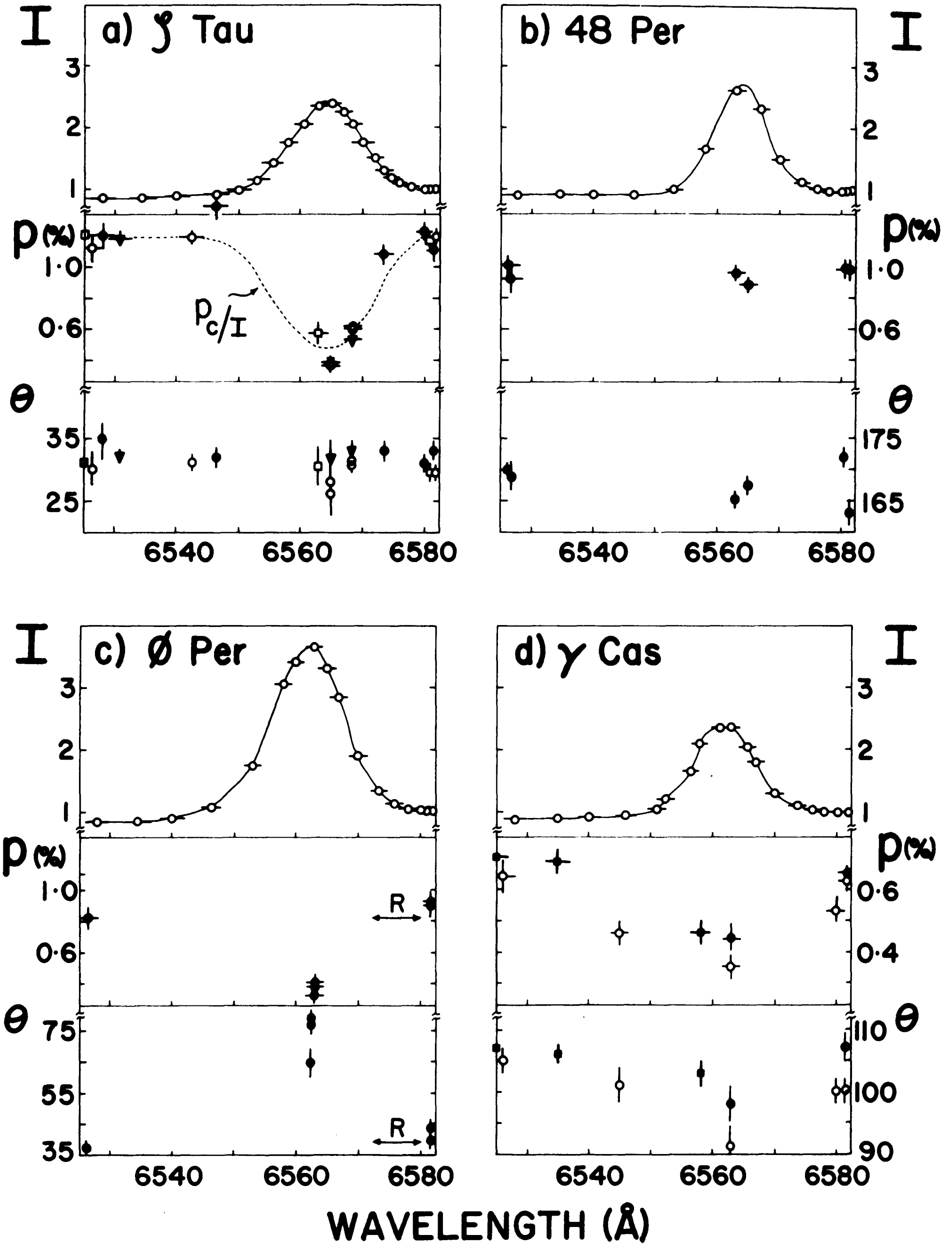

Fig. 1. The normalized intensity profile obtained by discrete tilt-scanning of an 8.5 Å Hα interference filter is shown, together with the degree of linear polarization p (in percent) and the equatorial position angle, θ, of the direction of vibration for the stars ζ Tau, 48 Per, ϕ Per, and γ Cas. Horizontal error bars represent the uncertainty of the wavelength setting. For ζ Tau (1(a)), the curve corresponding to dilution of the continuum polarization by unpolarized emission line flux is shown by a dashed line.

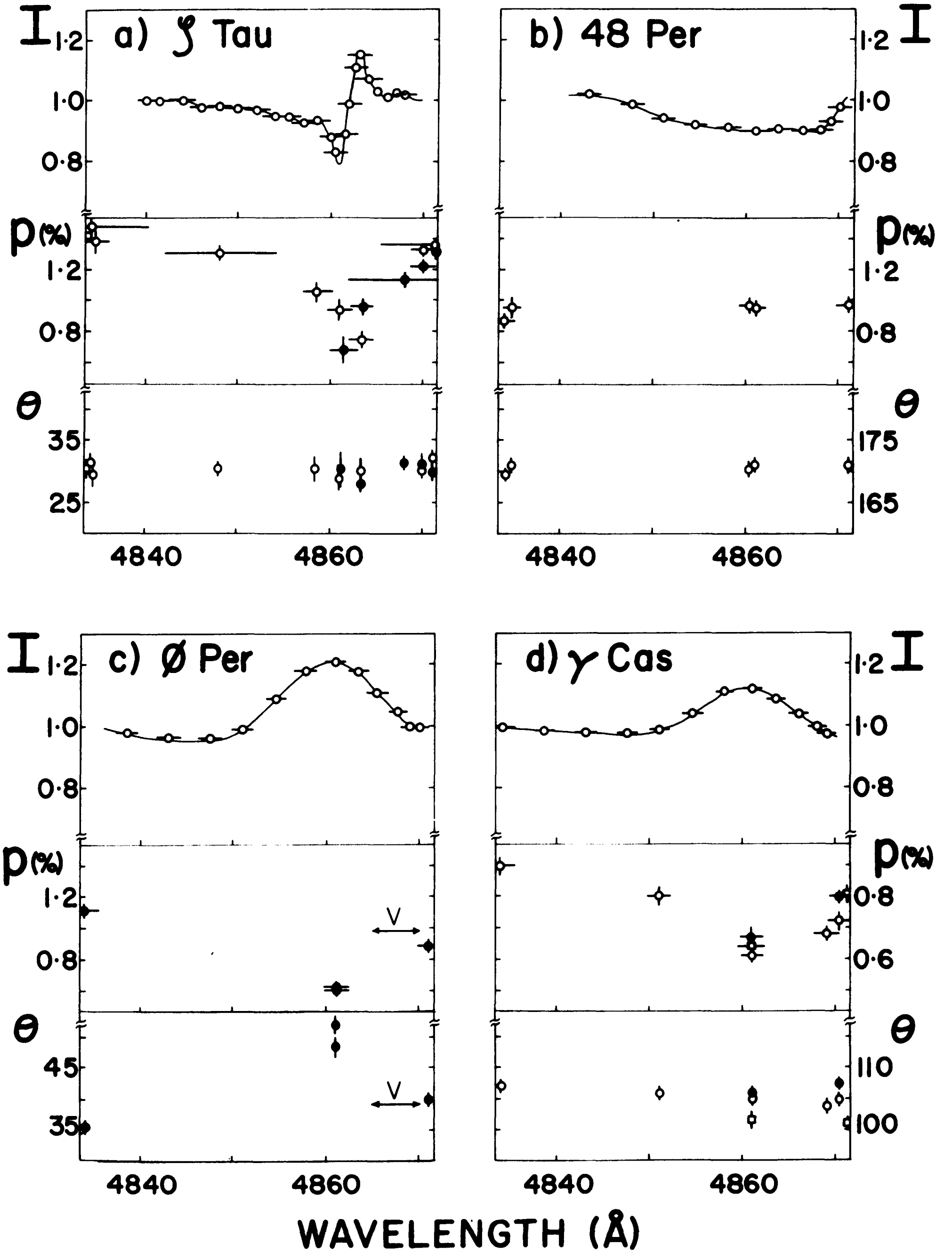

Fig. 2. As for Figure 1, but for the Hβ region. The tilt scans were made by a 12 Å filter except for ζ Tau, where a 2.3 Å filter was employed to resolve the shell absorption structure. Horizontal bars in Figure 2(a) represent the filter passband. Broad red and yellow filters used in the measurements of ϕ Per are denoted *R* and *V* in Figures 1(c) and 2(c), respectively.

the stars. The change in p is strongest across Hα. However, observations of Hβ in ζ Tau (Figure 2(a)) with a 2.3 Å filter also reveal a strong reduced polarization effect corresponding to a line profile with asymmetric emission wings and a central absorption feature. These measurements on ζ Tau constitute the highest resolution spectropolarimetry so far reported for Hβ. For γ Cas, the changes in p are shallow and commence well out from the line centers (Figures 1(d) and 2(d)); note the change of scale for p. Phi Per exhibits a very marked rotation of the position angle θ which is greatest at the Hα and Hβ line centers (Figures 1(c) and 2(c)), and there is some evidence of slight variability and wavelength dependence in θ for γ Cas. Neither 48 Per nor ζ Tau shows significant variations in θ. It is also clear from both Figures 1 and 2 that, despite the severe instrumental broadening of the line profiles, crude differences of shape are apparent from star to star.

To understand the observations it is necessary to be aware of two factors: (a) the effect of combining different interstellar and intrinsic (circumstellar) polarizations, and (b) the effect of a shell emission line of unknown polarization properties on the circumstellar continuum polarization. A discussion of these two factors is developed in the next section before attempting to interpret the observations of each star individually.

3. Separation of Interstellar and Intrinsic Polarizations

To be able to use polarization measurements as a constraint in modelling the extended envelopes of emission line stars, it is essential to remove from the observations the effect of the interstellar medium. There are several ways to approach this problem and, as stated in the Introduction, the most recently proposed method is that of line profile polarimetry. Alternative methods depend on statistical studies of the polarization of stars in the same region of sky as the program star or on differences between the wavelength dependences of intrinsic and interstellar polarization over a broad spectral region. Where possible, we have considered each method.

3.1. Methods employing the wavelength and time dependence of the intrinsic polarization

The wavelength dependence of the degree of polarization for interstellar grains $p_i(\lambda)$ differs considerably from that expected for the extended atmospheres of early-type emission line stars $p_*(\lambda)$. Serkowski (1973) has shown that $p_i(\lambda)$ follows the relation $p_{\max} \exp[-1.15 \ln^2(\lambda_{\max}/\lambda)]$, which is a smooth curve, while $p_*(\lambda)$ for Be stars undergoes quite sharp discontinuities at wavelengths corresponding to the Balmer and Paschen limits of hydrogen (Serkowski, 1968; Coyne and Kruszewski, 1969). However, in both cases there is unlikely to be any marked wavelength dependence of the position angles θ_i and θ_*. For most models of the scattering envelope the polarization is expected to be parallel to the star's rotation axis. When interstellar and intrinsic $p(\lambda)$ curves of similar strength are superposed with two different position angles ($\theta_i \neq \theta_*$), then the resultant (observed) position angle will, in general,

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show a dependence on λ which will depend in turn on p_i, p_* and their relative orientations.

Any time variations in the intrinsic degree of polarization (p_*) alone also lead to variability of both the observed degree of polarization and the observed position angle. This is an important effect since it can immediately yield the intrinsic position angle θ_*. Representing the observed polarization vector by its components, the normalized Stokes parameters $p_x = p \cos 2\theta$ and $p_y = p \sin 2\theta$, yields a point in the $p_x - p_y$ plane. At another epoch a different point will be obtained, but, provided the intrinsic position angle and the magnitude and direction of the interstellar polarization are all constant while p_* alone varies with time, the line joining the two points must be parallel to the line representing the direction of vibration of the intrinsic polarization. This line makes an angle $2\theta_*$ with the p_x axis.

Having obtained θ_* in the above manner, measurements at two different wavelengths can be employed, after some manipulation, to derive λ_{max}, the wavelength at which the interstellar polarization attains its maximum value p_{max}. Assuming a knowledge of the interstellar position angle θ_i ($\theta_i \neq \theta_*$), a series of broadband measurements, covering a wide spectral range and especially including the near ultraviolet, which have distinctly different observed position angles can be used by trial and error to derive p_{max}. Reasonable starting values of p_{max} can be estimated from the observed color excess of the star. The correct value of p_{max} should give values of the interstellar polarization which exactly cancel the wavelength dependence of the observed position angle. Clearly, this method depends on the presence of strong rotation effects in broadbands and on a previous knowledge of θ_i. Over certain small areas of the sky the interstellar material in that direction may be sufficiently uniformly distributed to enable the mean interstellar position angle $\bar{\theta}_i$ to be obtained by averaging the observed position angles for many stars in that area whose light is not expected to be contaminated by intrinsic polarization.

For the present work, a study of the Hall catalogue (Hall, 1958) of polarization measurements was carried out to derive $\bar{\theta}_i$ from non-Be stars contained within a small area ($\pm 4°$ in l^{II} and $\pm 4°$ in b^{II}) centered on the galactic coordinates of the program star in question. The results of this survey are shown in Table I, in which the column headings are as follows. Given in the first two columns, respectively, are the HD numbers and names of the observed stars, and in column three, the MK spectral type taken from the *Catalogue of Bright Stars* (Hoffleit, 1964). The fourth column contains the observed $(B-V)$ color index according to the *Photoelectric Catalogue* of Blanco *et al.* (1968). Using the intrinsic colors given by Johnson (1958), the color excess $E(B-V)$ was calculated and listed in column five. An upper limit to the amount of interstellar polarization corresponding to this reddening, estimated from the approximate relation $p_i(\text{lim}) \lesssim 2.36[3E(B-V)]$ percent (Hiltner, 1956) is given in column six. The last three columns contain the mean observed position angle ($\bar{\theta}_o$) of the program stars, the mean interstellar position angle with its standard error from the catalogue survey, and the number of stars used to form that mean.

Many of the stars in the Hall catalogue are faint and are consequently background stars, but this should not affect the estimate of θ_i if it is independent of distance, that is, if there is essentially a single 'interstellar cloud'. Only for γ Cas is there a very large number of stars within the selected area, and there appears to be strong

TABLE I

Data for the observed stars

HD	Star	SP[a]	$(B-V)$[b]	$E(B-V)$	p_i(lim) (%)	$\bar{\theta}_o$	$\bar{\theta}_i$[d]	N[e]
5 394	γ Cas	B0 IV?e	−0.22	0.08	0.66	105°	95° ± 1°	117
10 516	ϕ Per	B1 III–V?pe	−0.04	0.22	1.81	39.5[c]	104 ± 3	16
24 534	X Per	Ope	+0.31[a]	0.62?	5.14	55	88 ± 13	13
25 940	48 Per	B3 Vpe	−0.03	0.17	1.41	171	148 ± 4	13
31 964	ε Aur	F0 Iap	+0.54	0.31	2.57	144	154 ± 4	17
37 202	ζ Tau	B2 IV pe	−0.18	0.05	0.41	31	164 ± 5	19
142 983	48 Lib	B3? pe	−0.09	0.11?	0.91	117	Undefined	
149 757	ζ Oph	O9.5 V	+0.02	0.32	2.65	127	Undefined	

[a] *Catalogue of Bright Stars* (Hoffleit, 1964).
[b] *Photoelectric Catalogue* (Blanco, *et al.*, 1968).
[c] Observed position angle is wavelength-dependent.
[d] Mean position angle for stars, mostly distant, listed by Hall (1958) lying within ±4° in l^{II} and ±4° in b^{II} of the emission line star.
[e] Number of stars within the 8° × 8° box. If N was less than 10, the box was increased to ±5° in l^{II} and b^{II} (ϕ Per only); and if there were less than three stars in this box, the value of $\bar{\theta}_i$ was considered undefined.

evidence that the interstellar position angle in that direction, presumably by coincidence, is not much different from the mean observed azimuth $\bar{\theta}_o$. Of course, since γ Cas is comparatively close to the Sun (~29 pc) and not strongly reddened, the amount of interstellar polarization present must be small.

So far, the discussion on separating intrinsic and interstellar polarizations has involved only broad-band polarimetry and statistical results which have obvious limitations. Next, we turn our attention to the novel possibility of applying polarimetric measurements across emission line profiles to the same problem.

3.2. Methods employing the polarization effects produced by the shell emission lines

For the idealized case in which the emission line is regarded as arising in a 'layer' of the shell above that in which most of the electron scattering and self-absorption, responsible for the polarization of the stellar continuum flux, occurs then, by adding together the appropriate Stokes vectors, the following simple relations can be derived. If $\chi(\lambda)$ is the ratio of the additional unpolarized emission flux, at some wavelength point (λ) in the line, to the total flux at the same point in the original underlying spectrum, then the line polarization is given by (Clarke and McLean, 1975b)

$$p_*(\lambda) = p_*(\lambda_c)/[1+\chi(\lambda)], \tag{1}$$

where $p_*(\lambda_c)$ is the degree of polarization in the adjacent continuum. These expressions are, of course, for the *intrinsic* polarization only. When the emission line flux itself is partially linearly polarized with a constant degree of polarization p_e (at the same position angle as the continuum) then the relation becomes

$$p_*(\lambda) = [p_*(\lambda_c) + p_e\chi(\lambda)]/[1+\chi(\lambda)]. \tag{2}$$

A *negative* value of p_e would correspond to a position angle orthogonal to that in the continuum. Implicit in these formulae is the reasonable assumption that the polarization at wavelength λ in the underlying absorption spectrum is equal to that at λ_c in the adjacent continuum.

At Hα, the shape of the underlying spectrum (the shallow rotationally broadened photospheric absorption feature) can sometimes be neglected in comparison to the emission line strength. In that case, the added flux is essentially relative to the continuum and $1+\chi$ becomes the observed total intensity (I) with the continuum normalized to unity.

Observationally, we have two values of the observed polarization, $p_o(\lambda_c)$ for the continuum and $p_o(\lambda_1)$ for some wavelength λ_1 in the line (Hα, say) and in addition, $\chi(\lambda_1)$ or at least $I(\lambda_1)$ is known from the line profile scans.

The basic assumption in what follows is that, whatever the emission line flux does to the value of p_* in the adjacent continuum, it does without affecting θ_*, which remains constant and independent of wavelength. This situation can be achieved with unpolarized emission or partially polarized emission either parallel or perpendicular to θ_*.

Plotting once again the observed polarizations in the $p_x - p_y$ plane and joining the two points by a straight line immediately yields, from the length of this line, the intrinsic difference $\Delta p = p_*(\lambda_c) - p_*(\lambda_1)$. If the line through the two points does *not* pass through the origin, then the direction $\lambda_1 \rightarrow \lambda_c$ yields $2\theta_*$. However, if the line *does* pass through the origin, then the intrinsic and interstellar polarization components are either aligned with this direction or are orthogonal to it, and these cases cannot be separated by this method, or there is no significant interstellar effect.

Assuming the unpolarized emission case, $p_*(\lambda_c)$ can be derived from the observed values of Δp and $I(\lambda_1)$ by using Equation (1). If the emission feature is weak, then the underlying line shape must be estimated and $\chi(\lambda_1)$ used instead of $I(\lambda_1)$.

Since $p_o(\lambda_c)$, $\theta_o(\lambda_c)$, $p_*(\lambda_c)$, and θ_* are now known, it is straightforward to complete the vector addition problem and solve for $p_i(\lambda_c)$ and θ_i. Of course, a negligible contribution from the interstellar medium implies that the derived value of $p_*(\lambda_c)$ equals the observed polarization $p_o(\lambda_c)$.

We now have θ_i and θ_*, which are essentially constants, and the value of the interstellar polarization *near* the line (p_i does not change significantly across any given one of the lower Balmer lines). Since $p_i(\lambda)$ depends on two parameters $p_{\max}$, $\lambda_{\max}$, corresponding to the amount of material in the line of sight and the particle size, respectively, the value of p_i cannot be deduced for a distinctly different wavelength without further observations.

There are two possible courses which can be followed here. Since θ_i and θ_* are assumed known and constant, measurements of the observed polarization $p_o(\lambda)$, $\theta_o(\lambda)$ at any λ will yield simultaneously $p_*(\lambda)$ and $p_i(\lambda)$. Alternatively, repeating the observations at a different emission line (say, Hβ) should provide the same values for θ_i and θ_*, but a new value for p_i. Now, having two sets of results, the equation $p_i(\lambda) = p_{\max} \exp[-1.15 \ln^2(\lambda_{\max}/\lambda)]$ can be solved for $p_{\max}$ and $\lambda_{\max}$, hence obtaining the interstellar properties directly.

If the emission line flux is, in fact, uniformly polarized with degree of polarization p_e, as given in Equation (2), it is still possible to obtain some partial results and, in addition, estimate the value of p_e by using two observations within the line. Starting with $p_o(\lambda_c)$, $p_o(\lambda_1)$, $p_o(\lambda_2)$, and the corresponding intensities $I(\lambda_1)$ and $I(\lambda_2)$ and again assuming that θ_* is strictly constant, the length of the lines joining $p_o(\lambda_1)$ to $p_o(\lambda_c)$ and $p_o(\lambda_2)$ to $p_o(\lambda_c)$ in the $p_x - p_y$ plane gives the true change Δp. The three points should also be collinear and define θ_*.

Line profile polarimetry of Be-shell stars appears an attractive method for separating intrinsic and interstellar effects, provided that the simple expressions and assumptions underlying Equations (1) and (2) are at all valid. The basic assumptions are that θ_*, θ_i, and p_e are all constants and that the underlying stellar radiation is polarized near the star. Deviations from the simple formulae presented here should, in principle, indicate the validity of the assumptions. However, very good polarimetry and corresponding line profile photometry is obligatory to differentiate between, for example, unpolarized emission and partially polarized emission with $p_e \sim 0.2\%$. As yet, Hα and Hβ observations are not detailed enough to allow the full potential of the technique to be tested, but results typical of those obtained so far are discussed in the next section.

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4. Individual Discussion of the Program Stars

ζ Tau. Referring first to the Hα observations shown in Figure 1(a), it is apparent that the strong change in p across the line is not accompanied by a statistically significant change (rotation) in the direction of vibration. Any interstellar component in the polarization must therefore be either aligned or orthogonal to the intrinsic polarization. Alternatively, for an arbitrary orientation, the interstellar polarization must be very weak. The mean position angle for 19 non-Be stars in the same area of sky as ζ Tau (see Table I) was found to be $164° \pm 5°$ (equivalent to $-16° \pm 5°$). For five stars with tabulated values of p less than half of that for ζ Tau the mean is $10° \pm 6$, while the mean observed position angle for ζ Tau is about 31°. Alignment of the mean interstellar position angle with the intrinsic angle for ζ Tau is therefore not very convincing, and the small value of $E(B-V)$ implies that the amount of polarization cannot exceed about 0.4%. In fact, p_i must be somewhat smaller, or the above non-alignment would just become observable as a rotation effect at the Hα line center, thus the observed polarization should be nearly all intrinsic, enabling us to test the unpolarized emission hypothesis.

From Figure 1(a) it is clear that the observations of p across Hα do fit quite well the simplified relation (with $1+\chi$ replaced by I) corresponding to unpolarized emission line flux (see also the measurements by Poeckert (1975), which contain more spectral points). However, the line center measurements are systematically lower than expected, and a single observation on the extremity of the blue wing is higher than expected. These apparently discrepant results cannot be resolved by taking into account the underlying profile or a weak interstellar polarization. If Equation (2) is applied to the measurements, then a suitable agreement can be reached only with a variable emission line polarization such that p_e is zero at the wavelength which fits the p_c/I curve in Figure 1(a), positive in the line wings, and negative (i.e., orthogonally polarized) at the line center. A weak increase in polarization (at the same position angle) in the line wings may not be unreasonable due either to electron scattering (suggested by Marlborough as responsible for the broad emission wings in Be stars) or to partially polarized flux from the underlying rapidly rotating star itself (see, for example, the models of Cassinelli and Haisch, 1974). Orthogonal polarization at the line center is, however, more difficult to understand. One simple explanation worthy of consideration is that the observed value of I at the line center is not the value instrumental in reducing the continuum polarization because the observed profile has been flattened-off by the presence of a shell absorption line. Provided the bulk of the absorption occurs higher in the envelope than the bulk of the emission, then the line center polarization should be unaffected and the absorption only manifests itself in the intensity profile. With this concept in mind, we next refer to the Hβ polarimetry of ζ Tau shown in Figure 2(a).

Evidently the Hβ line profile of ζ Tau is comprised of a sharp absorption line and a displaced emission line. Again, there is no apparent change in θ across Hβ but a remarkably strong reduction in p which is a maximum between the red emission peak and the central reversal. Unlike at Hα, the shape of the underlying absorption cannot be ignored. Since this shape is poorly known, it is difficult to calculate χ; however, we can adopt the inverse process. Dividing the observed minimum value of p by the continuum value p_c allows χ to be predicted from Equation 1 for unpolarized emission. The result is $\chi \simeq 1.0$, i.e., the additional flux due to the emission line is equal to the flux at the same point in the original underlying spectrum. If the emission line is superposed on a shallow rotationally broadened photospheric absorption line with a central depth of 0.20 (relative to the continuum as 1.00), then the expected value of I at the line center would be 1.60.

Subtracting from this emission line a shell absorption line with a central depth of 0.80 and with a slight relative displacement results in a situation similar to that which is observed. This simple idea of the effect of the shell absorption enables us to maintain the concept that the shell emission is unpolarized or nearly so at both Hα and Hβ, and it would also explain the apparently anomalous strong reduction in p observed at Hγ in ζ Tau by Hayes (1975). However, shell absorption processes, localized to the line center, can be envisaged which will produce the same effect as unpolarized emission (Hayes, 1975).

In reality it may be doubtful that the extended envelope can be broken down into suitable layers of emission and absorption. However, we note that regions of the envelope more distant than 10 stellar radii from the star are thought to be the most likely places for the deep shell lines to be produced on theoretical grounds (Marlborough, 1969) and that Marlborough and Cowley (1974) found that an envelope extending to at least 30 stellar radii was required to reproduce the deep shell line at Hα in 1 Delphini.

48 Per. This star shows no significant changes in polarization across Hα, despite the presence of a strong emission line. A possible slight rotation in θ for the line center values (Figure 1(b)) is confused by the disparity of the two results at λ 6580 Å. No effects are apparent at Hβ (Figure 2(b)), with all the values of θ being closely aligned to 171°, which does seem marginally higher than for the Hα values.

Since 48 Per is regarded as an extreme Be star and has a fairly low $v \sin i$, it is reasonable to suppose that it is being viewed nearly pole-on. For an homogeneous scattering medium confined essentially to the equatorial plane, an almost pole-on aspect results in a low net circumstellar polarization because the disk appears symmetric. In contrast, in shell stars such as ζ Tau, the line of sight is nearer to the equatorial plane, and thus the scattering disk appears asymmetric and the polarization is high. The observed polarization, if any, of extreme Be stars should therefore be dominated by interstellar polarization. A comparison with the Hall catalogue yields a mean interstellar position angle of $148° \pm 4°$, while five stars with less observed polarization than 48 Per gave $158° \pm 7°$. The agreement is not as good as might be expected. Taking this fact together with the slight difference in θ between Hα and Hβ, the possible weak rotation effect at Hα, and the peculiar wavelength dependence of the observed polarization reported by Coyne and Kruszewski (1969), then the presence of some intrinsic polarization seems likely. For a given value of $\chi(\lambda)$ or $I(\lambda)$, the difference Δp between the line and continuum polarization is proportional to $p_*(\lambda_c)$ which, for an almost pole-on star such as 48 Per, may be only 0.2% and, therefore, for the typical value $I = 3$, Δp would be only 0.13%, compared to 0.80% for ζ Tau. In fact, on the basis of Equation (1) and the limit on Δp set by the observational errors, the intrinsic polarization near Hα is most probably less than

0.1%. Very accurate line profile polarimetry is essential to separate intrinsic and interstellar effects for almost pole-on stars.

Even when no line profile effect can be detected by high precision measurements, intrinsic polarization is still possible but with line and continuum flux equally polarized. In such a case, temporal variations are a good indicator of intrinsic polarization.

ϕ Per. At Hα and Hβ (Figures 1(c) and 2(c)), there is a very strong change in both p and θ relative to the continuum values, which is most likely attributable to a combination of interstellar and intrinsic polarizations with quite different position angles. Since only line center observations have been obtained so far, it would be premature to apply Equation (1) without additional support.

From Table I, the mean interstellar position angle is $104° \pm 3°$ for stars in the same area of sky as ϕ Per. With this value of θ_i and a value of 0.52 μm for λ_{max}, Coyne and McLean (1975) found that a maximum interstellar polarization of 1.00% was required to remove the strong rotation effects in the observed position angles for a large number of both narrow- and wide-band observations (0.3 μm to 2.2 μm) of ϕ Per. As discussed in the previous section, when the observed line and continuum polarizations are plotted in the $p_x - p_y$ plane, the magnitude and direction of the vector which joins them gives the true difference in intrinsic polarization Δp and the intrinsic position angle θ_*. The value of θ_* derived from the line profile method was in perfect agreement with the result of the broad-band method. However, when the interstellar polarization was removed from the Hα observations, the emission line flux was itself weakly polarized with $p_e \simeq 0.5\%$. Such a result could be consistent with an extensive disk-like envelope seen exactly edge-on since this aspect would provide the maximum optical depth for electron scattering; and, in addition, it should yield a very high intrinsic polarization. The edge-on aspect seems consistent with the very high value of $v \sin i$ for ϕ Per (493 km s^{-1}, Bernacca and Perinotto, 1971). However, intrinsic polarization at Hβ seems more consistent with unpolarized emission if one adopts a maximum depth of 0.15, relative to the continuum, for the underlying rotationally broadened line. If electron scattering is responsible for the polarization of the Hα emission then, since the scattering cross-section is independent of wavelength, the only way Hβ emission flux can escape becoming polarized is for the physical path length through the disk to be lower. This is opposite to what one would expect. Alternatively, some other process such as resonant scattering may be responsible for the Hα line center polarization; and, of course, the observed effect may be confined to the core of the line – the bulk of the emission line flux being unpolarized. Further measurements of ϕ Per at higher spectral resolution are needed to clarify the situation.

Had we assumed Hα to be unpolarized, then somewhat different interstellar values would have been obtained, viz., $\theta_i = 92°$ and $p_{max} = 0.53\%$. These values do still result in a cancellation of the rotation effects observed in broad bands in ϕ Per, but there is about three times more scatter about the mean intrinsic position angle of 26°. When the derived intrinsic polarization is normalized for purposes of comparing it to a model (Coyne and McLean, 1975), then the ultraviolet polarization is found to be very much lower, and the near infrared polarization higher, than obtained with the original interstellar values $\theta_i = 104°$ and $p_{max} = 1.00\%$.

γ Cas. The polarization changes which occur across Hα and Hβ are the most peculiar ones encountered to date. Evidence of variability and slight rotations of θ are just barely apparent for both lines. A similar weak rotation for the Hα line center has also been obtained by Coyne (private communication). If the Hα emission line flux is assumed unpolarized, then method (3.2) and Equation (1) yield the following values when applied to the point just off the line center, viz., $\theta_* \simeq 113°$, $p_*(\lambda_c) = 0.46\%$, $\theta_i = 96°$, and $p_i = 0.27\%$ near the wavelength of Hα. The value obtained for θ_i is in good agreement with that expected from the catalogue survey (see Table I). At Hβ the rotation of θ is barely discernible with the 12 Å filter, but a few preliminary measurements with the 2.3 Å filter gave the value 112° for θ_*. However, the above reasonable estimate of the interstellar polarization seems unable to account for the low values of p obtained at the extremities of the emission lines near the point of crossover with the underlying absorption. These points are well below the unpolarized emission curve and therefore imply an additional intrinsic mechanism which is reducing the continuum polarization in the line wings.

TABLE II

Polarization data on other emission line/peculiar stars

Star	Date	$\lambda/\Delta\lambda$	p (%)	θ (deg)
ε Aur	1974 Dec 11	4861/12	2.17±0.02	144.0±0.3
	1974 Dec 11	5100/51	2.14±0.02	143.3±0.3
	1975 Jan 10	4600/51	1.97±0.03	143.9±0.4
	1975 Jan 10	4872/12	1.98±0.04	143.7±0.6
	1975 Jan 10	4861/12	2.08±0.04	144.3±0.6
48 Lib	1975 May 9	6582/9	0.81±0.11	121±4
	1975 May 9	6563/9	0.79±0.04	101.5±1.5
	1975 Aug 24	4820/12	0.94±0.05	119±1.5
	1975 Aug 24	4861/2.3	0.70±0.08	110.5±3.3
	1975 May 9	4250/1000	0.76±0.03	123.6±1.1
	1975 May 13	5460/1000	0.85±0.05	119.7±1.7
	1975 May 13	3600/500	0.68±0.04	125.0±1.7
	1975 May 13	4600/51	0.83±0.03	122.1±1.0
	1975 May 13	5100/51	0.85±0.06	118.6±2.0
ζ Oph	1975 May 8	6540/9	1.46±0.07	123±1
	*1975 May 8, 14	6563/9	1.39±0.05	126±1
	1975 May 14	6582/9	1.35±0.06	128±1
	1975 Mar 20	5100/51	1.36±0.08	126±2
	1975 Mar 20	4861/25	1.34±0.09	126±2
	1975 May 8	4870/12	1.38±0.04	129±1
	*1975 May 8, 14	4861/12	1.32±0.03	127±1
	1975 May 14	4840/12	1.33±0.05	126±1

* Average of data from the two nights given.

48 Lib. Data for this star are listed in Table II. The intrinsic position angle θ_* derived from the rotation effect at Hα is 155°, while a somewhat more accurate measurement at Hβ gave 139°. The weighted mean is 144°, and the derived value θ_i is 82°. Further measurements will be required, especially at Hβ, before any final conclusions can be drawn regarding the wavelength dependence of the intrinsic polarization of this star.

X Per, ε Aur, and ζ Oph. No line profile polarization effects were found for any of these stars. Only X Per shows appreciable emission (our measurements have been reported elsewhere (Clarke and McLean, 1975c)), but the polarization of all three stars appears to be dominated by the interstellar medium. The observations of ε Aur and ζ Oph are reproduced here to indicate the stability of the polarimeter.

5. Summary and Conclusions

Changes in the degree and position angle of the observed polarization occur across the Balmer emission lines in Be and shell stars. These changes immediately indicate the presence of an intrinsic (circumstellar) polarization component. The variations in the line profile effects are partly due to differing combinations of interstellar and intrinsic polarizations and partly to processes inherent to the extended envelope of the Be star.

Of the stars discussed here, only ζ Tau shows negligible interstellar polarization, and it appears to be possible to attribute the reduction in polarization across both Hα and Hβ to dilution of continuum polarization by unpolarized emission line flux, at least in the line wings. The stars 48 Per, ϕ Per, γ Cas, and 48 Lib have an intrinsically polarized component superposed on an interstellar component which is usually revealed by a rotation of θ at the line center. For 48 Per the intrinsic polarization is very small ($\lesssim$0.1%), indicating an almost pole-on aspect; while for ϕ Per the intrinsic polarization is very high (1.61% near Hα), indicating an almost exactly equator-on aspect. Both ϕ Per and γ Cas exhibit polarization changes across Hα and Hβ which simply cannot be attributed to unpolarized emission flux alone, but these changes are quite different for the two stars.

We have discussed methods for separating interstellar and intrinsic polarizations and have shown that line profile polarimetry is potentially useful for this purpose. In future, very accurate measurements of the intensity and polarization at several points across, (a) two of the Balmer emission lines or (b) one emission line and in a narrow band at a distinctly different wavelength, should enable one to determine the interstellar properties θ_i, p_{max}, and λ_{max}, and hence the intrinsic (circumstellar) polarization parameters $p_*(\lambda)$ and θ_*. The wavelength dependence, $p_*(\lambda)$, should enable limits to be placed on T_e and N_e, the electron temperature and density of the envelope, while the absolute values of p may give some indication of the geometry of the shell – perhaps yielding sin i and limits on M_*/R_*.

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DISCUSSION

McLean: I would like to take this opportunity to announce that a program of line profile polarimetry on the eclipsing binary β Lyr was initiated in the spring of 1975. Polarization changes were observed across both Hα and Hβ and these lines were in emission.

Finally, line profile and broad band observations in the early stages of Nova Cyg 1975 did not reveal any evidence of intrinsic polarization.

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