POLARIMETRY OF CLOSE BINARY SYSTEMS; OBSERVATIONS AND INTERPRETATIONS

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ABSTRACT: Polarization caused by scattering of starlight on gaseous extrastellar material in close binary systems is reviewed. A simple physical derivation is given to illustrate how in principle, variations synchronous with the orbital period of the Stokes parameters of the linear polarization can yield the orbital inclination and other parameters. High resolution multichannel spectropolarimetry across the emission line profiles of binaries is discussed as a new technique in studying the physics and kinematics of gaseous streams and stellar winds. The methods have application to a range of binary objects including systems like Algol and Beta Lyrae, X-ray binaries, Of and Wolf-Rayet binaries, VV Cephei stars and symbiotic stars. Some new observational results are presented.

1. INTRODUCTION

There are many classes of objects now known to exhibit measurable intrinsic polarization at optical wavelengths. Among the most important of these are close binary systems undergoing mass loss and/or mass transfer. Whether we consider semi-detached, detached, contact or X-ray binaries, one property common to many of them is a gaseous extrastellar 'envelope'. Typically, in any such nonspherically-symmetric distribution of material or even in the component stars themselves, processes such as scattering, reflection and light emission in a magnetic field can produce partial linear and/or circular polarization of the emergent radiation. The polarization may be apparent in the continuum flux or in spectral lines or both. This intrinsic polarization will vary with the binary phase and will be dependent on the polarizing mechanism, the distribution and physical state of the material, and geometric factors such as the aspect of the system as seen from Earth. In practice the observed polarizations are small but the rapid development of new types of instruments over the past decade has led to a growing understanding of the role of polarimetry in astronomy. Most polarimeters are now capable of reliably measuring degrees of polarization as small as 10^{-4} (i.e. a polarized flux equal to 0.01% of total flux). Of particular

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importance is the application of polarimetry to complement or even supplement other means of deriving vital quantities such as the orbital inclination. Below is a brief review in which the aim is to indicate the current status and the changing trends in this field. Our emphasis is on hot (early-type) systems and on two different methods viz., (i) those using periodic variations in the polarization parameters and (ii) those employing polarimetry across certain spectral lines.

2. PERIODIC VARIABILITY OF POLARIZATION IN CBS

Lists of binaries already found to have variable, and hence, intrinsic polarization have been compiled by Kruszewski (1974) and by Pfeiffer and Koch (1977). More recently, it has been demonstrated by systematic observation that in many CBS the variations are indeed repetitive and phase-locked to the orbital period (see, for example, Rudy 1979, Rudy and Kemp 1978). There has also been a concurrent and rapid development in theoretical models, especially concerning analytic treatments of polarization due to single scattering in optically thin (ionized) circumstellar material (cf. Brown and McLean 1977, Brown, McLean and Emslie 1978 and Rudy and Kemp 1978). The essential physics relating polarization and binary parameters can be understood using the simple account given below. Here, the scatterers are free electrons.

Basically, expressions for the linear Stokes parameters ($Q = p\cos 2\theta$ and $U = p\sin 2\theta$) as a function of orbital phase are required. Consider a localized optically thin scattering volume, a 'blob', of N electrons moving in a circular orbit of radius R and inclination i about an isotropic (point) source star (O) as shown in Fig. 1. The stellar intensity is I_0, the scattered intensity is $I_1 = I_0\tau_B(1+\cos^2\chi)$ and its degree of polarization is $P_1 = \sin^2\chi/(1+\cos^2\chi)$. Here χ is the scattering angle and $\tau_B = 3N\sigma_T/32\pi R^2$ is an effective optical depth. For $I_1 << I_0$, the net (diluted) polarization is $P_R \simeq I_1P_1/I_0 = \tau_B \sin^2\chi$. When $i=0^\circ$ (pole-on), χ is always 90°, so $P_R = \tau_B$ independent of phase and the polarization vector (defined by the normal to the scattering plane) rotates uniformly. When i=90° this vector lies constantly along the normal to the orbit while χ varies through 360°. In the Stokes parameter plane, these two cases correspond to motion on a circular locus and to harmonic linear motion during each HALF of the orbital period. For general i the locus is an ellipse. When the blob is nearest (or farthest from) Earth U=0, $Q_1=-\tau_B\cos^2 i$ while at quadratures U=0, $Q_2=\tau_B$, hence the (Q,U) ellipse has eccentricity (e) defined by $(1-e)/(1+e)^2 = |Q_1/Q_2| = \cos^2 i$; a result derived independently by J. C. Kemp and the author. In fact, the derivable properties in this case may be summarized as follows; (i) shape of ellipse defines i; (ii) its size defines τ_B; (iii) orientation gives projection of orbit normal on the sky; (iv) phases of extrema in P_R locate longitude of the blob; (v) the sense of circulation defines the sense of orbital revolution. Note that since we deal with the (Q,U) locus, any interstellar polarization is by-passed and merely introduces a displacement of the origin.

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In a real binary system the situation is more complex, yet, the above canonical result can be maintained for an envelope of entirely arbitrary shape provided we have corotation, circular orbits and isotropic intensity distributions from both stars. Any absorption effects must not be phase-dependent. Material symmetric about the orbital plane yields SECOND harmonic (half-period) behaviour as described above while material asymmetric about the plane introduces FIRST harmonic terms in Q and U resulting in loci which are general Lissajou-type figures (cf. Fig. 4). Note that the material need only appear to be asymmetric about the plane due to absorption in the envelope. Often, however, such effects lead to a wavelength dependence of polarization which is separately detectable.

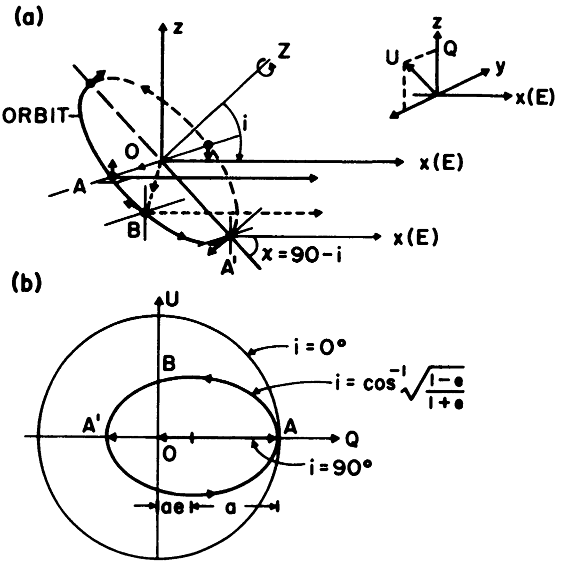

Fig. 1. Scattering geometry and (Q,U) loci for an orbiting blob of electrons or any Rayleigh particles.

Departures from the above assumptions generally destroys the canonical relation (cf. Brown et al. 1978 and Milgrom 1979) by addition of other harmonics and uneven scaling of the 2nd harmonics in Q and U. In mitigation, however, corotation is a good initial assumption and the effects due to eclipses can be recognized and smoothed-out or separately modelled to yield a further independent estimate of i (Piirola 1980). Furthermore, it is for non-eclipsing systems that the polarimetric method is most needed. For an envelope symmetric through the orbital plane, the effect of a mildly eccentric orbit mainly scales the second harmonics in Q and U by the same factor (ignoring terms of order e^4) and introduces 1st and 3rd harmonic terms which can be isolated by Fourier analysis and we again obtain the canonical result. Probably the most serious source of confusion could come from phase dependent absorption effects but in this case spectroscopic data could at least provide a warning. Recently, methods of statistical analysis have been developed (Simmons, Aspin and Brown 1980) which enable one to quantify the significance of the canonical model fit to observational data. Of course, in practice, a good model must also involve external constraints set by other observational methods and each system must be taken on its own merits.

A typical example of observational data is shown in Fig. 2; the variation of Q and U as a function of phase is given for Algol. The 2nd harmonic modulation is clear despite the rather small level of polarization (due mainly to the thinness of the gaseous stream), and the polarimetrically derived inclination of i=81° is in good agreement with the photometric value. The effect of the eclipse is quite marginal.

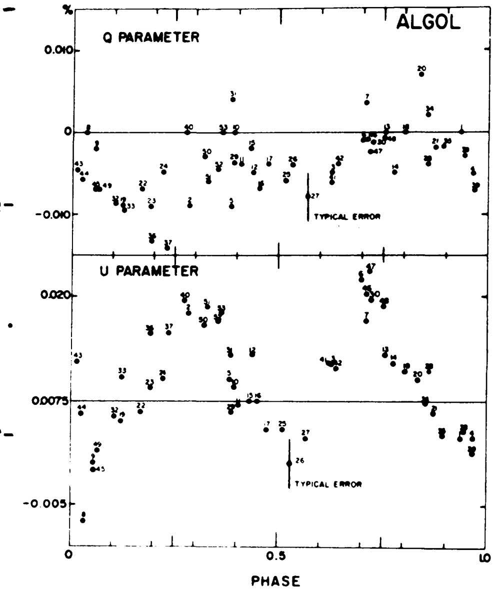

Fig. 2. Polarization (Stokes parameters) versus orbital phase for Algol (β Persei).

Figures 3 and 4 show respectively, (Q,U) versus phase and a (Q,U) locus for the Wolf-Rayet object HD 50896 (WN5) from McLean (1980). Recent observations by Firmani et al. (1979) of this apparently "single" WR star have revealed periodic variations in radial velocity and light on a period of 3.76 days; they interpret these variations in terms of orbital motion. The strong second harmonic modulation in the polarization gives some support to this contention and permits a rough estimate of i=71°. For a $10M_\odot$ WR star, this inclination together with the observed mass function implies a companion mass of $1.3M_\odot$. HD 50896 may be a member of a new class of WR stars having low mass evolved companions, probably neutron stars, with orbits essentially within the WR star's atmosphere. This is a fine example of the interplay of polarimetry and other methods and is one result in an extensive program being carried out at the University of

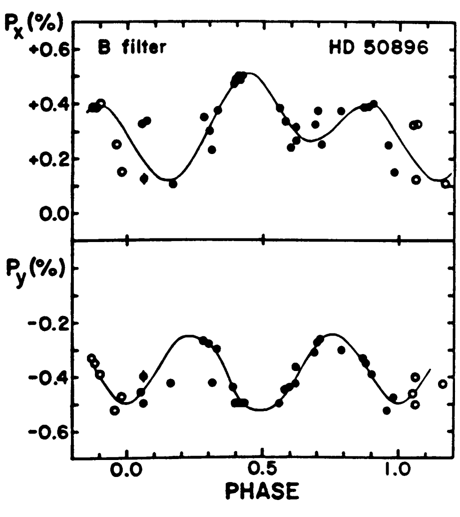

Fig. 3. Q,U phase curves in the B filter for HD 50896 (WN5).

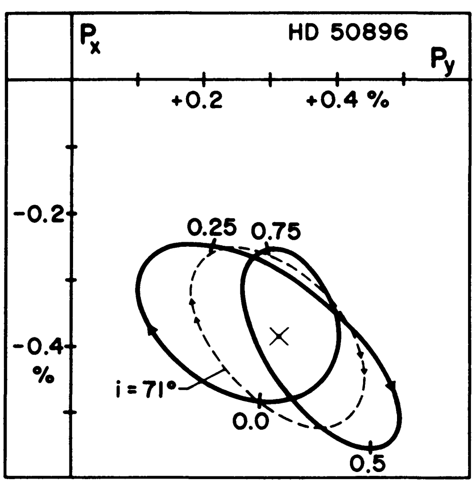

Fig. 4. The smoothed (Q,U) locus derived from the data of Fig. 3.

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Arizona. Some of the principles discussed here are applied in the paper on Cygnus X-1 by Dr. Kemp.

3. Polarimetry Across Doppler Broadened Emission Lines

It has recently become possible to measure polarization across wide, Doppler broadened spectral lines with high precision using multi-channel echelle spectropolarimetry. The only detailed work concerns the broad Balmer emission lines of Be stars, some of which are certainly binaries, but the same technique can be applied to numerous emission line binaries. Lines Doppler broadened by rotation and/or expansion in gaseous extrastellar material effectively provide us with a means of spatially resolving the envelope. Consequently, the polarization which we see is no longer that of an unresolved, axisymmetric envelope but rather that from non-axisymmetric portions moving toward (or away) from us. Hence, for arbitrary i, the amount and direction of the intrinsic polarization can change rapidly with wavelength across the line (McLean 1977,1979; McLean, Coyne, Frecker and Serkowski 1979; Poeckert and Marlborough 1978). For a simple case, consider an envelope which has no motion except rotation; the scattered flux at wavelengths in the blue wing of the line is more attenuated for the approaching

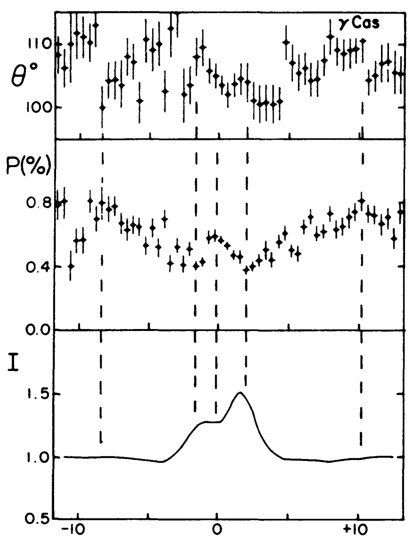

Fig. 5. Hβ flux and polarization with 0.5A resolution for the Be star γ Cas.

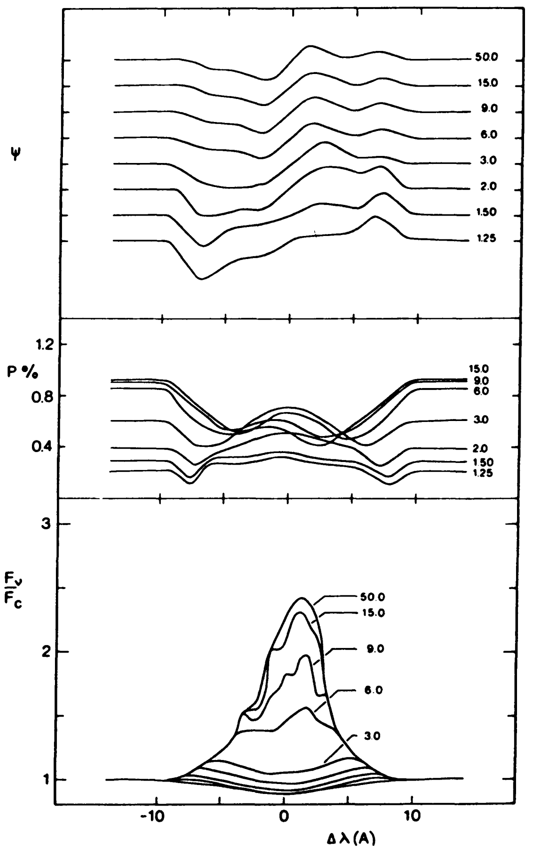

Fig. 6. Hα flux and polarization as a function of envelope extent for a stellar wind model of γ Cas.

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part of the envelope and less attenuated for the receding part. The opposite is true for wavelengths in the red wing. Since for each wing the integration of the scattered flux is not symmetrical with respect to the rotation axis, the polarization plane for the polarized flux in each wing will differ from that in the continuum, provided $i \neq 90$. For pure rotation, the variation in θ is of the same amplitude but opposite sense for the two wings. In practice, random motions and expansion dilute this simple effect and cause further variations in θ. Figure 5 shows the remarkably detailed polarization structure across Hβ in the weak X-ray source γ Cas obtained with a Digicon spectropolarimeter (McLean et al. 1979). The oscillations in θ imply that the Be star disk is not viewed edge-on and from the stellar wind model shown in Fig. 6 Poeckert and Marlborough (1978) derive an inclination in the range 45°-50°.

4. Summary

Intrinsic polarization should be relatively common in close binary systems and, at least in principle, polarimetry can provide three independent ways of obtaining the orbital inclination (and other parameters) viz., (i) periodic variations of polarization synchronous with the orbital motion, (ii) polarization changes during eclipses if these occur and (iii) polarization structure across emission lines formed in the envelope and Doppler broadened by mass motions. These new methods carry great potential and over the next several years a rapid development trend is expected.

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