POLARIZING GAS AT SMALL OPTICAL DEPTHS AROUND ALGOLS

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ABSTRACT. The origins of visible-band linear polarimetry of Algols and objects related to them are reviewed. It is pointed out, not for the first time, that the polarization signals of these systems can vary sporadically by significant amounts. The difficulty of evaluating the interstellar component of the observed polarization is discussed and these components are evaluated anew for each object studied in this paper. With one possible exception, the polarization signals intrinsic to these binaries derive from electron scattering. A well-defined model is applied to the constant and variable (but phase-locked) polarization signals. Limits to the mass associated with a scattering disk in each binary are derived. Within broad limits, concentrations of scattering mass within and above or below the orbital plane are also developed as are the centroid longitudes of these concentrations within the system. It is pointed out that very few measures of visible-band, circular polarization have been made but that cm-wavelength measures of Algol itself have been very informative.

1. INTRODUCTION

Algols and objects related to them are at the origin of polarization measures of stars. Öhman's (1934) photographic spectropolarimetry of Bet Lyr has never been repeated abundantly enough to check his claims. His paper existed as an isolated case until Chandrasekhar's (1946) theoretical study of radiative transfer in hot, electron-scattering atmospheres pointed to Algols as test objects for these atmospheres. Janssen (1946) and Hiltner (1947) almost instantly attempted observational verification with U Sge and RY Per and possibly with Z Vul but their results were inconclusive. Hall and Mikesell's (1950) and Hiltner's (1951) discovery of interstellar polarization followed quickly. As will be seen from citations below, it was not until the early 1960's that a polarized signal intrinsic to a close binary was actually discovered.

By now, more than 600 close binaries have been observed polarimetrically but most of them are not useful for this review.

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Table I. Algols and Algol-Related Close Binaries

N	BINARY	SPECTRAL CLASSIFICATIONS	P (days)	i (°)	L_3*	PTM. REF.	POL. REF.	BAND-PASS
(01)	(02)	(03)	(04)	(05)	(06)	(07)	(08)	(09)
01	U Oph[a]	B4V + B5V	1.68	88	0.00	18	19	B
02	γ Phe	B6V + B8V	1.67	88	0.00	5	44	B
03	AR Aur	B8V + B9V	4.14	88	0.00	12	15	W
04	DH Cep	O5.5V + O6V	2.11	51	0.00	28	6	B
								V
								R
05	Y Cyg[a]	B0IV + B0IV	3.00	86	0.00	4	20	B
06	AH Cep	B0.5Vn + B0.5Vn	1.77	69	0.00	2	46	W
07	V337 Aql	B0.5pV + (B2V)	2.73	86	0.00	9	45	W
08	V Pup	B1Vp + B2V	1.45	78	0.00	42	44	B
09	V641 Mon	B1.5IV + B2	1.30	43:	0.0	23	24,3	V
10	V640 Mon	O7I + O7	14.40	70:	0.0	11	37	B
11	UW CMA	O7fIa + O	4.39	70	0.00	26	44	B
12	ι Ori[a]	O9III + B1III	29.14	50	0.00	51	29	U
								B
								V
13	AO Cas	O9.5III + O9.5III	3.52	51	0.00	43	38	B
14	δ Ori[a]	O9.5II + (B2III)	5.73	68	1.0	17	48	B
15	XZ Cep	O9.5II + (B4)	5.10	90	0.00	10	41	B
16	RY Sct	B0e + (B3III)	11.12	73	0.00	31	45	W
17	V453 Sco	B0.5Iae + (B0)	12.01	73	0.00	55	44	U
								B
								V
18	π^1 Vel	B2III + ?	1.48	81:	0.0	30	30	B
								V
19	u Her	B2V + B5	2.05	78	0.00	4	39	B
20	λ Tau	B2V + A1IV	3.95	76	0.0	4	45	W
21	RZ Sct	B2II + A0(II-III)	15.19	84	0.00	54	45	W
22	SX Cas	(B7) + (K3III)	36.57	89	0.00	36	21	B
								V
								R
23	V367 Cyg	B8Ia + (A1III)	18.60	76	0.00	27	45	W
24	β Lyr	B8.5II + (B2)	12.93	85	0.00	53	1	U
								B
								V
25	TT Hya	B9.5V + K0III-IV	6.95	84	0.00	8	44	B
26	W Ser	? + ?	14.15	90:	0.0	25	25	U
								B
								G
								O
								R
								I
27	RY Per	B3V + F0III	6.86	81	0.00	52	47	W
28	Z Vul	B4V + A(2-3)III	2.45	88	0.00	4	46	W
29	U CrB	B6V + F8III-IV	3.45	79	0.00	4	45	W
30	U Cep	B6V + G8III-IV	2.49	86	0.00	32	35	B
31	GG Cas	B(5-8) + K0III:	3.76	90:	0.0	50	46	W
32	β Per	B8V + (G8IV) + Am	2.87	82	0.06	49	40	B
					0.06		13	B
					0.06		14	W
33	U Sge	B7.5IV-V + G2III-IV	3.38	89	0.00	52	40	B
34	δ Lib	A0V + (G2IV)	2.33	81	0.00	4	15	V
35	AX Mon[a]	B1e + K0III	232.5	50::	0.0	22	44,16	B
								V
								R
36	υ Sgr[a]	Ap + (OB)	137.9	75:	0.0	33	34,7	V

Note: [a] Any effects of orbital eccentricity are ignored.

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N	I*Q/I*U (%)/(%)	$\Delta p/\Delta\theta_e$ (%)/(°)	$\langle p^*\rangle/\langle\theta_e^*\rangle/\tau_0(1-3\chi)$ (%)/ (°) / -	τ_S/λ_S - /(°)	τ_A/λ_A - /(°)
(10)	(11)	(12)	(13)	(14)	(15)
01	-2.00 /+0.00[b]	0.1/ 5	0.29 / 44/2.9E-3[c]	7E-4 / 30	2E-4 / 30::
02	+0.04 /+0.00[b]	- / -	0.016/ 86/1.6E-4	- / -	- / -
03	+0.039/-0.108[b]	- / -	0.02:/ - /2.:E-4	- / -	- / -
04	-0.92 /+1.02	1.0/ 0	0.77 / 67/1.3E-2	<4E-4 / -	<4E-4 / -
	-0.93 /+1.03	1.0/ 0	0.86 / 67/1.4E-2	<5E-4 / -	<5E-4 / -
	-0.86 /+0.95	1.0/ 0	0.81 / 67/1.3E-2	<7E-4 / -	<5E-4 / -
05	-0.22 /-0.19	0.5/ 5	0.35 / 54/3.5E-3	<5E-4 / -	<5E-4 / -
06	-1.52 /+0.00[b]	0.3/71:	1.62 / 27/1.9E-2	1E-3 /320	8E-4 / 40::
07	-0.4 /+0.7[b]	- / -	1.5 / 43/2. E-2	- / -	- / -
08	-0.06 /+0.00[b]	- / -	0.20 / 88/2.1E-3	8E-5 / 20	<6E-4 /270
09	-0.07 /+0.28[b]	- / -	0.38 /160/8. E-3	<2E-4 / -	<2E-4 / -
10	+1.08 /-0.39[b]	- / -	0.82 /101/9.3E-3	4E-4 / 60	1E-4:/ 30::
11	+0.15 /+0.26[b]	- / -	0.63 /103/7.1E-3	- / -	- / -
12	-0.14 /+0.24[b]	0.0/ 0	0.19 /161/3.4E-3	- / -	- / -
	-0.17 /+0.30[b]	0.0/ 0	0.24 /149/4.3E-3	- / -	- / -
	-0.20 /+0.34[b]	0.0/ 0	0.30 /153/5.4E-3	- / -	- / -
13	-0.62 /+1.07[b]	0.3/10	0.72 /166/1.2E-2	9E-4 / 60	2E-4 / 20::
14	-0.18 /+0.30[b]	0.1/ 0	0.42 /139/4.9E-3[d]	2E-4[d]/ 20	2E-4[d]/ 40:
15	-1.2: /+1.0:[b]	1.6/10	2.2: /78:/2. E-2:	- / -	- / -
16	-0.7 /+1.1[b]	- / -	2.2 / 20/2. E-2	- / -	- / -
17	+0.18 /+1.03[b]	- / -	1.8 /153/2. E-2	- / -	- / -
	+0.23 /+1.28[b]	- / -	2.0 /154/2. E-2	- / -	- / -
	+0.27 /+1.53[b]	- / -	2.1 /152/2. E-2	- / -	- / -
18	-0.04 /+0.03[b]	- / -	0.10 /171/1.0E-3	- / -	- / -
	-0.05 /+0.04[b]	- / -	0.11 /171/1.2E-3	- / -	- / -
19	+0.003/-0.020[b]	0.00/ 0	0.05 / 84/5.2E-4	2E-4 /330	1E-4 / 20
20	0.0 /-0.1[b]	- / -	0.2 /159/2. E-3	- / -	- / -
21	-0.9 /-0.3[b]	- / -	0.7 / 70/7. E-3	- / -	- / -
22	-0.36 /+0.54[b]	0.3/20			
	-0.39 /+0.57[b]	0.3/20	0.7 /158/7. E-3	1E-3 /150	5E-4 / 60::
	-0.37 /+0.55[b]	0.3/20			
23	+0.9 /+0.7[b]	- / -	2.4 / 26/2. E-2	- / -	- / -
24	+0.17 /-0.24	0.1/ 0	0.14 /160/1.4E-3	6E-4 /330	2E-4 / 40::
	+0.25 /-0.34	0.1/ 0	0.29 /163/2.9E-3	8E-4 / 10	3E-4 /320
	+0.25 /-0.34	0.1/ 0	0.24 /166/2.5E-3	8E-4 / 10	1E-4 /140:
25	-0.08 /+0.13[b]	- / -	0.36 / 82/3.6E-3	- / -	- / -
26	-0.6: / 0.0:[b]	1.0/15	0.4: /72:/4. E-3:	- / -	- / -
	-0.7: / 0.0:[b]	0.6/ 5	0.5: /68:/5. E-3:	- / -	- / -
	-0.7: / 0.0:[b]	0.8/10	0.7: /48:/7. E-3:	- / -	- / -
	-0.6: / 0.0:[b]	- / -	0.5: /32:/5. E-3:	- / -	- / -
	-0.5: / 0.0:[b]	- / -	0.5: /31:/5. E-3:	- / -	- / -
	-0.4: / 0.0:[b]	- / -	0.9: /21:/9. E-3:	- / -	- / -
27	-0.87 /-1.04[b]	- / -	1.1 / 30/1. E-2	5E-4 / 20	4E-4 / 40
28	+0.7 /+0.3[b]	- / -	0.7 / 42/7. E-3	- / -	- / -
29	-0.1 /+0.2[b]	- / -	0.1 /100/1. E-3	- / -	- / -
30	-0.11 /-0.02	0.9/40	0.05:/ 92/5. E-4	<3E-4 / -	- / -
31	-2.3 / 0.0[b]	- / -	0.4 /162/4. E-3	- / -	- / -
32	0.000/ 0.000	0.2/60	0.014/153/1.4E-4[d]	8E-5[d]/320	- / -
	0.000/ 0.000		0.012/ 21/1.2E-4[d]	6E-5[d]/320	3E-5:/330::
	0.000/ 0.000		0.018/152/1.8E-4[d]	9E-5[d]/340	- / -
33	+0.15 /+0.04[b]	- / -	0.05 / 19/5.1E-4	2E-4 / 10	4E-5:/320::
34	-0.54 /+0.45[b]	- / -	0.30 /149/3.0E-3	2E-4 / 10	8E-5:/ 90::
35	+1.07 /-0.97[b]	- / -	2.23 / 76/3. E-2	- / -	- / -
	+1.26 /-1.14[b]	- / -	2.43 / 72/4. E-2	- / -	- / -
	+1.14 /-1.03[b]	- / -	2.23 / 70/4. E-2	- / -	- / -
36	+0.7: / 0.0[b]	0.4/10	0.5 /153/5. E-3	- / -	- / -

Notes: [b] Determined by present authors; [c] e.g. 2.9E-3 = 2.9×10^{-3};
[d] Corrected for L_3^*.

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This occurs either because there are but a few sporadic measures per star and these forbid even striking a mean or because the evolutionary stages of the systems are unknown. A PC-readable file referencing all measures of all the systems has been compiled by RHK and was used as a fundamental source for this paper. From this file there were extracted all Algols and systems "closely related" to them. For present purposes "closely related" is defined operationally in the following way with specific reference to Table I. Systems 01 through 03 are hot and massive enough so that they should eventually leave the main sequence and pass into the Algol stage. Systems 04 through 09 are comparably hot and massive and have already begun this evolution even though only some of them are assigned luminosity classifications of IV. Systems 10 and 11 have clearly evolved with mass transfer but probably are pursuing Case A evolution and so they may function here as control systems. Systems 12 through 20 are further advanced than systems 04 through 09, typically being still hot and massive but assigned luminosity classes III, II, or I. The early stages of Case B evolution are represented by systems 21 through 26 and late stages of Case B are demonstrated by systems 27 through 34. Very advanced evolutionary stages following late Case B are indicated by systems 35 and 36. It is contended here that systems 21 through 34 are Algols and all the rest are "closely related" to them.

Obviously, some of the present assignments are debatable because of limitations on the interpretations of the stellar parameters and some workers may easily challenge our assignments. There are also some obvious biases in the data base: it is heavily skewed toward eclipsing binaries and the individual evolutionary stages are not equally represented. Columns 3 through 6 of Table I give orbital or stellar particulars for the systems taken from the most modern references which could be found and which are keyed in column 7 of the table. Column 8 lists the keys to polarimetric data. These number keys are repeated in the Reference List following the page number of a reference.

2. INTERSTELLAR POLARIZATION COMPONENTS

Any attempt to quantify the intrinsic polarization of a binary confronts the evaluation of the interstellar polarization. An early approach to this matter sought to accumulate a sufficient number of data so that their centroid could be evaluated and to assert that this centroid displayed the interstellar polarization. In effect, this procedure declares the systemic polarization to be vanishingly small within the errors of observation. Other approaches, such as those of Shakhovskoi (1964) and McLean and Clarke (1979), rest upon invariance of the orientation of the binary electric vector. This may indeed be a realistic possibility during the interval of a bounded stellar wind episode but it does not describe the generality of behavior shown by evolved systems. For this paper, no attempt was made at this stage to work in the intrinsic frame of the binary so as to isolate the interstellar V-parameter as Brown, McLean, and Emslie (1978) have shown to be possible.

The procedure used here was to map the polarization observed for field stars within +/-5° of a program star in each galactic coordinate as a function of distance modulus. For the most part, distances to the program binaries are not a disabling problem. The consequences of standardized color indices, good radial velocity and light analyses, and the impact of the Barnes-Evans calibration as summarized, for instance, by Lacy (1979) have all contributed to distance determinations which are usually quite adequate. The references for field stars are those given by Koch (1988a) supplemented by Hsu and Breger (1982), Klare and Neckel (1977), Klare, Neckel, and Schnur (1972), Korhonen and Reiz (1986), Piirola (1977), Tinbergen (1982), and the long series of papers from the Arizona workers.

There are numerous pitfalls in the use of these data. It is prudent, of course, to exclude known emission line stars and close binaries. Supergiants are also likely to be polarization variables but, unfortunately, their exclusion depletes the number of field stars significantly for the case of a distant program star. It would certainly be useful to improve the distances to the field stars with modern spectral types and absolute magnitudes, which are better than those available to the original survey workers but this task is too large to undertake here. Typically, it is also necessary to assume that the orientation of the electric vector is independent of wavelength - an unlikely situation. Lastly, the discontinuous distribution of the field stars and the small-scale structure of the polarizing clouds mean that only a coarse evaluation of the interstellar polarization is possible. All these effects lead to errors in assigned interstellar polarization of about +/-0.05%, +/-0.10%, and +/-0.45% (in absolute percentage scale, not a percentage of the polarization value) for distance moduli of 5.0, 7.5, and >8.5, respectively. The imprecision of the orientation of the interstellar vector varies between +/-5° and +/-20° irrespective of distance. The spectrum of the interstellar polarization and the wavelength of maximum polarization were assumed to follow the precept and map, respectively, of Serkowski, Mathewson, and Ford (1975). For the bandpasses indicated (W = unfiltered) in the 9th column of Table I, the interstellar components are given in the (double) 11th column of the same table. Even though the interstellar polarization evaluated in this way is very large for certain distant binaries, its value never exceeds 9E(B-V).

A few attempts were made to look into the success of the removal of the interstellar components. The (multiple) 13th column of Table I gives the calculated intrinsic polarization. (a) This was examined as a function of the interstellar polarization and a convincing correlation was evident in the sense that the larger the interstellar polarization removed, the larger is the residual intrinsic polarization. However, this need not signify an error since the larger interstellar polarizations are typically those associated with the most distant and intrinsically brightest systems, which are themselves known to have large intrinsic polarizations. (b) A second test examined if the orientation of the intrinsic electric vector showed any memory of the interstellar orientation. There appears to be some possibility of contamination of this sort for 3 binaries within 1 kpc and for 2 others

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beyond 1 kpc. Histograms of the difference between the intrinsic and interstellar orientations show a lack of orientation differences between 110° and 165° compared to the remaining 125° interval. (c) The polarization spectrum also provides a clue to the success or failure of removing the interstellar polarization. Within the errors of measurement and the errors assigned above to the interstellar values, there is no intrinsic polarization spectrum which looks significantly different from that for electron scattering. It is concluded that at most 20% of the program binaries have significantly fallacious intrinsic polarizations as a result of improper evaluation of the interstellar components. No Algol object falls in the suspect group.

The present authors have themselves analyzed all data sets referred to herein and have generated the subsequent numerical results themselves. In all cases, these results are similar to all those published hitherto. It must be recognized that older data sets and those with poor phase coverage are used simply because no better information is available.

3. INTRINSIC VARIABILITY

The entries in (double) column 12 of Table I indicate the sporadic, non-phase-locked variability of the intrinsic polarization parameters. For the most part, the entries have been developed from comparison of observations from different seasons and, inevitably, from different stations. Lack of an entry simply indicates that a system has been studied only once.

The clearest evidence concerns 12 post-main sequence binaries: all but 2 of these have shown sporadic variability. For the hot, massive stars it is undoubtedly the stellar winds which generate the variable density, distribution, and geometry of the scatterers. Variability is apparently certain once a binary evolves into the fast-mass-exchange stage. A stellar wind explanation for these is also possible but, more likely, most of the activity is seated in the disk which is characteristic of these objects.

Much the most impressive evidence of sporadic variability comes from Bet Per itself. The binary has been observed at least a few times in each of 11 seasons since the mid-1950's. Typically, the systemic polarization has been small - of the order of 0.01%. Yet Coyne and Wickramasinghe (1969) present very precise measures of 0.22% in late 1966. If there has been no misidentification of the star, this change is (in percentage sense) the largest that has ever been seen for close binaries. It may be noted that a change this large can actually be detected photometrically for it is of the order of 0.002 mag. It should also be remembered that Bet Per has shown easily-detectable changes in its radio polarization. (This will be referred to in more detail in a later section.) Perhaps there may be some relationship between the variabilities at the very different frequencies.

For all binaries the sporadic changes in the orientation of the electric vector reveal no pattern. The change in this parameter for Bet Per is again the largest seen and requires detailed consideration of the phase of the eclipsing pair within the triple system but it is most likely due to an uncommon variation of the mass-transferring process.

4. THE NATURE OF THE SCATTERERS

The entries of (multiple) column 13 of Table I that are based on 2, 3, 4, or more bandpasses can be interpreted as polarization spectra for 9 of the binaries. These may be supplemented by survey data for AH Cep and DH Cep by Coyne (1974). Except for W Ser and AX Mon,the spectra may convincingly be interpreted as arising from electron scattering or from such scattering modified by self-absorption by neutral hydrogen. The case of Bet Per weakly conforms to this conclusion as well in that the unfiltered data are consistent with the B-bandpass measures. Kruszeweski (1972) concluded that dust scattering predominated for W Ser. His data form the basis for the entries in Table I but here they were treated as a whole and not isolated at selected phases. The internal dispersions on the intrinsic polarization means for W Ser are of the order of +/-0.2% so that, even for this star, electron scattering may be considered the dominant polarizing mechanism. Intrinsic variability confuses the situation for AX Mon so it is not possible to assert the identity of its scatterers confidently.

Obviously, data at non-visible wavelengths would be of great value, not only for AX Mon, but also for other systems as well. A few IR measures have been published but no great precision has been claimed for them. At present, it is possible to say only that electrons appear to be the dominant scatterers for binaries in many different evolutionary stages and that more exotic species, such as proposed by Svatoš (1983), appear unnecessary on the basis of polarization data alone. These statements appear to be appropriate for Algols as well.

5. THE "ISOTROPIC" SCATTERING OPTICAL DEPTH

For present illustrative purposes, reference is made to the model of a stationary, scattering envelope co-rotating with the Keplerian motion of a close binary as originally propounded by Brown, McLean, and Emslie. Illustrations of the model's capabilities for a variety of specific circumstances have appeared in a continuing series of papers. Here it is convenient to refer to the algebraic formalisms in Simmons, Aspin, and Brown (1980) even though this particular paper had a very tight focus that is not the formulation of the algorithm. A variety of non-stationary conditions has been treated in Clarke and McGale (1988). The present section is concerned with a product of τ_0, an isotropic scattering optical depth, and of γ, a specific moment of the distribution of scatterers, which product is formulated as $\tau_0(1-3\gamma)$. For each binary studied here this product appears as the final entry in the (triple) column 13 of Table I and has been derived from the intrinsic polarization after division by $(100 \sin^2 i)$.

From one evolutionary stage to another, considerable overlap exists in the values of the isotropic scattering optical depth. It is true, however, that the early-Case B systems show values considerably larger than the classical Algols of late-Case B development. These, in turn, are not distinguishable from u Her and Lam Tau, identified here as products of Case A mass exchange.

It is possible to ask if the polarizing scatterers derive from the stellar winds. For this purpose consider Figure 1 wherein the ordinate scales the mass of the wind in the system. After summation from the contributions by both binary components, the wind mass has been calculated as:

$$\log(M_W) = 25.80 + \log(\dot{M}) + \log(a) - \log(v_\infty), \quad (1)$$

where $\dot{M}$, a, and v_∞ are, respectively, the mass lost per year in units of the solar mass, the semi-major axis in km, and the terminal wind velocity in km/s. For purposes of calculation, the binary components have been assigned the mass loss rates given by de Jager and Nieuwenhuizen (1987) appropriate for their positions in the theoretical HR diagram by de Jager, Nieuwenhuizen, and van der Hucht (1988). Terminal wind velocities have been developed for the assorted binary stars by interpolating among the numerical precepts of Dupree (1981) and Hearn (1987). Errors are assumed to be the same for both massive and

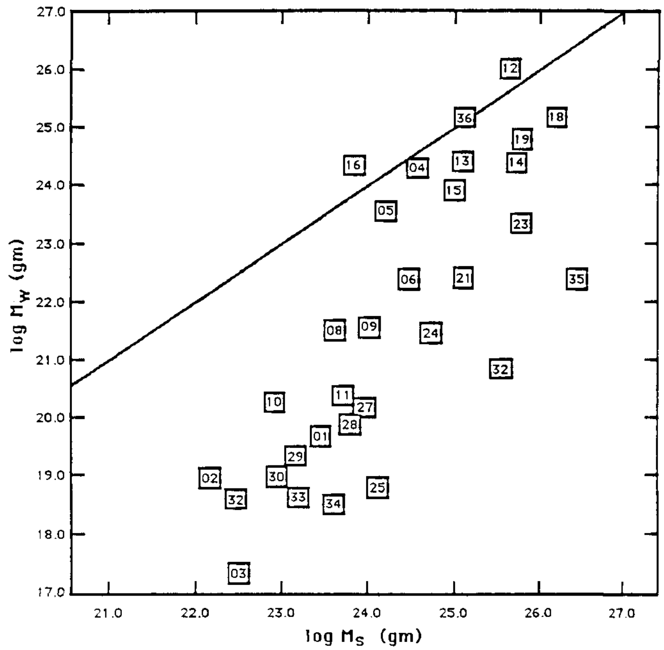

Figure 1. The mass of the wind from (1) as a function of the mass of the scatterers from (2). The binaries are coded as in Table I. For systems such as 02, 03, and 32 errors are very large in this plane.

light winds: +/-500 km/s and +/-0.5, respectively, for terminal velocity and log of mass loss rate. The abscissa in Figure 1 represents the mass due to the systemic scatterers and has been calculated by:

$$\log(M_S) = 26.23 + 2\log(a) + \log(p), \tag{2}$$

where a, and p are, respectively, the semi-major axis in units of 1E7 km (e.g., 1E7 = 10^7), and the intrinsic polarization in percent scale. Complete ionization is assumed. The scattering mass is, in effect, calculated in the manner of Simmons, Aspin, and Brown so as to fill an equatorial binary disk with a radius of 2.5a since this separation is close to the distance from the stars at which terminal wind velocity is reached. Errors are chosen to be +/-0.01% and +/-0.5% for small and large polarizations, respectively.

The case displayed in Figure 1 has an internal inconsistency in that the abscissa refers to a thin equatorial shell while the ordinate is calculated for a spherical shell. The consequence of moving to a more spherical scattering shell can, however, be predicted to result in a larger, right-ward deviation from the 1:1 line in the figure. Further, the consequence of a non-isotropic wind is a deviation from the 1:1 line in the same sense. It may, therefore, be concluded that the stellar winds are only fractional sources of the scatterers in Algol systems and their immediate ancestors of early-Case B binaries and that most of the scattering mass derives from the mass-transferring process itself. (We are indebted to S. Rucinski for the following emphasis. The polarization signals must arise from the outermost layers of the circumstellar material; this is shown by the very small observed optical depths. Consequently, the total mass of the circumstellar material may be larger than calculated here.)

A parenthetical remark may be appropriate. The aforesaid conclusion applied to Algols appears not to be appropriate for hot, massive pairs which are so evolved as to be assigned III through I luminosity classes. For these objects the wind action appears almost sufficient to account for the polarization and it can be made completely so by postulating a prolate distribution of scatterers. There is no independent evidence for such a geometry - obviously reminiscent of a polar jet - but it remains a possibility since the stars are fractionally very large in terms of their orbital radii.

Simmons, Aspin, and Brown consider several geometries for a scattering disk and these have also been investigated in order to see if something additional can be learned. Unfortunately, all cases are under-determined on the basis of polarization data alone: neither the specific distribution of the scatterers nor the dimensions of the disk can be specified uniquely. For very flat disks, electron number densities of the order of 1E11 to 1E13 can easily be calculated for Algol systems. Again, it is possible that these values are lower limits to the true ones.

Despite these limitations, it is possible to predict effects in other types of data which, properly modelled, can lead to a more comprehensive understanding of Algols (and other evolutionary stages as well). Consider the case of RY Per, admittedly an extreme one. No matter whether the scattering environment be large or small with respect to the radius of the hot star, the intrinsic polarization given in Table I shows that about 0.01 mag of predominantly hot photospheric light is scattered toward the terrestrial observer from a non-photospheric distribution of (presumably) electrons. Scale and zero point in the light curve must respond to this bias, so that (approximately) third-order changes must be expected for the values of the stellar figures and possibly the radius of at least one star.

6. PHASE-LOCKED POLARIZATION MODULATIONS

For some systems in Table I the polarization has been shown to vary in a pattern phase-locked to the Keplerian period. Within the model of Brown, McLean, and Emslie this condition is represented to the second order by 4 additional parameters. Two of these, τ_S and τ_A, can represent optical depths of additional scatterers, symmetrically concentrated toward and asymmetrically distributed with respect to the orbital plane, respectively. These same authors emphasize that interpretations other than the obvious ones just described are also possible.

Double columns 14 and 15 list these optical depths after the polarization data have been rotated into the preferential frame of each binary. For systems which lack these entries, observational data are so insufficient that they could not be evaluated. It is clear, first of all, that τ_S is always smaller than τ_O, and this condition is emphatically displayed by Algols. This should be expected, for a 100% modulation of scattering from the systemic disk is very unlikely. Typically also, τ_A is smaller than τ_S for Algols, permitting the straightforward (although not unambiguous) conclusion that the out-of-the-orbital-plane scatterers are less numerous than those within and close to the plane. Some exceptions (even 1 Algol and particularly V Pup) to this condition should be checked with newer, more abundant data because this is a potentially an extremely important detail bearing on the gas flow.

The remaining two parameters, λ_S and λ_A, isolate the localized concentrations in longitude around the binary. For the same systems the entries in columns 13 and 14 show these longitudes, precision for which is various ranging from about +/-10° to +/-45°. Figure 2 shows a

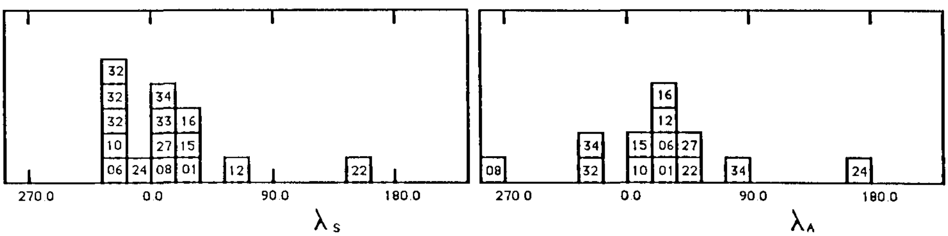

Figure 2. The distributions of the longitudes for the concentrations of scatterers symmetrically (left) and asymmetrically (right) arrayed with respect to the orbital plane.

histogram of their distributions. The most direct interpretation of this information is that the longitudes refer to the mass-transferring streams. Since the stellar radii and orbital radius are known, it is possible to calculate an electron number density within the stream if a cross section is assumed. For purposes of illustration, the cross section has been assumed circular with a radius of $0.05R_h$. For the Algols in the present sample, electron density ranges from 1E9.3 to 1E10.6 and from 1E8.9 to 1E10.3 for the concentrated and asymmetrically-distributed scatterers, respectively. These numbers appear small compared to some published evaluations based on other techniques, which again recalls the possibility that these values may be lower limits to the true ones, but more detailed consideration of the stream dimensions may also be indicated.

It is apparent that the longitudes of the scatterers do not conform to those of the ions in the accretion regions discussed for U CrB by Peters and Polidan (1984) and for U Cep by Plavec (1983). Even though the electron densities calculated here are comparable to those in the accretion regions, the situation in an HTAR close to the hot star does not usually offer a favorable scattering angle for polarimetric detection and the region can itself be eclipsed in whole or in part when the scattering angles are favorable. Perhaps these conditions lead to the higher-than-second-order polarization modulations which have been seen in the best data sets.

7. MISCELLANEOUS

A considerable amount of detailed cm-wavelength circular polarization work on Bet Per itself has culminated in the recent paper by Lestrade, et al. (1988). This has resulted in considerable insight into the magnetospheric activity of the cool star in the binary. Very few visible band circular polarization data exist for binaries. Two measures for Bet Lyr by Serkowski and Chojnacki (1969) and by Kemp, Wolstencroft, and Swedlund (1972) yielded only null results within the errors of measurement. Skul'skii's (1982, 1985) discovery of a 1 kG field in the mass-losing member of Bet Lyr did not lead to renewed observational effort. Since Bet Per is surely more evolved than Bet Lyr, the possibility of a non-zero field for the former system must be entertained. This was sought by Borra and Landstreet (1973), who were able to place only weak upper limits on the circular polarization and field strength for the hot eclipsing star.

Even though a significant circular measure might not be attributable uniquely to a magnetic environment (since scattering itself can convert a linear to a circular signal), it is important to attempt to place meaningful limits on any circular polarization from Algols and objects related to them. For this reason, sporadic observational efforts continue to discover just these effects in visible band data for Bet Lyr and Bet Per.

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DISCUSSION

Eaton asked how the mass-loss rates for Koch's Figure 1 had been determined. Koch replied that for some stars the rates had actually been measured, but for most they had been estimated from the location of the star in the HR diagram, under the assumption that mass was lost by an isotropic wind from each component. The values were therefore uncertain, since some stellar winds are known to be variable. Eaton also asked where the scattering particles were situated. Koch replied that in binaries whose components are just leaving the main-sequence, he believed that the polarization originated in a shell around the system. By the time the stars reach the Algol stage, he thought that some polarization arose from the disk around the star and from the stream. Rucinski emphasized that polarization originates at very low optical depths, which may correspond to the very outermost regions of any structure around the stars or the system. He questioned the large polarization Coyne and Wickramasinghe found for β Per, suspecting that instrumental factors had not been fully allowed for. Koch agreed with the first comment, adding that the total mass of scattering particles and the spatial density may both be larger than deduced on the simplest possible interpretation. He believed that the determination of a polarization of greater than 0.02 per cent in the light from β Per remained significant even with the instrumental component removed. Rucinski also suggested that it was just as important for spectroscopists to pay attention to the results of polarimetry as for polarimetric observers to be aware of spectroscopy, which prompted Andersen to ask what substantial data polarimetry could offer. Rucinski replied that although the observations are difficult to interpret they can provide results of spectroscopy. For example: if polarization is observed in emission lines, they probably originate in the flat portions of the disk rather than from the boundary layer (where light is probably not polarized). Geometrical information such as the ratio of radius to thickness of the disk might be provided. In the light from β Lyr, polarization practically disappears during secondary minimum - setting an upper limit to the size of the disk, which must be fully eclipsed.

Bolton asked about circular polarization in Algols. Since the streams may reasonably be expected to be magnetized, observations of circular polarization might be of interest. Koch's answer is now summarized in section 7 of the foregoing paper.

Budding pointed out that polarization variations are relatively strong in Algols and that the streams in such systems produced asymmetries that were probably significant. He felt that Kemp and Piirola had discovered the same effect in Algol itself, localized in eclipses, but Kemp had interpreted it as the Chandrasekhar effect and Piirola as an effect of the disk. He was concerned that the simplest possible interpretation of the Algol observations implied that the two orbital planes were mutually perpendicular. Koch emphasized that, absolutely, polarization variations in Algol systems were small (of the order of 0.03 per cent in Algol itself). He had given reasons at the Beijing conference for believing these variations in the light of Algol to be caused by the stream and disk, rather than by the limb effect. The phenomenon was similar to that studied by Piirola in the light of U Cep.