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THE MAGNETIC FIELD OF ZETA PUPPIS

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ABSTRACT

We report a null magnetic field measurement for the O4ef star ζ Pup, with $\sigma \approx 100$ gauss. The observations do not eliminate a corotating magnetic wind model for the star because a surface field of over 2 kilogauss could escape detection. However, theoretical arguments do not support the suggestion that Type III P Cygni profiles may result from corotation of the stellar wind. If an expanding envelope is forced into solid body rotation by a global magnetic field, the resultant line profiles are expected to be of Type VI (Be-like) and not Type III.

Subject headings: line profiles — magnetic fields — stars: individual — stars: mass loss — stars: rotation

I. INTRODUCTION

It has been proposed by Mihalas and Conti (1980) that the Type III P Cygni profiles seen in some early-type stars—in which there is extra blueshifted emission visible beyond a blueshifted absorption feature in an emission line—may occur in rapidly rotating stars for which a global magnetic field enforces corotation of the expanding envelope to the extent that the wind rotation velocity exceeds the radial wind velocity in the region where the absorption contribution to the line arises. On the basis of this hypothesis, Mihalas and Conti roughly estimated that a surface field of several hundred gauss would be required to produce the observed Type III Hα profile in ζ Pup.

We present circular polarization observations of ζ Pup which show that the stellar mean longitudinal field (measured as 48 ± 65 gauss in one of our three observations) is probably close to zero. This is certainly much less than the several hundred gauss surface field estimated for the Mihalas and Conti model, but such a model is not necessarily excluded by these observations. One must consider various possible field geometries and their resultant observable field strength; we evaluate three physically acceptable choices of geometry and demonstrate that even kilogauss surface fields may exist in ζ Pup.

The reasoning of Mihalas and Conti (1980) is clarified and expanded by an examination of the dynamics implied in their hypothesis, using results from the Weber and Davis (1967, hereafter WD) theory for the rotating magnetic solar wind. Given the set of assumptions inherent to the WD theory, it is shown that, in fact, the qualitative class of the solid body rotation model proposed by Mihalas and Conti is not the behavior to be expected in a rotating expanding magnetic envelope, inasmuch as the observed Type III profile would not be produced even if solid body rotation out to 2 R_* were to occur in the manner suggested by Mihalas and Conti for ζ Pup. According to the WD theory, a solid body rotation velocity law can occur only if the radial velocity remains very small for most of the distance from the photosphere out to the Alfvén radius.

On the other hand, if it *is* the case that for certain stars a magnetic field causes near solid body rotation in the wind, the observed profile would be of Beals's (1951) Type VI—more or less symmetric, centrally placed emission with a pronounced central reversal, *exactly* like the typical emission profile seen at Hα in many Be stars. Thus the mechanism proposed by Mihalas and Conti may actually be dominant in the Be star winds but not in the Oef star winds—a suggestion supported by the model calculations of Barker (1979) and the magnetic field upper bounds estimated by Nerney (1980) for Be stars, both of whom found that exceedingly weak global fields are capable of producing major effects in winds of low mass loss rate.

II. OBSERVATIONS AND IMPLICATIONS

Zeta Puppis was observed for magnetic fields with the 2.6 m (C100) and 1.0 m (C40) telescopes at Las Campanas in 1980 March and April. The University of Western Ontario photoelectric Pockels cell polarimeter was used to measure the circular polarization in the wings of Hβ produced by the longitudinal Zeeman effect, with the red and blue wings alternately isolated by tilt-scanning a 5 Å FWHM interference filter. The general technique is discussed by Landstreet (1980), while the performance of the instrument is considered by Borra and Landstreet (1980). For the very broad and shallow Hβ profile of ζ Pup, we derive a conversion factor of 28,200

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TABLE 1

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JD 2,444,300+	B_e (gauss)	σ (gauss)
27.83	−110	138
48.62	−71	113
50.58	+48	65

gauss per percent used to transform measured circular polarization to magnetic field strength.

Our results are presented in Table 1. The quantity extracted from the observations is the effective (or mean longitudinal) field B_e, which is the surface brightness weighted average, over the visible hemisphere, of the signed field component along the line of sight. In Table 1, the quoted error for B_e represents a single standard deviation calculated from the photon-counting statistics. However, some additional error sources may exist. The effective temperature of ζ Pup is so high that He II λ4859 will be present in the spectrum and will distort the Hβ profile, which may also be partially filled by emission. Certainly there is appreciable variation in the Hβ equivalent widths reported in the literature: 1.26 Å was measured by Baschek and Scholz (1971); 1.78 Å by Conti (1973); and 1.62 Å by Conti and Frost (1977). We estimate the concomitant additional error in the Table 1 values of B_e to be equivalent to an uncertainty in the correct conversion factor of the order of 20%. This adds little further uncertainty to the data quoted in Table 1.

In interpreting these results one must consider the sampling nature of the observations. The rotation period of ζ Pup is of the order of 5 days (Lamers and Morton 1976; references therein), so our last two observations are separated by about 0.4 in phase, but four rotation cycles after the first observation. The radius, projected rotation velocity $v \sin i$, and inclination i of the rotation axis to the line of sight are not known well enough to phase sensibly the first observation relative to the second two. Therefore, we cannot exclude the possibility that ζ Pup may present a much larger B_e at some rotational phase not yet observed; however, at the 3 σ confidence level Table 1 does show that on our line of sight the azimuthally symmetric portion of any mean longitudinal field in ζ Pup must be bounded by the limits −150 gauss and +250 gauss.

Next, in order to set limits on any true stellar surface field, it is necessary to consider the geometrical form of the stellar field and the relative orientation of rotation axis, magnetic axis, and line of sight to the observer. Three specific examples are depicted in Figure 1, and for convenience the results of Table 1 are condensed to state that *no* effective field was detected in three separate observations with $\sigma \approx 100$ gauss. Taken at face value, these results suggest that the true effective field of ζ Pup is probably zero. The purpose here is to demonstrate that quite large surface fields may exist if the combination of field geometry and stellar orientation is unfavorable to the observer. In this regard we note that the $v \sin i$ of 210 km s^{-1} (Conti and Ebbets 1977) is sufficiently high that ζ Pup is probably seen quite close to equator-on, and for simplicity we adopt this observer aspect in the following illustrative discussion.

Dipole ($\beta \approx 0°$).—Figure 1*a* shows a centered dipole field with the dipole axis parallel to the rotation axis ($\beta = 0°$) observed along the rotational equatorial plane ($i = 90°$). Fields with small values of $\beta(\lesssim 30°$, say) are certainly found among the known magnetic stars (Borra and Landstreet 1980), although not commonly. The expressions derived by Schwarzschild (1950) show that in this case the observed $B_e = 0$ and is independent of the

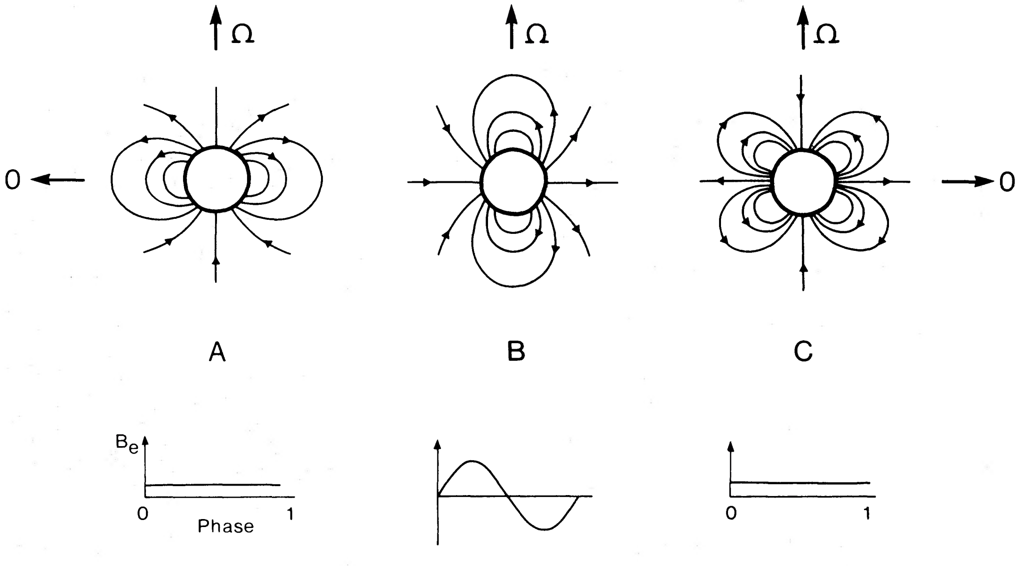

FIG. 1.—Three possible magnetic field geometries for a star with angular velocity Ω, and the mean longitudinal field B_e measured during a rotation period by an observer whose line of sight lies nearly in the equatorial plane 00. (*a*) Centered dipole with rotation and magnetic axes parallel. (*b*) Centered dipole with rotation and magnetic axes orthogonal. (*c*) Linear quadrupole with an axisymmetric purely radial field in the equatorial plane.

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surface field strength B_p at the pole. For this geometry the observations offer little constraint; for example, if actually $\beta = 0°$ and $i = 70°$, one could still have $B_p \approx 1$ kilogauss without contradicting $B_e \lesssim 100$ gauss. The relation between B_e and B_p for a dipole is not very sensitive to the limb darkening coefficient, and we have used a value of 0.5 throughout.

In this class of model for a magnetic stellar wind, one expects circumstellar material to flow out freely along open field lines near the magnetic poles. If the field is strong enough or the mass loss rate is low enough, material will be trapped or impeded around the equator and perhaps also funneled toward the equatorial plane from mid-latitudes. This is not the mechanism proposed by Mihalas and Conti (1980). In the absence of any line radiation force, this class of model reduces to the centrifugal wind of Mestel (1968).

If the mass loss rate is high enough or the field weak enough, the trapped equatorial magnetosphere may not exist and all the dipole field lines will be open. Even assuming azimuthal symmetry, any theory to describe this situation (with or without a trapped magnetosphere) must necessarily be at least two-dimensional, in the meridional planes.

Dipole ($\beta \approx 90°$).—Figure 1*b* shows a centered dipole with the axis in the rotational equatorial plane; this is common among the known magnetic stars. For this geometry the observed B_e will vary sinusoidally on the rotation period. In the orientation most favorable for field detection, with a magnetic pole at the subsolar point, the observed $B_e \lesssim 100$ gauss implies $B_p \lesssim 300$ gauss. Because of the incomplete phase coverage, our observations alone do not completely exclude this possible model for any field in ζ Pup. However, for a symmetrical B_e wave and $B_p = 1000$ gauss (with $i = \beta = 90°$), our chances of observing $B_e < 150$ gauss three times in a row are less than 4%, if we consider our result as simple sampling. Further, any undetected strong field with this geometry would result in magnetic trapping of circumstellar material near the magnetic equator together with a mass losing wind arising from the magnetic poles. Thus, pronounced rotational modulation of the circumstellar matter would be observed; this is seen in σ Ori E, HD 37017, and HD 37776 (Shore, Adelman, and Rappaport 1980), all of which are in fact oblique magnetic rotators with winds. Very rapid variability (with no evident periodicity) has been observed by Snow, Wegner, and Kunasz (1980), whereas Moffat and Michaud (1981) report periodic variations in the depth of the Hα absorption component on a period of 5.075 days. This weak periodic line profile modulation, if rotational in origin, may be interpreted as evidence for a stellar magnetic field; polarization observations giving complete phase coverage with high accuracy are required to settle this issue. Any complete theoretical description of this class of geometry must necessarily be three-dimensional.

Quadrupole.—Figure 1*c* shows a linear quadrupole oriented so that $\beta = 0°$, again observed along the equatorial plane. The cancellation of field line contributions to B_e over the visible hemisphere is such that our measured limit $B_e \lesssim 100$ gauss implies only $B_p \lesssim$ 2–4 kilogauss for this geometry. Notice from Schwarzschild (1950) that this result is very sensitive to the limb darkening law, and also that $B_e = 0$ independent of B_p when $\beta \approx 35°$ (for $i = 90°$). For some of the known magnetic stars, observations of unequal pole strengths may be modeled by a centered dipole plus a parallel linear quadrupole (Landstreet 1980). However, no stars with predominantly quadrupolar fields are known among the chemically peculiar magnetic stars, so it is not clear how plausible a pure quadrupole model of ζ Pup might be. This geometry requires a theory at least two-dimensional in the meridional planes.

Finally, just to explore a radically different topology, we draw attention to the potential for toroidal field detection in rapidly rotating stars. Consider a toroidal field wrapped around the star, all in one sense, going smoothly to zero at the poles. Normally an azimuthally symmetric toroid produces zero net contribution to the effective field of a star, but such a field is detectable in a rotating star, because rapid rotation has the effect of breaking the cancellation of Zeeman polarization profiles which arise from opposite (approaching and receding) portions of the visible stellar disk. The effect is illustrated in Figure 2. For ζ Pup we observed only in the wings of

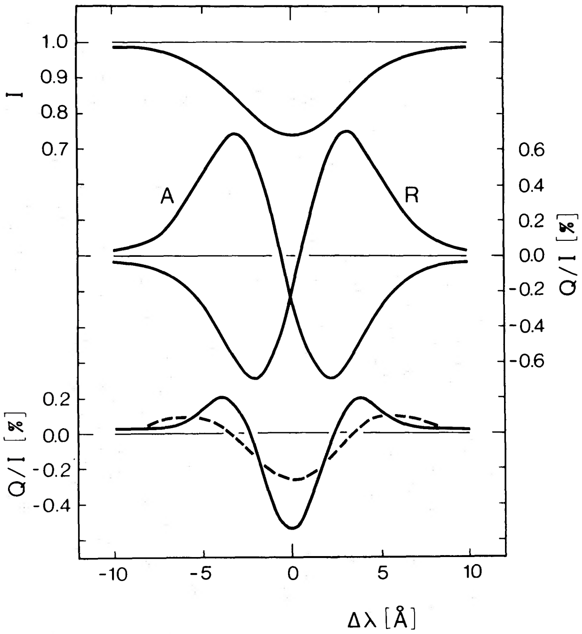

FIG. 2.—In the upper part of the figure we show a theoretical rotationally broadened Hβ profile appropriate to ζ Pup ($T_{\rm eff} = 50{,}000$ K, $\log g = 4.0$, $v \sin i = 210$ km s^{-1}; non-LTE unbroadened profile from Mihalas 1972). This profile is almost unchanged when viewed at 5 Å resolution. The middle figure shows (schematically only) the Zeeman polarization profiles from the approaching (A) and receding (R) half-hemispheres for a toroidal field of field strength of 10^4 gauss at the equator. Because the Zeeman polarization profile A is Doppler shifted to shorter wavelengths while that of R is shifted to longer wavelengths, when the two are added they do not cancel. The resulting polarization profile as calculated for the toroidal field of strength of 10^4 gauss at the equator is shown at the bottom, as observed at high resolution (*solid curve*) and through 5 Å filters (*dashed*).

Hβ, not at line center where a toroidal field is most sensitively detected by this effect, and unfortunately observations were made about 3.7 Å from line center (to maximize the sensitivity to longitudinal fields) just where the polarization profile of Figure 2, as seen through our 5 Å interference filters, is crossing zero. Thus our observations offer essentially no constraint on such a field. However, measurement of the line center with $\sigma \approx 0.003\%$ (as in our best longitudinal field measurement) would have measured such a toroidal field with an effective σ of about 100 gauss; an equally accurate measurement in the line wings about 6 Å from line center would have yielded $\sigma \approx 300$ gauss. Thus toroidal fields of the type discussed here may certainly be detected with appropriate measurements.

III. ROTATING MAGNETIC WINDS

To facilitate the following discussion, we first restate the central thesis of Mihalas and Conti (1980) concerning their postulated wind-field interaction in ζ Pup. It was suggested that a global magnetic field could enforce corotation of the expanding stellar wind, thereby producing the observed Type III Hα profile. To quantify this model, Mihalas and Conti considered the relative energy densities in the wind of the fluid flow and the magnetic field, as expressed in their analysis by the Alfvén Mach number

$$M_{\mathrm{A}}{}^2 = (\tfrac{1}{2}\rho v_r{}^2)/(B^2/8\pi) = (\mathscr{M} v_{\mathrm{A}}/r_{\mathrm{A}}{}^2 B^2)\,, \qquad (1)$$

where ρ is the fluid density, v_r is the radial flow velocity, v_{A} is the value of v_r at the Alfvén radius r_{A} where $M_{\mathrm{A}}{}^2 = 1$, $\mathscr{M}$ is the mass loss rate, and B is the magnetic field strength at r_{A} (but the direction of B is unspecified). Mihalas and Conti argued that at radii where $M_{\mathrm{A}}{}^2 < 1$ the field constrains the fluid motion to effectively enforce solid body rotation, whereas at larger radii where $M_{\mathrm{A}}{}^2 > 1$ the wind reverts to radial expansion. By adopting the $v \sin i$ of 210 km s^{-1} as the true photospheric rotation velocity, Mihalas and Conti deduced that solid body rotation out to $r_{\mathrm{A}} \approx 2.1\ R$, where R is the photospheric radius, would give the maximum wind rotation velocity of 450 km s^{-1} desired to form the observed Hα profile in ζ Pup (Ebbets 1980). Plausible choices of $\mathscr{M}$ and v_{A} in equation (1) then gave Mihalas and Conti an estimate of 70 gauss for the field strength at r_{A}. Note that in their estimate of B at r_{A}, Mihalas and Conti explicitly used *only* the Hα profile observed by Ebbets (1980) and *not* the He II λ4686 profile, as misquoted by Nerney (1980).

On the basis of this analysis one could thus expect a stellar surface field of a few hundred gauss. As previously discussed, a field of this magnitude is quite possible in ζ Pup, depending on the field-observer geometry, even given our observation of $B_e \approx 48 \pm 65$ gauss on one occasion. We now clarify the arguments of Mihalas and Conti by considering explicitly the field geometry and the nature of the field-wind interaction and discuss the consequences of that interaction.

Suppose we restrict attention to the equatorial plane of a steady-state spherically symmetric rotating stellar wind of infinite electrical conductivity and zero viscosity. Following the WD analysis, suppose further that all the field lines are combed out by the stellar wind and thus are open, with no component B_θ normal to the equatorial plane $\theta = \pi/2$. Then a one-dimensional magnetic wind model may be constructed. Strictly, the only field geometry describable with this kind of model is that of a magnetic monopole at the center of the star, although we may use the WD theory as a reasonable first approximation to analyze equatorial wind flow for both the linear quadrupole (Figure 1*c*) and the parallel dipole (Fig. 1*a*—but with no trapped magnetosphere). Suess and Nerney (1973) have shown that (even for a monopole field and slow stellar rotation) the WD modification of the radial momentum equation is inconsistent with the neglect of meridional flow, but that the WD analysis of the azimuthal momentum equation *is* valid. In the following we use only the azimuthal momentum equation.

Then, from Maxwell's equations and the azimuthal momentum equation one may derive

$$v_\phi(r) = \Omega r(1+f)\left[\frac{1 - v_r/v_{\mathrm{A}}}{1 - (v_r r^2/v_{\mathrm{A}} r_{\mathrm{A}}{}^2)}\right], \qquad (2)$$

where the new symbols are the azimuthal velocity v_ϕ and the angular velocity Ω of the stellar photosphere, and $(1+f)$ is the correction to the WD theory which takes into account the nonzero mass loss of the wind. Barker and Marlborough (1981) have shown that here

$$f = \left.\frac{v_r|B_\phi|}{v_\phi B_r}\right|_R = \left.\frac{M_{\mathrm{A}r}}{M_{\mathrm{A}\phi}}\right|_R, \qquad (3)$$

where the radial Alfvén Mach number $M_{\mathrm{A}r}$ is given by

$$M_{\mathrm{A}r}{}^2 = \frac{\tfrac{1}{2}\rho v_r{}^2}{B_r{}^2/8\pi} = \frac{v_r r^2}{v_{\mathrm{A}} r_{\mathrm{A}}{}^2}, \qquad (4)$$

and the azimuthal Alfvén Mach number is $M_{A\phi}{}^2 = (\tfrac{1}{2}\rho v_\phi{}^2)/(B_\phi{}^2/8\pi)$. Compare equation (4) especially with the corresponding definition in Mihalas and Conti, and notice that the present version takes explicit account of the field and flow directions. Equation (2) thus gives a relation between the azimuthal and radial velocities in the equatorial plane of a rotating magnetic wind. The derivation of this relation does not depend on the form of the radial momentum equation; therefore the relation between v_ϕ and v_r is independent of whether the wind is primarily line radiation driven, or purely magnetically driven, or driven by any combination of mechanisms. Without loss of generality in the present discussion, we may consider $f \approx 0$ (see Barker and Marlborough 1981). Inspection of equation (2) shows that for $v_\phi(r) \approx \Omega r$ from the photosphere out to a radius $r_0 < r_{\mathrm{A}}$, it must be true that $v_r \ll v_{\mathrm{A}}$ throughout $R < r < r_0$. This is shown in Figure 3*a* where, for comparison with Mihalas and Conti, we have adopted $v_\phi(R) = 210$ km s^{-1}, $r_{\mathrm{A}} = 2\ R$, and $v_{\mathrm{A}} = 1000$ km s^{-1} as parameters appropriate for the wind of ζ Pup. The figure shows $v_\phi(r)$ calculated *via* equation (2) from an assumed $v_r(r)$ which is of the form required for the azimuthal velocity to tend toward a solid body rotation law. It is very clear that even

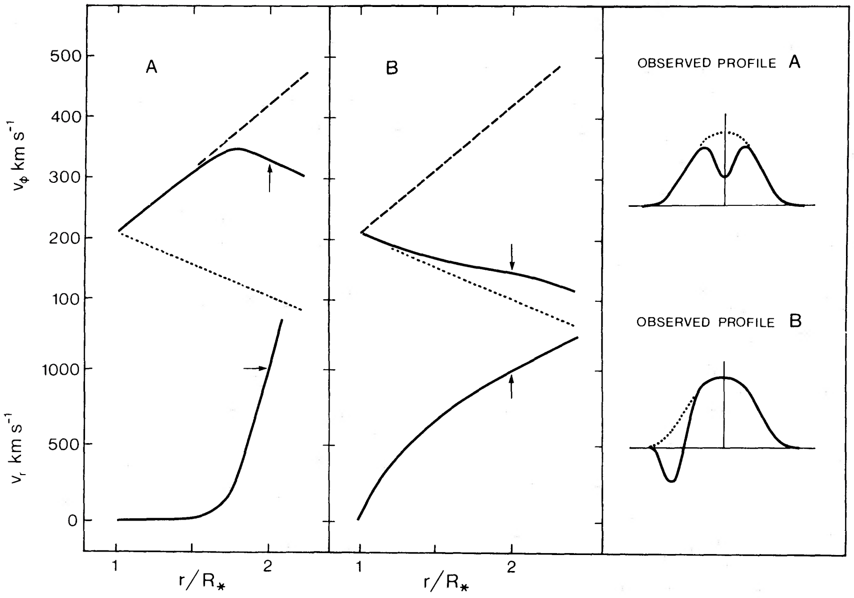

FIG. 3.—Schematic representation of the relation between radial expansion velocity v_r and azimuthal velocity v_ϕ in the equatorial plane of a rotating magnetic stellar wind, with photospheric parameters for ζ Pup discussed in the text. Case A: The solid line shows calculated $v_\phi(r)$ resulting from an assumed $v_r(r)$ of the form required to induce solid body rotation. Case B: $v_\phi(r)$ resulting from Abbott's soft velocity law for $v_r(r)$. In panels A and B the dashed line shows $v_\phi(r)$ for solid body rotation, the dotted line shows $v_\phi(r)$ for material angular momentum conservation, and arrows mark the Alfvén radius 2 R_*. The third panel shows the qualitative kind of line profile observable in cases A and B.

with v_A as large as 1000 km s^{-1}, v_r must be essentially zero in the region inside r_0, and that as soon as v_r departs even slightly from zero, $v_\phi(r)$ immediately turns over, thereby losing all tendency to solid body rotation.

Therefore under the conditions of this model, if we accept the Mihalas and Conti postulate that a magnetic field in ζ Pup enforces solid body rotation in the wind out to $\sim 2\ R$, it is necessary that $v_r \approx 0$ out to 2 R. The observed profile must then have a pronounced *central* reversal as shown qualitatively in Figure 3 and will not be of Type III, as proposed by Mihalas and Conti.

The theoretical wind velocity law with the most shallow radial velocity gradient is that of Abbott (1977). Figure 3*b* shows v_ϕ resulting from Abbott's law for v_r, again adjusted so that $v_A = 1000$ km s^{-1} at $r = 2\ R$. The azimuthal velocity is increased only marginally over the $1/r$ dependence of a nonmagnetic wind; hence the expected qualitative profile in this case reverts to the usual Type I typical of a purely expanding wind.

Thus we conclude that the characteristic signature of near perfect corotation in a magnetic wind is the presence of a very small radial velocity gradient throughout the region where solid body rotation occurs; the shallow velocity gradient is manifested as a Type VI P Cygni profile.

These arguments also show that one should exercise caution in interpreting the solar wind paraphrase (e.g., Brandt 1970) that the total angular momentum in the wind may be calculated *as if* there is solid body rotation out to $r = r_A$. This statement does *not* mean that $v_\phi(r) = \Omega r$ for all $r < r_A$, because angular momentum is carried in the wind by magnetic stresses as well as by fluid motions. In fact, for winds with $v_r(R) \neq 0$, this solar wind result (total angular momentum $L = \Omega r_A{}^2$) is only approximately correct (Barker and Marlborough 1981). It is important to realize that *corotation* of plasma in an expanding rotating wind means only that the fluid particles trace out the spiral magnetic field lines; that is, there exists a rotating frame in which $\boldsymbol{v}$ and $\boldsymbol{B}$ are everywhere parallel (Barnes 1974). Corotation does not of itself imply *solid body* rotation. Even for the solar wind, $v_\phi(r)$ has a maximum at $r \approx \frac{1}{2}r_A$ (WD) because $v_r \ll v_A$ only for $r \lesssim \frac{1}{2}r_A$.

Numerous sources of evidence suggest that the very early-type stars in general have large radial velocity gradients quite close to the stellar photosphere. Our arguments suggest then that the rotation velocity in these stellar winds is not likely to be significantly affected by any global magnetic field. The empirical model for ζ Pup in particular (Lamers and Morton 1976) shows that v_r already exceeds 600 km s^{-1} at $\sim 1.6\ R$, while the velocity field derived by Hamann (1980) from UV line profile fitting rises even more steeply. Lamers and Morton did not however derive any $v_r(r)$ for $r < 1.6\ R$.

On the other hand, many Be and Oe stars have exactly the kind of Type VI profile shown in Figure 3, especially at Hα. This indicates that if there are any early-type stars with magnetically dominated winds (other than the σ Ori E type), they will be found among the Be and Oe stars, not the Oef stars. This suggestion is supported by several prior investigations. For example, it is significant that ad hoc models of Be envelopes (Poeckert and Marlborough 1978) require an extremely shallow radial velocity gradient for many stellar radii away from the photosphere in order to match the observed profiles. In this case, equation (2) means that if the central star does have any global magnetic field there could be substantial modification of v_ϕ in the circumstellar envelope. A search has been made for magnetic fields in 10 Be stars (Landstreet, Marlborough, and Thompson, in preparation); no fields were detected, but the observations typically have standard deviations of 100–200 gauss. Therefore this remains a promising approach to the Be stars; hydrodynamical models of line radiation driven rotating magnetic winds (Barker 1979) show that for Be-like mass loss rates, surface fields of tens of gauss are sufficient to substantially modify the wind flow. Such fields are well below the current observational limits. Nerney (1980) found that winds of very low mass loss rate could be effectively driven entirely by magnetic fields on the order of 10 gauss in very rapidly rotating stars.

Our treatment is strictly kinematic; we are arguing that *if* $v_r(r)$ rises very steeply from the photosphere, then we do not expect any significant modification of $v_\phi(r)$ due to the magnetic effects in the wind (and conversely, if v_r has a very shallow gradient). We do not yet know what processes may determine $v_r(r)$ in a real three-dimensional magnetic wind. The best evidence so far (Barker 1979) is that it is the form of the line radiation force which determines the gross properties of v_r; the magnetically induced modification of $v_\phi(r)$ (greater for winds with a shallow radial velocity gradient) in turn modifies v_r but does not have the radical effect of transforming a steeply accelerating wind into a very shallow wind. No attempt has yet been made to consider the magnetic effect on the microscopic interactions which drive the wind.

In conclusion, we must note the obvious highly restrictive nature of the assumptions leading to equation (2). The behavior of a naturally occurring rotating magnetic stellar wind might well be such that its characteristic signature is indeed the Type III profile, not the Type VI. On the other hand, the Weber and Davis theory remains the only available theory, and we cannot resist the temptation to use it. In the case of ζ Pup, the most serious conflict with our discussion may arise from the definite absence of a steady-state wind (Conti and Niemela 1976; Snow, Wegner, and Kunasz 1980). Even if the large-scale properties of a magnetic wind are contained in equation (2), the well-established complex ionization structure of early-type winds could work to modify the observed profile. Mihalas and Conti also point out other possible mechanisms not requiring a magnetic field whereby a Type III profile may be generated. We add one more to their list by noting that Poeckert and Marlborough (1978) showed that the Balmer line profiles formed in an expanding rotating envelope are particularly sensitive to inclination effects. Their Figure 3, for instance, depicts the way in which an ordinary, material, angular momentum-conservation rotation law can result in an observed Type III profile.

IV. SUMMARY

Circular polarization observations show that the mean longitudinal magnetic field of ζ Pup is probably close to zero. This does not necessarily invalidate the suggestion that circumstellar envelope structure may be substantially modified by enforced solid body rotation in a magnetic wind, because the true surface field of ζ Pup may exceed 2 kilogauss, depending on the magnetic geometry and observer aspect.

Application of the Weber and Davis theory for a rotating magnetic wind demonstrates that the relation between azimuthal and expansion velocities (regardless of the wind driving mechanism) requires an almost zero radial velocity gradient throughout the region of solid body rotation. Thus the characteristic profile observed from such a wind must be of Type VI (not Type III), and it is therefore suggested that the Be and Oe stars may have magnetically dominated envelopes.

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REFERENCES

Abbott, D. C. 1977, Ph.D. thesis, University of Colorado.
Barker, P. K. 1979, Ph.D. thesis, University of Colorado.
Barker, P. K., and Marlborough, J. M. 1981, *Ap. J.*, submitted.
Barnes, A. 1974, *Ap. J.*, **188**, 645.
Baschek, B., and Scholz, M. 1971, *Astr. Ap.*, **15**, 285.
Beals, C. S. 1951, *Pub. Dominion Ap. Obs.*, **9**, 1.
Borra, E. F., and Landstreet, J. D. 1980, *Ap. J. Suppl.*, **42**, 421.
Brandt, J. C. 1970, *Introduction to the Solar Wind* (San Francisco: Freeman).
Conti, P. S. 1973, *Ap. J.*, **179**, 161.
Conti, P. S., and Ebbets, D. 1977, *Ap. J.*, **213**, 438.
Conti, P. S., and Frost, S. A. 1977, *Ap. J.*, **212**, 728.
Conti, P. S., and Niemela, V. S. 1976, *Ap. J.* (*Letters*), **209**, L37.
Ebbets, D. 1980, *Ap. J.*, **236**, 835.
Hamann, W.-R. 1980, *Astr. Ap.*, **84**, 342.
Lamers, H. J. G. L. M., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 715.
Landstreet, J. D. 1980, *A.J.*, **85**, 611.
Mestel, L. 1968, *M.N.R.A.S.*, **138**, 359.
Mihalas, D. 1972, National Center for Atmospheric Research Technical Note NCAR-TN/STR-76.
Mihalas, D., and Conti, P. S. 1980, *Ap. J.*, **235**, 515.
Moffat, A. F. J., and Michaud, G. 1981, *Ap. J.*, **251**, in press.
Nerney, S. 1980, *Ap. J.*, **242**, 723.
Poeckert, R., and Marlborough, J. M. 1978, *Ap. J. Suppl.*, **38**, 229.
Schwarzschild, M. 1950, *Ap. J.*, **112**, 222.
Shore, S. N., Adelman, S. J., and Rappaport, B. 1980, paper presented at the Midwest Astronomers Meeting, Warner and Swasey Observatory, E. Cleveland, Ohio.
Snow, T. P., Wegner, G. A., and Kunasz, P. B. 1980, *Ap. J.*, **238**, 643.
Suess, S. T., and Nerney, S. F. 1973, *Ap. J.*, **184**, 17.
Weber, E. J., and Davis, L. 1967, *Ap. J.*, **148**, 217 (WD).

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