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ZETA PUPPIS: AN O-TYPE OBLIQUE ROTATOR?

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ABSTRACT

Extensive spectrophotometric observations of the P Cygni type Hα profile from the O4ef star, ζ Puppis, show periodic variability in the depth of the nearly central absorption reversal. The 5.075 day period derived implies that the Hα-forming part of the stellar wind corotates with the photosphere, for which $2\pi R/(v \sin i) \approx 4.8$ days.

The periodic variations can most simply be explained by a rotating magnetic multipole, as observed in Ap stars. This suggestion could be tested by further high resolution measurements of radial velocity or polarization variations of the absorbing matter.

Subject headings: stars: emission-line — stars: individual — stars: magnetic — stars: rotation

I. INTRODUCTION

Zeta Puppis = HD 66811 is the brightest *O* star in the sky (1950: $\alpha = 8^h01^m.8$, $\delta = -39°52'$). It is classified O4ef by Conti and Leep (1974) because of the Of type emission lines and the Be type, nearly central absorption reversals in some subordinate emissions (Beals type III P Cygni profiles). Such stars tend to be fast rotators (Conti and Ebbets 1977). The moderately high mass loss rate is consistently found to be $7 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ from studies in the radio through the UV (cf. Barlow and Cohen 1977; Lamers and Morton 1976); this consistency makes ζ Puppis a kind of standard mass loser. More recently, however, Abbott *et al.* (1980) obtained $3.5 \times 10^{-6} \pm 50\%\ M_\odot\ \mathrm{yr}^{-1}$ from radio continuum VLA observations.

Zeta Puppis is probably not a binary system, at least with semiamplitude $K > 15$ km s^{-1}, since the radial velocities of the absorption lines remain essentially constant (Garmany, Conti, and Massey 1980). However, variability in the line profiles *has* been observed (Brucato 1971; Conti and Frost 1974, 1977; Conti and Niemela 1976; Snow 1977; York *et al.* 1977; Wegner and Snow 1978) but never based on sufficient quantity or precision of data to be sure about the possible presence of a periodicity, which would be extremely interesting in the context of rotation, duplicity, or other cyclic phenomena.

Mihalas and Conti (1980, hereafter MC), recently proposed a model to explain the Beals type III P Cygni emission line profiles by magnetically forced rotation, causing at least the inner parts of the envelope to corotate with the photosphere out to the Alfvén radius, where the magnetic field energy density ceases to dominate the stellar wind energy density. This would imply a rotation period $P = 2\pi R/w_{\mathrm{rot}} \simeq 4.8$ days, adopting the interferometrically observed photospheric radius $R = 20\ R_\odot$ (Hanbury Brown, Davis, and Allen 1974*a*, *b*), rotation of the stellar surface $w_{\mathrm{rot}} = 208/\sin i$ km s^{-1} from photospheric absorption lines (Conti and Ebbets 1977) and inclination of the rotation axis not too different from 90°, since ζ Pup is already a rapid rotator for its spectral type (Conti and Ebbets 1977). However, the interferometric radius may be an overestimate, referring to an extended electron scattering shell rather than the photosphere (Holm and Cassinelli 1977). If $R = 16R_\odot$ as implied by stellar models with $T_{\mathrm{eff}} = 50{,}000$ K and log g (cgs) = 4.0 (Baschek and Scholz 1971; Snijders and Underhill 1975), the above estimate for P will be correspondingly reduced. In any case, we suppose the above estimated corotation period may be in error by as much as 20% from one source or another.

In this paper, moderate resolution photoelectric scanner observations are reported for the Hα profile of ζ Pup, obtained during two epochs separated by about a year. They lend support to the MC speculation. Implications for the presence of a magnetic field are discussed. Other models for the Beals type III profiles in ζ Pup (cf. MC) are more difficult to reconcile with the present observations.

II. OBSERVATIONS

First-order spectral scans with a resolution of 2 Å per channel were obtained in the range λλ 6490–6630 by A. F. J. M. during ten nights spread over a 28 day interval in 1975, and by M. Buchholz during 24 nights over a 38 day interval in 1976. The photoelectric scanner is described by Haupt *et al.* (1976); it was mounted on the 61 cm telescope operated by the Ruhr Universität on La Silla, Chile. At 3 counts s^{-1}, the dark current plus sky background was small compared to the stellar signal which was always at least 2000 counts s^{-1} per channel. With a total time spent on the star of 10–30 minutes for each observation, the time per channel was 9–26 seconds, after adding forward and back scans.

Inspection of the scans revealed that the profiles remained virtually constant from one night to the next and even between the two years, except for one obvious feature: the depth (and, to a lesser degree, the width) of the nearly central absorption reversal of Hα. This is illustrated in Figure 1, which shows two of the 1975 scans

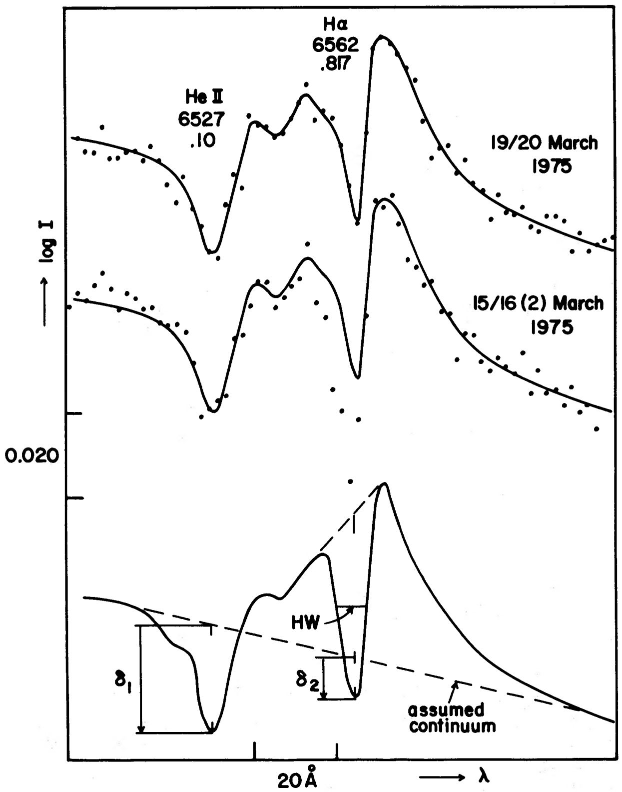

FIG. 1.—Photoelectric scans around Hα with resolution 2 Å. The two upper scans show the original data on two different nights; a hand-drawn curve is fitted through the upper data and forced through the second set of data. The lower curve is a smoothed mean of all 1975 spectra, showing how the three parameters were measured on each individual scan. The dip half-way between the He II and Hα absorption is probably caused by a crowding of unresolved atmospheric H_2O lines.

together. Note the extension of the red emission wing out to ~ 2400 km s^{-1} from the line center, much like the terminal wind velocity of ~ 2600 km s^{-1} (Lamers and Morton 1976) but further than the limit given by Ebbets (1980) for Hα. The simplest and most objective way to analyze these changes quantitatively is to measure the depth, δ_2, and the half-width, HW, of the absorption relative to some well defined level (cf. Fig. 1). These values are listed in Table 1 along with the depth, δ_1, of the photospheric absorption line of He II 6527 Å, for comparison. The approximate wavelength zero point can be obtained from the (constant) position of the 6527 Å He line. Measurements of the equivalent width (E.W.) require judgment or modeling of the "missing" emission contribution and are not derived here.

Strong evidence for the presence of intrinsic variations in δ_2 is revealed in Table 2. While the mean of δ_2 remained constant from 1975 to 1976, its standard deviation retained a highly significant level of $\gtrsim 3$ times the standard deviation (s.d.) of δ_1 in 1975 to $\gtrsim 2$ times in 1976. By comparison, δ_1 did not change from 1975 to 1976 (difference of the means: 0.003 ± 0.003 mag, standard error of the mean—s.e.m.) and its standard deviation corresponds

TABLE 1

JOURNAL OF OBSERVATIONS AND LINE PARAMETERS

Julian Date 2,442,000	Phase[a]	δ_1 (mag)	δ_2 (mag)	HW (km s^{-1})
1975 March 15–16 to 1975 April 12–13				
487.560..........	0.952	0.052:	+0.057	300
487.571..........	0.954	0.057	+0.070	270
491.679..........	0.763	0.054	+0.015	200
493.597..........	0.141	0.059	+0.050	220
496.579..........	0.729	0.054	+0.011	220
498.565..........	0.120	0.061	+0.057	210
501.588..........	0.716	0.057	+0.004	180
504.553..........	0.300	0.069	+0.002	170
506.715..........	0.726	0.074	+0.031	210
512.553..........	0.876	0.070	+0.035	200
515.551..........	0.467	0.074	−0.004	200
1976 April 29–30 to 1976 June 6–7				
898.522..........	0.929	0.065	+0.026	220
899.525..........	0.127	0.069	+0.061	180
900.468..........	0.313	0.052	+0.017	280
901.501..........	0.516	0.063	+0.030	240
902.485..........	0.710	0.057	+0.035	170
906.499..........	0.501	0.052	+0.043	200
908.526..........	0.901	0.067	+0.067	220
909.499..........	0.092	0.061	+0.033	180
910.471..........	0.284	0.048	+0.017	240
911.468..........	0.480	0.059	+0.002	210
912.485..........	0.681	0.057	+0.007	220
913.506..........	0.882	0.067	+0.033	170
914.485..........	0.075	0.078	+0.035	260
916.465..........	0.465	0.052	+0.028	200
918.481..........	0.862	0.050	+0.059	200
919.470..........	0.057	0.056	+0.046	140
923.459..........	0.843	0.056	+0.022	190
927.525..........	0.644	0.081	+0.013	210
928.476..........	0.832	0.056	+0.037	220
929.472..........	0.028	0.061	+0.067	280
930.473..........	0.225	0.052	+0.043	260
931.462..........	0.420	0.052	+0.006	210
934.458..........	0.010	0.057	+0.015	200
936.499..........	0.413	0.044	+0.011	260

[a] Epoch 2,442,503.03 ± 0.10; $P = 5.075 \pm 0.003$ days.

exactly to the extrinsic noise according to Poisson statistics for 20,000 counts per channel, which is close to the observed number of counts. The constancy of δ_1 is not surprising for a photospherically formed line in contrast to the part of the Hα absorption which is formed in the wind.

The next important question is whether the variations in δ_2 are periodic. A period search was thus made according to the algorithm of Lafler and Kinman (1965) over the range $0.3 < P(d) < 120$ with increment

TABLE 2

MEAN VALUES AND CORRESPONDING STANDARD DEVIATIONS OF THE DEPTH PARAMETER

Year	He II 6527 Å δ_1 (mag)	Hα 6562 Å δ_2 (mag)
1975:..............	0.062 ± 0.008	0.030 ± 0.026
1976:..............	0.059 ± 0.009	0.031 ± 0.019

$\Delta P = P^2/16\pi T$, where T is taken to be $\sim$ 40 days for each epoch. The results are as follows: the 1975 data yielded the best period around 5.05 days followed by two aliases of this below 2 days (sampling interval is $\sim$ 1 day), and 2.61 days. The 1976 data revealed a period close to 10.5 days with several aliases and simple multiples thereof below 2 days. A similar period search of the form $\delta_2 = C_0 + C_1 \sin 2\pi t/P + C_2 \cos 2\pi t/P$ resulted unambiguously in the best period 5.06 $\pm$ 0.03 days for the 1975 data, and 5.12 $\pm$ 0.05 days and 10.87 $\pm$ 0.10 days of equal quality for 1976. The 5 day period is considered to be the more likely, although its double cannot be entirely excluded. Combining the 1975 and 1976 data yields the following adopted ephemeris for the time of maximum depth of δ_2: JD 2,442,503.03 $\pm$ 0.10 + (5.075 $\pm$ 0.003)E. It is noted that this period is subject to improvement in view of the large window between the 1975 and 1976 observations. Phase diagrams are shown in Figure 2; both sets of data reveal a single wave with narrower maximum than minimum depth. However, the 1976 data are noisier and show reduced amplitude, reflecting the changes of the s.d. of δ_2 in Table 2. The rms $O-C$ values about each curve traced by hand through the data in Figure 2 are $\pm$0.009 mag for 1975 and 0.016 mag for 1976. The former value is in line with the s.d. in δ_1, while the latter is much noisier.

The behavior of the width parameter is depicted in Figure 3 where it is plotted versus δ_2. While the absorption feature of Hα appears to become wider when deeper in 1975, any such correlation is apparently masked by noise in 1976. In any case, the E.W. of the absorption feature seems to vary in phase with δ_2. It is also noted that the mean HW (216 $\pm$ 11 s.e.m. km s^{-1} in 1975 and 215 $\pm$ 7 s.e.m. km s^{-1} in 1976) is fortuitously (?) close to the value of $w_{\mathrm{rot}} \sin i$ from the photospheric lines: 208 $\pm$ 10 km s^{-1} (Conti and Ebbets 1977). Thus, one should be aware that some of the near central absorption reversal may be photospheric in origin.

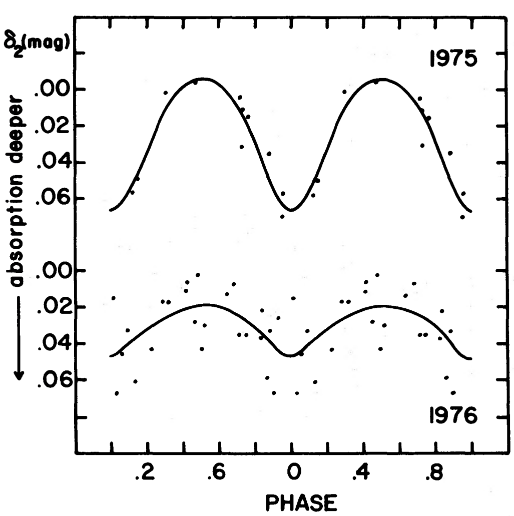

FIG. 2.—Depth parameter of the Hα absorption reversal versus phase calculated according to the 5.075 day ephemeris in the text. The curves are estimated trends.

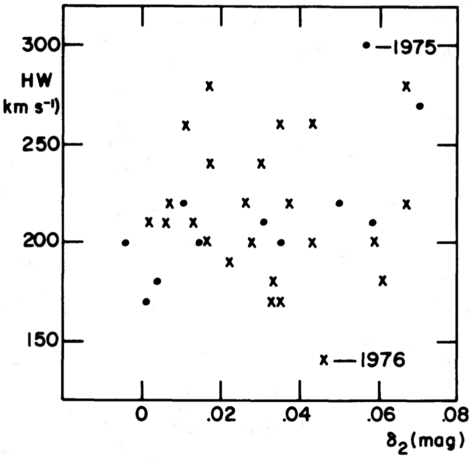

FIG. 3.—Width parameter versus depth parameter for Hα absorption.

Finally in this section, mention is made of the optical light curve of ζ Pup obtained in 1975 by Moffat (1977) relative to the constant magnitude star γ^1 Vel. These data, which have a standard deviation about the mean of 0.008 mag, show no significant trend with the 5.1 day phase. However, plotted in a 10.2 day phase, there is marginal evidence for a dip with full amplitude 0.010 mag. Corresponding magnitude differences (unpublished), including one filter centred near He II 4686, are constant to within a s.d. of 0.004 mag.

III. INTERPRETATION

a) *Corotation?*

The spectroscopic data yield a period of 5.025 $\pm$ 0.003 days for the variation in depth of the nearly central absorption reversal of Hα. The fact that this agrees quite closely with the rotation period of the photosphere (4.8 $\pm$ 1.2 days) is trivial only if the Hα absorption reversal is formed in or very near the photosphere. This is unlikely, however, since the radial velocity of the Hα reversal is displaced to $v \sim$ 150 km s^{-1} towards the blue in the mean, and reaches ~ -400 km s^{-1}. This implies that it is formed within the accelerating wind, albeit in the inner regions. Exactly where it is formed is difficult to establish in view of the current uncertainty in velocity-distance laws, $v(r)$, of the inner regions of hot stellar winds. If one adopts a radiation pressure type law of the form $v(r) = v_\infty(1 - R_*/r)^{1/2}$ where $v_\infty \sim$ 2600 km s^{-1}, R_* is the stellar radius and r is the distance from the star's center, one finds that the absorption is formed *within* $r/R_* = 1.02$. If one uses Lamers and Morton's (1976) linear $v(r)$ law for ζ Pup out to $r/R_* = 1.5$, one obtains that Hα could be formed as far as $r/R_* \approx 1.3$. If, instead, one uses Castor's (1979) law for the same star, one finds that Hα is formed as far as $r/R_* \approx 1.6$. If the law is even flatter, like that supposed in a model by Cassinelli, Olson, and Stalio (1978) for ζ Ori, it could reach $r/R_* \sim 2.0$. Unfortunately, no unique model is available. MC note that most model dependent velocity laws are probably too steep.

From the blue wing of the Hα profile, MC determined that hydrogen had to corotate at least as far as $r_0/R_* \sim 2.1$. This is a lower limit because of the excessive electron scattering (Ebbets 1980) assumed to derive it. Even though the Hα absorption may form at the same distance as the Hα emission, it need not do so. The radius where the Hα absorption forms is then rather uncertain. In what follows, we will consider the absorption components formed at 1.1, 1.5, and 2.0 $R_\odot$. It will be seen not to change our model qualitatively.

In this model, a magnetic field configuration is supposed to cause nonuniformities in the stellar wind density which crosses the line of sight to the star during each rotation, thus creating cyclic variations, e.g., in Hα absorption. Variations in the emission component would be more subtle by comparison, because the emission arises in a much larger volume so that local variations would tend to be smeared out. This may be why the overall emission profile and the continuum light curve remain constant. This is analogous to the oblique rotator interpretation for Ap stars (Deutsch 1958; Borra and Landstreet 1980). Similar phenomena may be operating in the rapidly rotating O9.5 V star ζ Oph (Walker, Young, and Fahlman 1979) and in σ Ori E (Berger 1956; Landstreet and Borra 1978).

MC estimated the magnetic field strength *at* the corotation radius ($r_0 \approx 2.1\ R_*$), assuming an outflow velocity there of $v_0 \sim 1000$ km s^{-1}. A more realistic value of $v_0 \lesssim w_0 \sim 450$ km s^{-1} in the expression for the Alfvénic Mach number, leads to $B = (\dot{m}v_0)^{1/2}/r_0{}^2 \lesssim 50$ gauss. This will scale with $1/r^3$ to ~ 400 gauss at the stellar surface.

An alternative explanation for the periodic behavior of the Hα reversal is that we are seeing the effects of perturbation by the cyclic passage of a low mass object orbiting with period 5.075 days within the wind envelope. Taking the sum of its mass along with the O star to be 50(100) $M_\odot$ leads to a mean orbital separation of 46(57) $R_\odot$, much like the above estimated maximum radius where the envelope Hα line is formed (2.1 R_*). While the observed simple sine wave modulation of the Hα reversal is compatible with such a model, it is not easy to reconcile the fact that the radial velocities of the photospheric absorption lines are virtually constant, leaving uncertain the possibility of a velocity semiamplitude $K < 15$ km s^{-1} (Garmany, Conti, and Massey 1980). If the low mass star is a neutron star with a mass of $\sim 1.5\ M_\odot$, it would cause the O star to orbit with semiamplitude $\leq 15(8)$ km s^{-1} depending on the orbital inclination. Hence, a more scrutinous search for a velocity orbit may be warranted, although there remains the problem of explaining the lack of hard X-rays if the hypothetical low mass star were in fact compact.

b) Magnetic Field Configuration

Insofar as the appropriate magnetic field configuration is close to dipolar, one would expect a double wave for any variations of the density related to such a magnetic field. For instance, if the density enhancement is symmetric about the polar regions, it is not expected to depend on the sign of the projected magnetic field, and it should repeat as *each* pole appears when the star rotates. For ζ Pup, we observe a single wave in hydrogen line absorption. We show in this section how a single wave phenomenon is just as likely, using more complex magnetic fields, similar to those observed in some Ap stars.

In the presence of a magnetic field, mass loss will be highly nonspherical. Elements will diffuse across the field lines at a negligible velocity compared to the stellar wind velocity of hundreds of kilometers per second. Using, for instance, equation (2-39) of Spitzer (1962) with $B = 10G$, $T = 5 \times 10^4 K$, $N = 10^{10}$ cm^{-3}, $\ln \Lambda = 6$, and characteristic lengths of 10^8 cm, gives a velocity of approximately 10^{-4} cm s^{-1}. Even if the driving term of the diffusion were 10^8 times stronger than a characteristic density gradient, the velocity across magnetic field lines would still be negligible. As long as the field vaguely resembles the dipole, the off-center dipole, or the dipole plus quadrupole configurations that reproduce the magnetic fields observed on Ap stars, one expects the stellar wind to flow freely at the poles but hardly at all where the magnetic field lines are horizontal. If, as is assumed here, magnetic pressure dominates in the region where hydrogen P Cygni absorption lines are formed, hydrogen will remain virtually bound to the star and will not flow outwards where magnetic field lines are horizontal. It will flow unimpeded where the magnetic field lines are vertical. As the star rotates, one will alternatingly see regions over the star where elements are flowing outwards and regions where they are bound to the star. One then expects to see the core of the Hα line shift in wavelength with advancing phase. Figure 1 shows a shift in the Hα core of 10^2 km s^{-1}; this is the range of shifts to be expected in an oblique rotator with equatorial velocities of a few hundred km s^{-1}, although the geometry is a little more complex here than in oblique rotators without envelopes. Here, only the matter passing in front of the star absorbs. If the bulk of the absorption region is located at two stellar radii, the radial velocity of the absorbing material frozen in the horizontal magnetic field lines deviates only up to $\pm 10\%$ from the equatorial velocity. As the star rotates, the absorption occurs alternatingly in regions of frozen-in material and material that can escape at the pole. When it occurs in the frozen-in material, the radial velocity of the absorption reversal averaged over the stellar surface will vary from about -30 km s^{-1} to about $+30$ km s^{-1}. It will reach some (or perhaps more) -100 km s^{-1} where the material in the wind causes the Hα absorption.

Insofar as the horizontal magnetic field forces the material to remain bound to the star, one expects more absorbing material to be concentrated there. To show that the observed single maximum per rotation cycle can then follow, we have calculated the equivalent width variations expected for material trapped where the magnetic field is horizontal in the dipole plus quadrupole configurations, typical of these reproducing H_e and H_s fields on Ap stars (for details see Michaud, Mégessier, and Charland 1981). This is consistent with the suggestion that ζ Pup is a hot example of a magnetic star. In Figure 4 are shown the magnetic field lines for the chosen

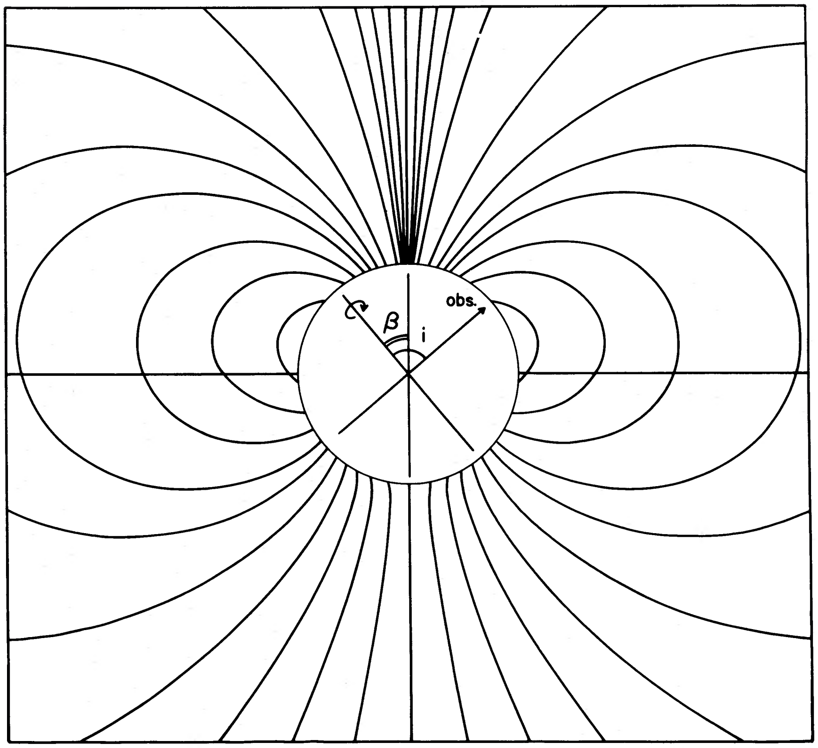

FIG. 4.—The magnetic field lines of a configuration that qualitatively leads to the variations observed in Hα self-absorption. The density of magnetic field lines is *not* proportional to the field intensity. The magnetic and rotating axes are assumed to lie at an angle β from each other. On the stellar surface we assumed $H_q/H_d = 0.9$ where H_q and H_d are the strengths of the quadrupole and of the dipole, assumed to be aligned. This is consistent with magnetic fields observed in Ap stars (Michaud, Mégessier, and Charland 1981). The radius of the circle is $2R_* = 32\ R_\odot$.

configuration and in Figure 5 the ensuing equivalent width variations with $i = 90°$, $\beta = 40°$. Although chosen to match qualitatively the variation in δ_2, these angles are not unusual in any way. They are underdetermined by the observations. The calculations are similar to those of

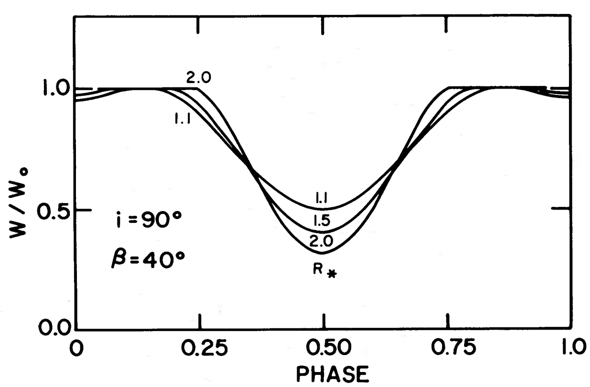

FIG. 5.—Equivalent width variations caused by material situated within a ring from 20° to 120° from the positive magnetic pole. The ring is centered where the magnetic field is horizontal (70° from the pole) and extends equally on both sides. It is assumed to lie at 1.1, 1.5, or 2.0 stellar radii, depending on the curve. Qualitatively, the behavior is the same. Maximum value, W_0, is attained when the ring entirely covers the visible part of the star. There is only one observable maximum and one minimum per rotation, even though the elements are in a ring. The variations of W calculated here are upper limits since hydrogen is assumed to be present only in the ring.

Michaud, Mégessier, and Charland (1981) except that the material is assumed to lie either at 1.1, 1.5, or 2.0 stellar radii and cause absorption only as it passes in front of the star. Because the material is concentrated on the hemisphere containing the strong magnetic pole, the equivalent width variations have only one maximum per rotation. Note that the effect has been exaggerated by assuming hydrogen in the envelope to be present only in a ring where the magnetic field is horizontal and totally absent elsewhere. The size of the rings has been justified by Michaud, Mégessier, and Charland (1981, § VI).

It is interesting to compare our variations of the Hα absorption with the recently observed variations in X-ray flux from ζ Pup (Snow, Cash, and Grady 1981). Although they disregard as possibly spurious the fluctuations seen for ζ Pup, the spread does reach a maximum of $\sim 17\%$ over 4 days with maximum flux occuring close to the predicted time of maximum Hα absorption. If this proves to be real, the two effects may be physically related.

c) *Diffusion effects*

While chemical separation is important in magnetic Ap stars, one may wonder whether it is so here. Where there is no wind, i.e., where the magnetic field lines are horizontal, some chemical separation can take place in the atmosphere, *if* turbulence is small enough there. This need not be the case even within the context of the diffusion model for Ap stars (see Michaud, Mégessier, and Charland 1981). Where there is a wind, one can show that element separation is negligible. One may first calculate the chemical separation flux as a function of depth in the star. One has (using eq. [6] of Michaud 1976 with $A = 4$ and $\partial \ln c/\partial r = 0$ and $g_R = 0$):

$$N_{\mathrm{He}} v_{D\,\mathrm{He}} = 7 N_{\mathrm{He}} T^{3/2}/(N_p Z^2) .$$

If $Z = 2$ throughout, the diffusing helium flux increases with depth as $T^{3/2}$. The maximum effect diffusion can have on a stellar wind may be evaluated by calculating the effect of diffusion inside the star where the elements that constitute the stellar wind once were located. A rough upper limit is obtained by comparing the flux in the stellar wind to the diffusion flux at the deepest point in the star where diffusion has time to act in a stellar lifetime. This may be verified to be at $T \approx 3 \times 10^5 K$ using, for instance, the results of Vauclair, Michaud, and Charland (1974).

Then, with $g = 10^4$ and $N_{\mathrm{He}}/N_p = 0.1$:

$$N_{\mathrm{He}} v_{D\,\mathrm{He}} \approx 1.6 \times 10^{11} \text{ particles (s cm}^2)^{-1} ;$$

thus,

$$4\pi R^2 \times N_{\mathrm{He}} v_{D\,\mathrm{He}} m_{\mathrm{He}} \approx 10^{-13}\, M_\odot \text{ year}^{-1} .$$

This would correspond to a total mass flux of the order of $10^{-12}\, M_\odot$ year^{-1}. Since the observed mass outflux is $\gtrsim 10^{-6}\, M_\odot$ year^{-1}, the chemical separation must have a negligible effect. It can have a significant effect only for mass outflux of 10^{-11}–$10^{-12}\, M_\odot$ year^{-1} or smaller in hot stars. Note that this is very similar to the results Vauclair (1975, 1981) obtained from a slightly different point of view.

IV. CONCLUSIONS

Qualitatively, the present Hα profile variations of the central absorption are compatible with forced corotation of the Hα—absorbing part of the stellar wind. This is likely caused by the presence of a multipole magnetic field, although the presence of a low mass companion cannot be excluded. To be more quantitative, more data are needed: attempts should be made to detect the predicted magnetic fields, weak as they may be, and one should survey other Oef stars for a similar periodic phenomenon as found for ζ Pup, not only at Hα, but also for other lines showing Beals' type III P Cygni lines. Also, further observations of ζ Pup are needed to check on the stability of the wind perturbations which were of reduced amplitude but noisier in 1976 than 1975.

In this paper, we have assumed the magnetic field always able to impose its structure on the outflowing matter and in particular always able to keep the matter from flowing beyond where the field lines are horizontal. However, it is possible that, as stresses accumulate, the horizontal magnetic field becomes unable to retain the wind, and the matter leaves, taking some magnetic field lines along with it, just as on the sun. Irregular variations are then possible.

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