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EVIDENCE FOR COROTATING CLOUDS IN THE Be STAR ζ TAURI

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ABSTRACT

We reexamine a time series of spectroscopic data of the Be star ζ Tauri obtained by Kaye & Gies. When the difference spectra are folded with the 0.777 day period, a distinctive pattern emerges. This pattern is not the standard "barber pole" diagram expected from nonradial pulsation but is instead a pattern of two sinusoidal variations of enhanced absorption having different amplitudes. We interpret these results as additional evidence for corotating clouds, recently suggested as an explanation of the variations observed in several other Be stars and as indirect evidence for the possible presence of magnetic fields.

Subject headings: line: profiles — stars: early-type — stars: emission-line, Be — stars: individual (ζ Tauri)

1. INTRODUCTION

The mechanism that is responsible for the episodic mass loss in Be stars is unknown. Many Be stars show periodic light and line profile variations, which are generally interpreted as due to photospheric nonradial pulsation (NRP) (e.g., Gies 1994). However, attempts to explain the mass loss in terms of NRP have not been successful. These models assume that NRP is capable of accelerating the surface layers to escape velocity (e.g., Saio 1994), but it is well known that although Be stars are rapid rotators, the velocity of rotation at the equator falls short of the critical velocity by at least 100 km s^{-1} in most cases.

The correlation between the photometric period and the projected rotational velocity in periodic Be stars is consistent with this period being identical to the period of rotation (Balona 1990, 1995). The correlation also places strong constraints on the maximum pulsational velocity. The maximum allowable pulsational amplitudes are smaller than the pulsational amplitudes required to explain the radial velocity amplitudes in some Be stars (Balona 1990, 1995). Recently, Štefl, Aerts, & Balona (1999) and Balona, Aerts, & Štefl (1999) have shown by careful modeling that NRP cannot explain the line profile variations in the Be star 28 Canis Majoris (HD 56139, B2 IV–Ve; Houk 1982). They are able to obtain reasonable line profile fits using a model in which a region on the surface has a lower intrinsic line width than the surrounding photosphere.

Recent line profile observations of another Be star, η Centauri (HD 127972, B1 Vn; Houk 1975), by Balona (1999) show complex emission and absorption patterns appearing in the difference spectra of the helium lines. These patterns repeat with the photometric period and are too complex to be attributed to NRP even if multiperiodicity is assumed. Moreover, enhanced emission is present every half-cycle on alternate limbs of the star, another fact which rules out NRP. This evidence suggests that η Cen provides an example of cloud patterns suspended above and rotating with the photosphere (Harmanec 1999). This "corotating cloud" model also explains the complex light curves, which have always been difficult to understand in terms of NRP. The patch observed by Balona, Aerts, & Štefl (1999) in 28 CMa can now be placed in its proper perspective; it is likely to be a cloud suspended above the photosphere.

Clearly, it is important to verify this model in other stars. Recently, Kaye & Gies (1997) studied the B2 IIIpe star ζ Tauri (HD 37202). They conclude, in agreement with most other spectroscopic studies, that the line profiles in this star can only be understood in terms of NRP. Here we present evidence that this interpretation is most probably not correct. Instead, we find evidence for corotating clouds similar to those thought to be present in η Cen and 28 CMa. We use the same line profile observations of Hα and He I λ6678 data that Kaye & Gies (1997) use in their study of ζ Tau, but we restrict ourselves to the interval HJD 2446799–2446804 (94 spectra), as this is best suited to a time series analysis. Additional data presented by Kaye & Gies (1997) that we do not use (32 spectra) are from a previous season and are too sparsely sampled to be useful in this study. Table 1 gives a log of the observations.

2. THE He I λ6678 LINE PROFILE

Inspection of the He I λ6678 line profile shows that is quite different from a typical, rotationally broadened, photospheric profile. The core of the line is sharp, and the wings are extended. There is little doubt that most (if not all) of the profile is formed in the circumstellar envelope. To demonstrate this, we compare the mean line profile with the best fitting rotationally broadened photospheric profile in Figure 1. We used the He I λ6678 intrinsic line profiles tabulated by Auer & Mihalas (1973) convolved with rotation. We adopted an effective temperature $T_{\rm eff} = 19{,}000$ K (Zorec & Briot 1991), log $g = 3.0$, and a linear limb darkening law with coefficient $u = 0.23$. The best-fit value of the projected rotational velocity, $v \sin i = 204$ km s^{-1}, is clearly inadequate. Even the addition of substantial macroturbulence does not lead to any significant improvement. Variations in the circumstellar matter are probably the cause of the large range of $v \sin i$ estimates; values between 220 (Slettebak 1982) and 320 km s^{-1} (Yang et al. 1990) have been reported.

TABLE 1

LISTING OF DATA USED IN THIS ANALYSIS

HJD (−2,446,000)	Phase Range	N
799.57–0.97	0.45–0.97	14
800.58–0.97	0.76–1.25	16
801.59–0.98	0.05–0.56	20
802.59–0.96	0.34–0.81	27
803.60–0.97	0.64–1.12	17

NOTE.—Heliocentric Julian date of the first and last spectrum of the night is given (modulo 2446000), followed by the range in phase using a period of 0.777 days and (arbitrary) epoch of phase zero of HJD 2,446,000.0. The last column is the number of spectra per night.

TABLE 2

FOURIER PARAMETERS OF PERIODICITIES MEASURED IN He I λ6678 IN ζ TAU

Feature	ν	P	A	ϕ
Mode	2.29	0.436	1.2 ± 0.2	-0.31 ± 0.13
EW:				
1	1.29	0.775	0.020 ± 0.003	-0.31 ± 0.13
2	1.96	0.510	0.022 ± 0.003	0.75 ± 0.13
M_1	1.28	0.781	8.1 ± 0.5	2.32 ± 0.57
M_2	1.29	0.775	895 ± 113	0.38 ± 0.13

NOTE.—The parameters are defined by $y = A_0 + A \cos [2\pi\nu(t - T_0) + \phi]$. The frequencies are listed in day^{-1}; the periods are in days. For the mode and M_1 the units are km s^{-1}. The units for M_2 are km^2 s^{-2}. For the equivalent width, the units are angstroms. The phase, ϕ, is in radians with $T_0 = 2,446,790.000$.

3. PERIOD ANALYSIS

Yang et al. (1990) made a detailed study of profile variations in ζ Tauri based on the Hγ, He I λλ4388, 4471, and Si III λ4552 lines obtained during a total of seven nights spread out over 1983, 1986, 1987, and 1988. They discovered weak subfeatures moving from blue to red, which were interpreted as nonradial pulsation. The behavior of these subfeatures varied markedly from season to season. Nevertheless, they were able to detect a coherent periodicity of 0.683 days in the width of the He I λ4471 line over three seasons. The period of the moving subfeatures was found to be 0.095 days. It should be noted that there are considerable aliasing problems owing to scant data taken over a long temporal baseline.

By studying the intensity variations at a given wavelength, Kaye & Gies (1997) found a period of 0.777 days ± 0.002 days. They were unable to find any moving subfeatures. The period of 0.777 days (=1.287 day^{-1}) is distinctly different from the 0.683 days (=1.464 day^{-1}) period found by Yang et al. (1990). The data presented in Kaye & Gies (1997) were well sampled over a five night period, and aliasing is not a serious problem.

In order to verify the results of Kaye & Gies (1997) and to detect other periods, we undertook a period analysis of quantities other than the intensity at a given wavelength. In particular, we measure the position of minimum intensity (the mode) and the moments of the He I λ6678 line profile. These were analyzed for periodicities by means of simple Fourier periodogram calculations between frequencies of 0 and 40 day^{-1}. The mode shows a linear trend, being about 24 km s^{-1} on the first night and 17 km s^{-1} on the last night. The equivalent width was lower by 0.05 Å in the middle of the run. In both cases the trend was removed by fitting a straight line and quadratic (respectively) before the periodogram was calculated. Our results are shown in Table 2 and Figure 2.

We confirm the period derived from the analysis of Kaye & Gies (1997), i.e., the only consistent periodicity present in this datum is the single period of 0.777 ± 0.002 days. We

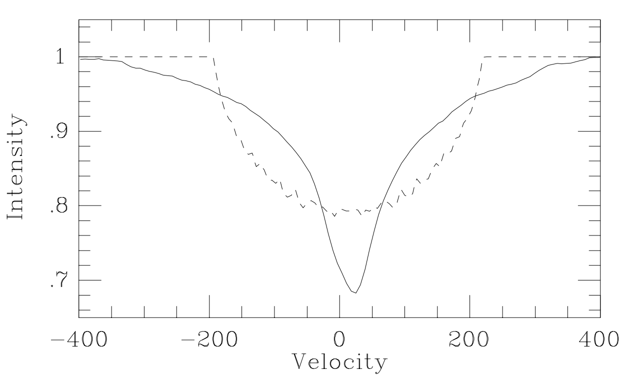

FIG. 1.—Observed mean line profile of He I λ6678 (*solid line*) and the best fit with a rotationally broadened profile (*dashed line*).

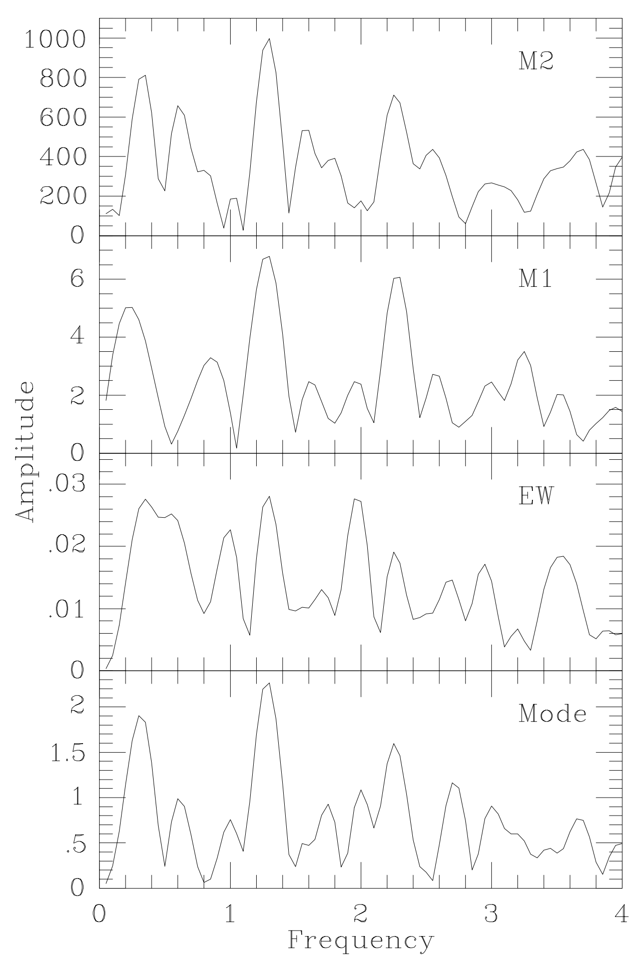

FIG. 2.—Periodograms of the position of minimum intensity (mode), equivalent width (EW), the centroid (M_1), and second moment (M_2). The frequency is in cycles day^{-1}; the amplitudes are in appropriate powers of km s^{-1} or angstroms for the EW.

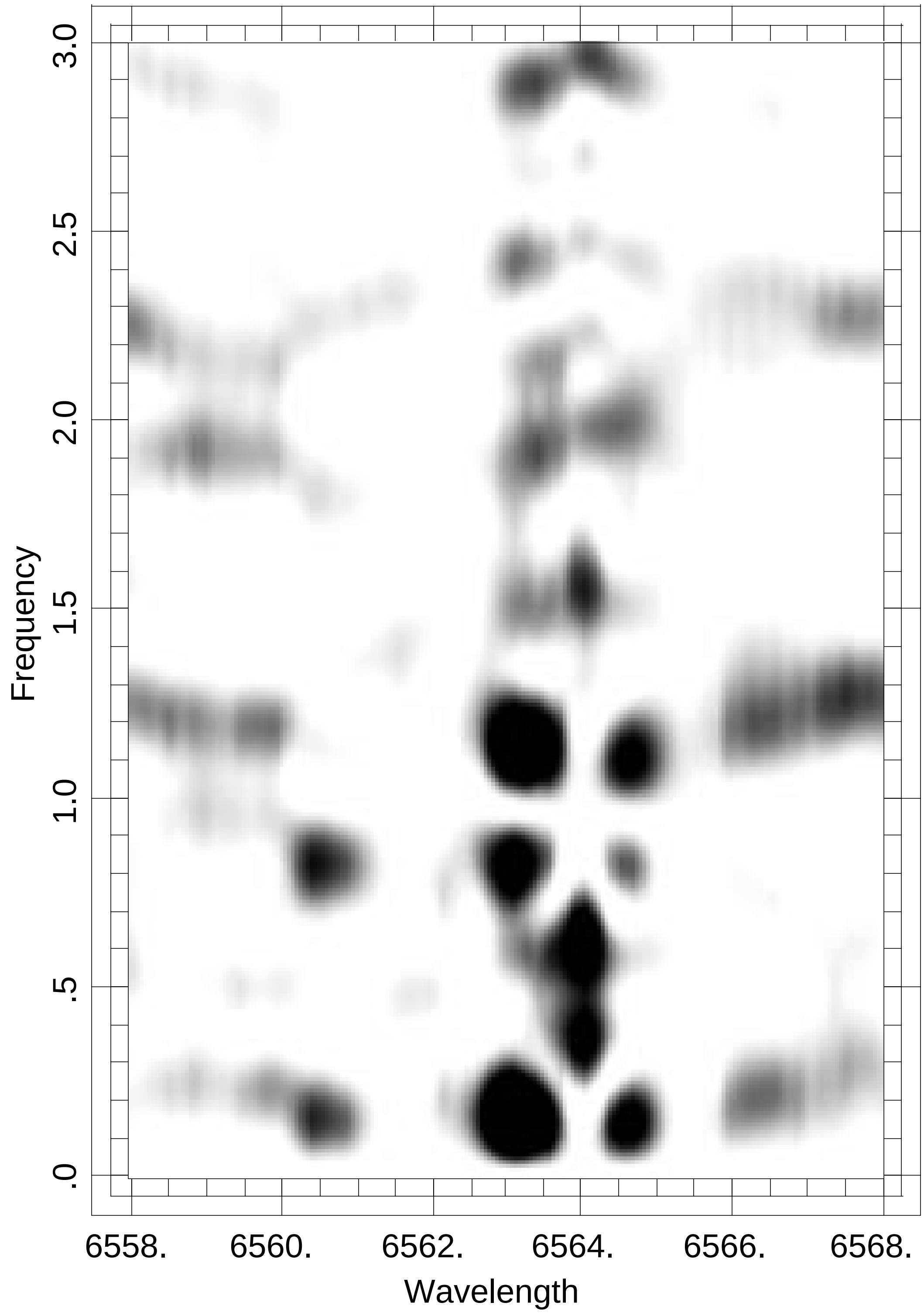

FIG. 3.—Periodogram across the Hα line profile. The frequency is in cycles day^{-1}.

also confirm the result presented by Kaye & Gies (1997) in that there are no signs of the 0.683 or 0.095 day periodicities found by Yang et al. (1990), despite the fact that the two data sets are contemporaneous.

Whereas the 0.683 day period found by Yang et al. (1990) is probably an alias of the true (0.777 day) period, it is less easy to understand why the 0.095 day period is not present in the Kaye & Gies (1997) data. Kaye & Gies suggest that the amplitude of this signal may be highly variable and below the detection limit at the time of their observations (which are contemporaneous with those of Yang et al. 1990) or that the variations are not strictly periodic. We know that Be stars often undergo outbursts of activity, and the star may have been at an active phase during part of the time when it was observed by Yang et al. (1990).

We also investigated the Hα line profile for periodicities. Here the situation is complicated by the fact that the peak emission intensity is about twice the continuum level. In

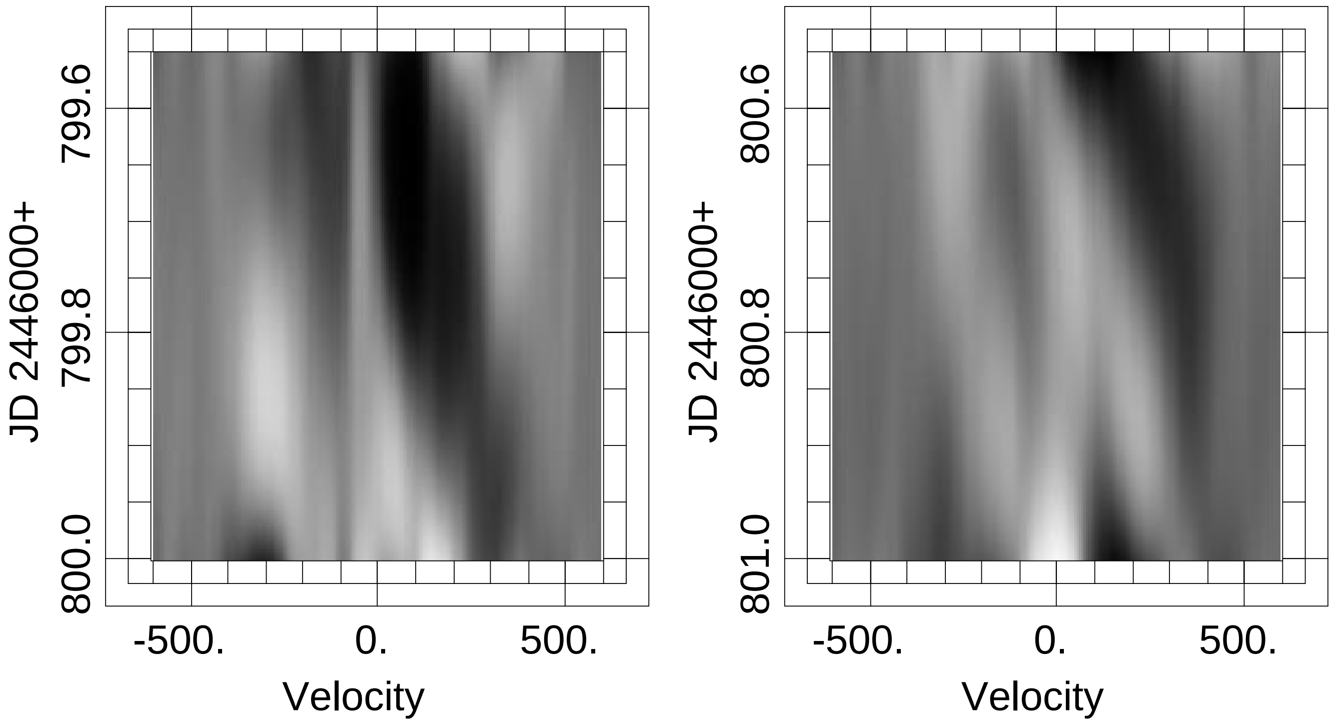

FIG. 4.—Interpolated gray-scale images of difference spectra for the He I λ6678 line. Light areas represent emission relative to the mean line profile.

addition, variations in the relative strengths of the violet and red emission components (V/R variations), influenced by both photospheric- and disk-related processes, are seen in the Hα line profiles. Consequently, the variations present in these data may occur on several different timescales (and perhaps even stochastically). A periodogram of the intensities across the line profile shows maximum power at about $P = 0.88$ days ($\nu = 1.14$ day^{-1}) (Fig. 3), although a signal closer to $\nu = 1.28$ day^{-1} appears in the wings of the line. Whether the $P = 0.88$ day period is significantly different from the period found in the He I λ6678 line remains to be confirmed.

4. NRP OR CLOUDS?

Kaye & Gies (1997) assert that the only plausible explanation for the periodicity and line profile variations in this star is NRP. The inclination of the circumstellar disk is known to be about $i \gtrsim 74°$ from optical interferometry (Quirrenbach et al. 1997). Using $v \sin i = 320$ km s^{-1} and $i \approx 90°$, Kaye & Gies (1997) estimate $P_{\rm rot} = 1.53$ days $\pm$ 0.46 days. The main source of error is the large uncertainty in the stellar radius ($\sim$30%). This period is consistent with the corotating cloud model if it is assumed that there are two diametrically placed density enhancements of roughly equal size. Kaye & Gies (1997) also consider the possibility that the variation is due to two disk enhancements close to the photosphere. This they rule out because one might expect to see emission features outside the rotationally broadened line, and these are not seen. It should be noted, however, that the presence or absence of emission depends on the geometry and physical conditions of the circumstellar material. Since we do not know these details, no definite statement can be made based solely on the expected presence of emission.

Kaye & Gies (1997) also argue that in the corotating circumstellar material model, the flux changes will have greatest impact at line center. This may be true in certain circumstances, particularly for slowly rotating stars. In the case of ζ Tau, we are dealing with rapid rotation, and there may be only a slight difference in physical conditions between the cloud and its surroundings (or its projected surroundings). The greatest impact will then be in the line wings because it is here that the flux is redistributed by the rapid rotation of the star. We also note that the same argument applies to NRP if the temperature perturbations are significant (see below), because in this case we have, in effect, a traveling "starspot."

Balona (1990, 1995) demonstrates that the temperature perturbation is dominant for NRP when the observed period is nearly the same as the period of rotation, i.e., when the period of pulsation in the corotating frame is very long. Since NRP-generated waves are almost stationary in the corotating frame of the star, this model is practically indistinguishable from a corotating cloud model, as mentioned above. Consequently, arguments directed at the cloud model apply equally well to the NRP model.

We show in Figures 4–6 gray-scale images of difference spectra of the He I λ6678 line analyzed in this paper. Careful inspection of the figures shows that there are two distinct systems of excess emission and absorption. One system has a significantly smaller amplitude than the other. This is best seen by phasing the spectra by the 0.777 day period, as shown in Figure 7. The enhanced emission and absorption is typically 0.5%–1.0% of the continuum level.

In Figure 7, we notice a dark sinusoidal lane running down the figure reaching a maximum positive velocity of 150 km s^{-1} at phase $\phi = 0.25$ and maximum negative velocity of about -100 km s^{-1} at phase $\phi = 0.85$. There is a separate dark lane with maximum negative velocity of -300 km s^{-1} at phase $\phi = 0.25$ and maximum positive velocity of 250 km s^{-1} at phase $\phi = 0.70$. These lanes are embedded in a background of excess emission lying

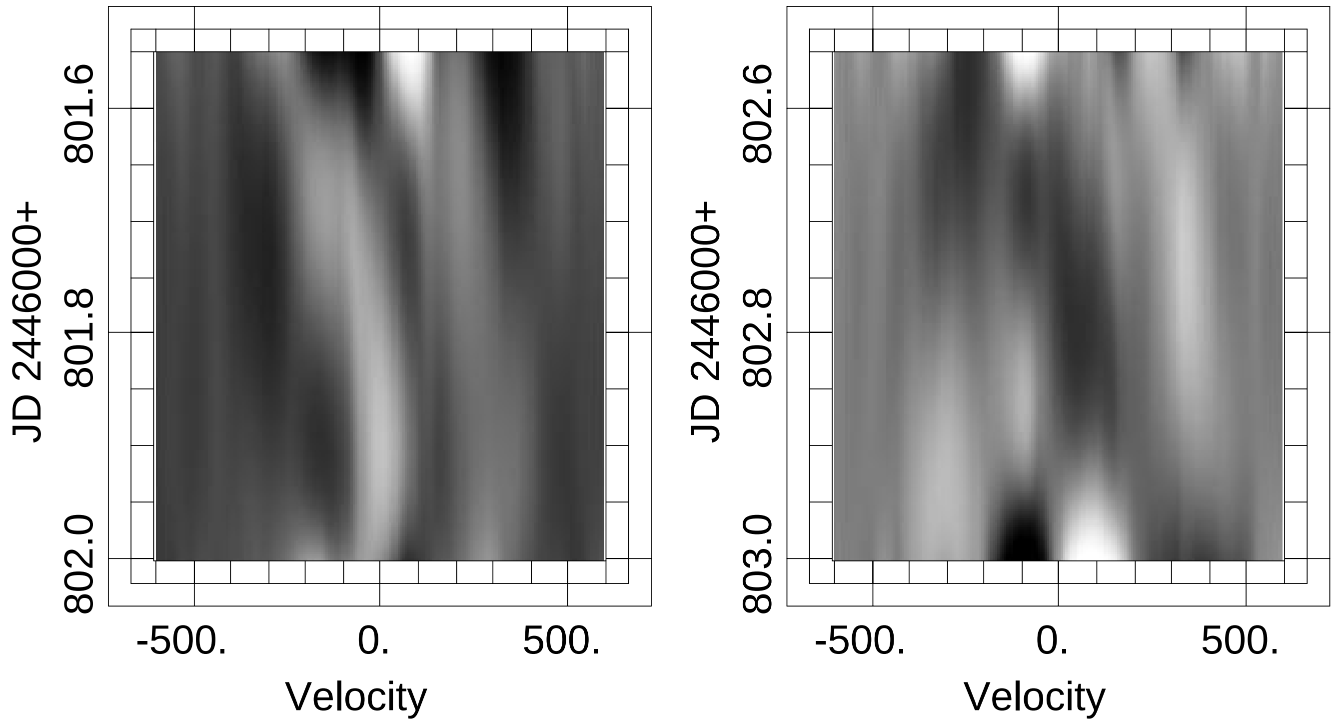

FIG. 5.—Interpolated gray-scale images of difference spectra for the He I λ6678 line. Light areas represent emission relative to the mean line profile.

between -300 and 300 km s^{-1}, i.e., *within* the rotationally broadened profile.

A similar figure was generated from the Hα line profile variations. In this case, there is little of interest to be seen. Between -400 and 400 km s^{-1}, emission in Hα is somewhat reduced from phases 0.6–1.0 on the blue side and between phases 0.4–0.8 on the red side, assuming a period of 0.777 days. The diagram for $P = 0.88$ days looks much the

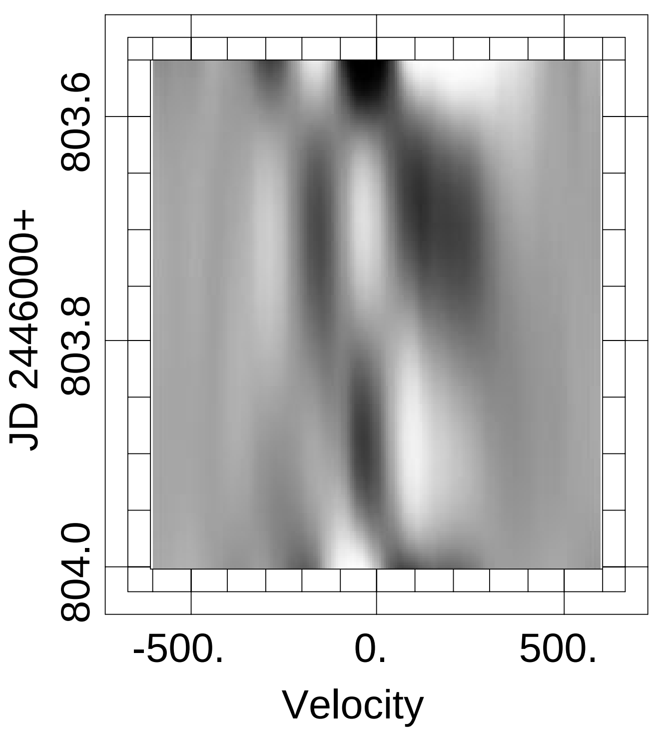

FIG. 6.—Interpolated gray-scale image of difference spectra for the He I λ6678 line. Light areas represent emission relative to the mean line profile.

same. Presumably, the Hα line samples a higher region of the circumstellar material and is opaque to the photospheric clouds seen in the helium line.

If we are to assume that the observations show pulsation in the stellar photosphere, we should expect to see a "barber pole" diagram, examples of which are shown in Schrijvers et al. (1997). The morphology of the barber pole diagrams due to photospheric NRP *do not* qualitatively resemble Figure 7. The problem is that one cannot explain the two systems of different amplitudes in terms of prograde or retrograde sectoral modes. Based on measurements of the slope of the phase of the 0.777 day signal as a function of position across the line profile, and by assuming a priori that $l = |m|$, Kaye & Gies (1997) conclude that ζ Tau pulsates in a single gravity-mode oscillation characterized by the solution $l = -m = 2$. In Figure 8 we show the barber pole diagrams for all $l = 2$ modes, assuming that the horizontal pulsational velocity dominates, as expected for g-mode pulsation. In this example the ratio of horizontal to vertical pulsational velocity amplitude is $k = 10$. Clearly, this figure does not resemble Figure 7 in any way.

It should be noted that a difference in pulsational amplitude does not cause a difference in the amplitude of the sinusoid seen in Figure 7 but rather a difference in intensity and path across the line profile. In NRP the disturbance always travels the full distance across the line profile, as can be seen in Schrijvers et al. (1997). In any case, it is rather unlikely that any part of the photosphere is seen in the He I λ6678 line, which, as Figure 1 demonstrates, is mostly formed in the circumstellar material.

Instead of NRP, we propose that what we see here closely resembles what is seen in 28 CMa and η Cen and may be attributed to corotating photospheric clouds. We note that, very recently, Smith, Robinson, & Hatzes (1999) have proposed the same model for the Be star γ Cassiopeiae (B0 IVpe; Lynds 1959). It is fairly easy to understand

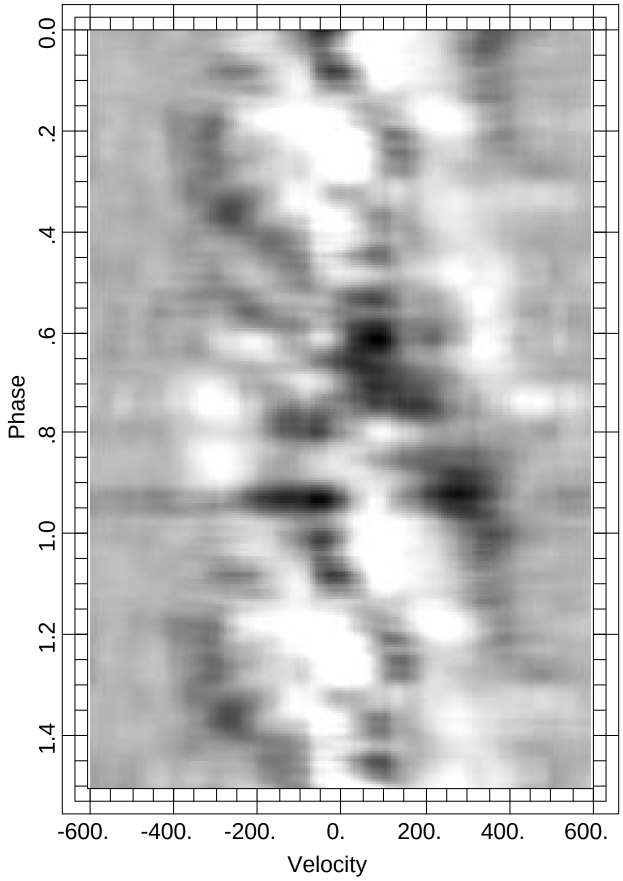

FIG. 7.—Difference spectra phased with the 0.777-day period; the epoch of phase zero is HJD = 2,446,000.000. Notice the dark sinusoidal lane (excess absorption is typically 0.5%–1.0% of the continuum level) with peak-to-peak amplitude of about 250 km s^{-1} and another lane, in antiphase, with a peak-to-peak amplitude of about 550 km s^{-1}. These are embedded in excess emission of 0.5%–1.0% of the continuum level.

Figure 7 in terms of corotating clouds or density enhancements in the circumstellar material. In this scenario, one cloud would be near the equator and the other cloud near the pole. To prove that such a model is plausible, we show in Figure 9 the results of a calculation of a crude model of two circular "spots" in corotation with the star. The parameters are $R = 5.6\ R_\odot$, $v \sin i = 350$ km s^{-1}, and $i = 75°$. The two spots are located at longitude $\lambda = 180°$ and latitude $\beta = 75°$; radius $\gamma = 15°$, relative brightness $F/F_0 = 0.80$, $\lambda = 0°$, $\beta = 20°$, $\gamma = 25°$, and $F/F_0 = 0.97$. In these calculations, we assume that the circumstellar material is spherically distributed and that the "spots" are regions of smaller surface brightness, as would be the case for corotating density-enhanced areas suspended above the photosphere. A "patch" model, where the surface brightness is unchanged but the intrinsic line profile is different, will produce the same effect. At present, there are insufficient data to merit more realistic modeling.

If the clouds are located at approximately the same places on the photosphere, the same period (which is the period of rotation) will be observed from season to season. Changes in the shapes and densities of the clouds would account for the peculiar and sometimes dramatic changes in the light curves of λ Eri stars (see e.g., Balona, Sterken, & Manfroid 1991). Observations of η Cen over a 20 day period (Balona 1999) indicate that the clouds do not move significantly with respect to each other, which suggests that the mechanism that generates and/or maintains the density enhancements is long-lasting. Observations over a longer time interval are clearly needed to confirm this conclusion. The geometry of the circumstellar material in the immediate vicinity of the star is not known, although it is clear that a flattened, equatorial disk is present some distance away. It is possible that the whole photosphere, from pole to pole, may be covered with clouds—in other words, that the clouds form, in effect, a detached photosphere. In η Cen and in ζ Tau, it appears as if there is a concentration of material

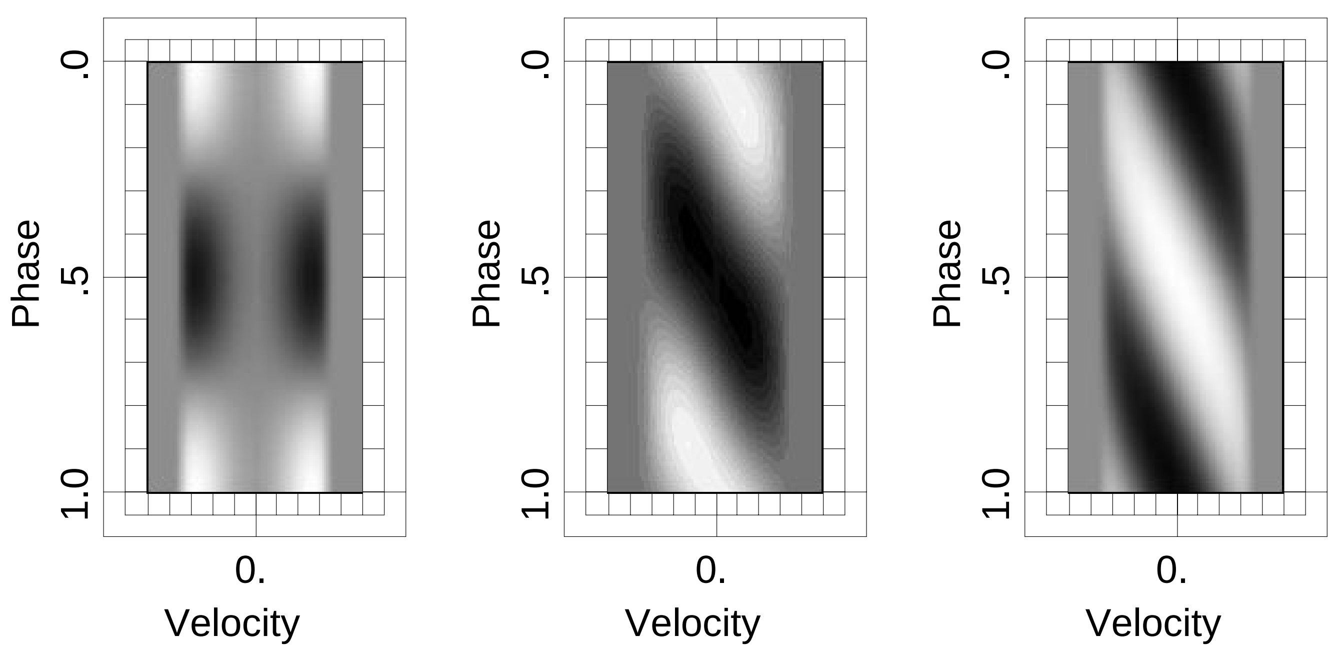

FIG. 8.—Gray-scale image constructed in the same way as Figure 7,but for a synthetic NRP model with, from left to right, $(l, m) = (2,0), (2,-1)$ and $(2,-2)$. Changing the sign of m reverses the direction of the dark absorption lane and is equivalent to reversing the sign of t.

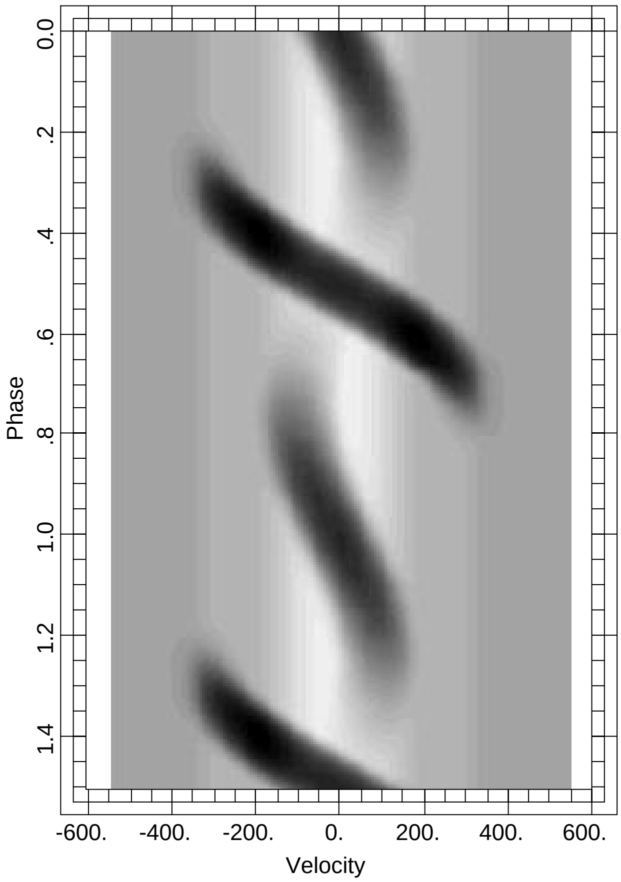

FIG. 9.—Synthetic difference spectra phased using a crude model of two circular spots at stellar latitudes 20° and 75°.

near one (or both) poles and at the equator. It would be interesting to see if this geometry is a general property of Be stars or specific to just a few special cases.

5. CONCLUSION

We have reexamined spectra of ζ Tau presented in Kaye & Gies (1997) in the light of recent findings on three other Be stars, 28 CMa (Štefl et al. 1999; Balona, Aerts, & Štefl 1999), η Cen (Balona 1999), and γ Cas (Smith et al. 1999). We find that when the difference spectra are phased with the well-determined 0.777 day period, a distinctive pattern can be discerned. This pattern consists of two systems of enhanced absorption traveling across the He I λ6678 line profile at different rates and approximately 90° out of phase. The equivalent diagrams produced by standard NRP models do not show such features. The observations can be qualitatively understood in terms of two density enhancements in the circumstellar material immediately surrounding the photosphere. These findings add further support to the hypothesis that the periodic variations of Be stars are due to corotating photospheric clouds.

There is no definite evidence for more than one period in ζ Tau, although the slightly longer period suggested by the Hα profile variations should be confirmed. The 0.683 day period found by Yang et al. (1990) is probably an alias. However, recent results for 28 CMa, μ Cen, and (possibly) η Cen show that transient periods, close to the single, stable, photospheric period, are sometimes present (Štefl at al. 1998). These transient periods appear only in lines formed in the upper atmosphere or the inner circumstellar material. The reason transient periods should be present is not at all clear. Photospheric differential rotation is a possibility, although the rather large patch observed in 28 CMa has been in existence for many decades (Balona et al. 1999).

However, we know that the observed transient periods present in some Be stars *cannot* be due to NRP because the thermal timescale in the inner circumstellar material (or upper atmosphere) is much too short. In other words, the thermal capacity of the low-density, cool gas is far too small to store the thermal energy released during a pulsational cycle. This is a crucial requirement for pulsational instability. By contrast, modes that have significant amplitudes in the dense, hot regions below the photosphere may be able to satisfy this requirement. Even so, linear nonadiabatic models fail to show instability in early B stars at the periods reported for the periodic Be stars (Balona & Dziembowski 1999).

If the model of corotating photospheric clouds is correct, weak magnetic fields (50–100 G) are required to anchor the clouds to the photosphere. Direct evidence for magnetic fields in Be stars is negative (Bohlender 1994), although observations of X-ray and UV flaring provide indirect evidence (Smith, Robinson & Corbet 1998). We suggest that the observations discussed here provide further, indirect, evidence for magnetic fields.

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