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THE FK COMAE CANDIDATE UZ LIBRAE

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ABSTRACT

New optical spectroscopic and photometric data are presented for the active chromosphere FK Com candidate UZ Lib. The star is shown to have an extremely large photometric amplitude in V of 0.35 mag, and its rotation period is established as 4.75 ± 0.01 days. The optical spectrum is that of an early K giant, broadened by a rotation velocity of ~ 65 km s^{-1}. Hα is visible as a very broad emission feature, with a profile resembling that seen in FK Com. The emission intensity and profile are variable over the rotation period, with the strongest emission present at photometric minimum, in accord with dark starspot models. The photospheric absorption line profiles show variable asymmetries and distortions which we interpret as due to the effects of the dark starspot rotating across the line of sight.

New radial velocity measures are combined with published data to demonstrate that UZ Lib is a member of a binary system, in synchronous rotation with a secondary of mass $\sim 0.5\ M_{\odot}$. This information is considered in light of the conflicting models for the origin of the optical and spectral variability of the FK Com stars, as well as their uncertain evolutionary status.

Subject headings: stars: binaries — stars: chromospheres — stars: emission-line — stars: individual — stars: rotation

I. INTRODUCTION

The class of variables known as FK Comae stars has been defined by Bopp and Stencel (1981, hereafter Paper I) as consisting of late-type giant stars with very high values of $v \sin i$ (75–100 km s^{-1}) and evidence for extreme chromospheric activity, and which show no sign of large velocity variations. Three stars were assigned to the FK Comae class in Paper I: the prototype, FK Com; the G5 III–IV star HD 199178; and the rapidly rotating K giant UZ Librae. Additional spectroscopic and photometric observations of HD 199178 ($V \sim 7.2$) have been reported by Bopp (1982) and Bopp *et al.* (1983), which confirm many of the similarities between FK Com and HD 199178, though the evolutionary status of these objects is admittedly uncertain. At $V \sim 9.3$, UZ Lib is the faintest of the three stars proposed in Paper I as FK Com objects, and until now not even its photometric period has been established.

This paper presents new optical photometry and spectroscopy of UZ Lib obtained at Kitt Peak National Observatory (KPNO) during 1983. The photometric and spectroscopic variability of UZ Lib is shown to be explicable in terms of cool starspots on a rapidly rotating K giant. In contrast with FK Com and HD 199178, the velocity of UZ Lib is shown to be variable with a range of ± 40 km s^{-1}. A binary orbit for the star is presented, with the revolution period 4.76783 days. The period of rotation is established from optical photometry as 4.75 days, implying synchronism. The mass ratio of the single-line binary (SB1) is $\sim$4:1. Finally, the new information regarding the binary nature of UZ Lib is used to rediscuss the nature of the FK Com phenomenon, as well as the evolutionary status of these variables.

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II. OBSERVATIONS

UBV photometric observations of UZ Lib were obtained at KPNO during the interval 1983 March 30–May 31. The No. 2 0.9 m telescope was used with the automated filter photometer and a dry-ice cooled 1P21 photomultiplier. Standard *UBV* filters were employed, with a redleak filter to remove the long wavelength transmission of the U filter. The comparison stars used for our differential observations were C1 = BD −07°4044, C2 = BD −08°3998, the same stars used by Rucinski (1981). Magnitudes and colors derived for these comparisons are given in Table 1. The sequence of observations was C1–UZ–C1–UZ–C1–C2–C1, with 10 s integrations per star and with sky measurements taken after each stellar observation.

Since data collection was done in a structured and repetitious manner, a differential photometry program (DPHOT) was implemented on the Varian 620/f computer at the No. 2 0.9 m telescope. The program allows the computer to control telescope pointing, filter sequencing, and data acquisition, and to display raw differential magnitudes. The data were transformed to the Johnson system using the matrix inversion method described by Harris, FitzGerald, and Reed (1981). Approximately 30 standard stars were observed each night to

TABLE 1
COMPARISON STAR MEASURES

Star	V	$(B-V)$	$(U-B)$	Source
BD −07°4044 (C1)......	9.402 $\pm$0.004	1.100 $\pm$0.002	0.989 $\pm$0.006	This paper
	9.406 $\pm$0.011	1.077 $\pm$0.010	0.946 $\pm$0.061	Rucinski 1981
BD −08°3998 (C2)......	8.962 $\pm$0.004	1.176 $\pm$0.003	1.114 $\pm$0.010	This paper
	8.974 $\pm$0.009	1.156 $\pm$0.014	1.103 $\pm$0.112	Rucinski 1981

give a 1% accuracy in the transformation. The internal *precision* of the observations is of order 0.005 mag.

The spectroscopic observations of UZ Lib were obtained at KPNO from 1983 March 27–April 1. The weather was excellent during this interval, and data were obtained on six consecutive nights. The coudé feed telescope was used with an RCA CCD detector at camera number 5 to obtain spectral data over the wavelength interval $\lambda\lambda$6400–6650, with two pixel resolution ~0.9 Å. Integrations of 1500 s yielded 600–900 counts per pixel in the continuum. With the exception of March 29, multiple integrations were made on each night and the individual scans co-added to obtain 1500–3000 counts per pixel, or a signal to noise of ~40–50:1.

The reduction of the CCD scans took place in a standard fashion, using KPNO routines. Flat-field corrections were applied using observations of a quartz lamp; wavelength calibration was provided by an iron-argon hollow cathode lamp.

III. RESULTS AND DISCUSSION

a) Photometry

Photometric measures of UZ Lib are presented in Table 2. Standard period finding techniques applied to the V data yield a best-fit period 4.75 ± 0.01 days, and the data are plotted with respect to this period in Figure 1. Note that the spacing of our photometric observations specifically precludes the 9.50 day period suggested by Wisniewski (1973). The correct period is half that value, a possibility first suggested by Evans and Bopp (1974).

The 1973 observations presented by Wisniewski have been reanalyzed, and we present an amended light curve in Figure 2. The earlier data extend over an interval of ~100 days, and a period search yields $P = 4.7441 \pm 0.0002$ days, essentially identical to that derived from the 1983 data. Note, however, the change in mean light level between the two sets of photometry: UZ Lib was nearly 0.2 mag brighter in 1983. The shape of the light curve has also changed substantially between 1973 and 1983. Hoffmann (1980) noted this same effect in photometric data obtained in 1977—his light curve (phased with a 4.75 day period) showed suggestions of *two* minima, separated in phase by 0.3.

TABLE 2

PHOTOMETRY OF UZ LIBRAE

H.J.D. 2440000+	V	$(B-V)$	$(U-B)$
5423.969......	9.136	1.065	0.695
5424.866......	9.237	1.059	0.653
5424.890	9.251	1.060	0.683
5424.938......	9.264	1.064	0.657
5424.961......	9.270	1.063	0.688
5425.836......	9.475	1.070	0.728
5425.886......	9.460	1.078	0.691
5447.835......	9.144	1.043	0.640
5448.926......	9.329	1.067	0.690
5449.843......	9.421	1.078	0.668
5449.931......	9.418	1.055	0.696
5450.869......	9.300	1.070	0.628
5450.969......	9.289	1.052	0.673
5451.850......	9.151	1.055	0.608
5451.912......	9.119	1.042	0.661
5484.846......	9.201	1.051	0.655
5484.878......	9.190	1.059	0.647
5485.707......	9.147	1.054	0.686
5485.735......	9.150	1.053	0.691

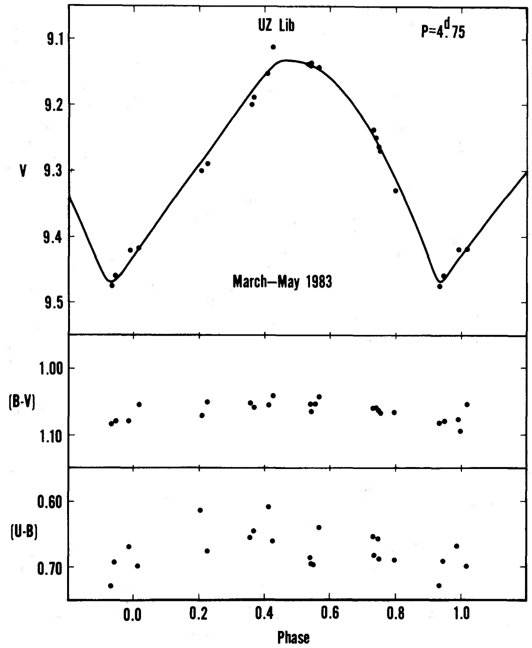

FIG. 1.—The light curve of UZ Lib during the spring of 1983. Phase is computed as ϕ = J.D. 2443222.15 + 4.75E (Hoffmann 1980).

All of this photometric behavior is readily interpreted by the presence of spots on a rotating star (see, e.g., Vogt 1981; Bopp and Noah 1980). The spots must be cooler by at least a few hundred degrees than the surrounding photosphere. The variation in $(B-V)$ and $(U-B)$ shows the star to be redder at light minimum (Fig. 1), in agreement with the behavior expected for cool starspots (Vogt 1981).

The amplitude of the light variation in UZ Lib is extremely high for an active chromosphere star. Hall (1981) tabulates the photometric behavior of 69 RS CVn systems and related types. Of these, only four have ever exhibited photometric distortions as great as 0.25 mag; typically the stars have amplitudes of only 0.1 mag or less. In contrast, the three sets of photometric data on UZ Lib (Wisniewski 1973; Hoffmann 1980; this paper) all show a V amplitude >0.25 mag and the 0.35 mag amplitude seen in 1983 exceeds that of any of the stars listed by Hall (1981). It is necessary that nearly half the visible hemisphere of UZ Lib be covered by spots to produce such a light curve.

b) Spectroscopy

Figure 3 compares the Hα regions of UZ Lib and the rapidly rotating (but chromospherically inactive) giant 31 Com. The obvious peculiarity is the presence of strong, broad Hα emission in the spectrum of UZ Lib. Apart from this, the widths of the absorption lines are similar in both stars. The infrared energy distribution of UZ Lib is consistent with a spectral type K2 III (Bopp, Gehrz, and Hackwell 1974), so the absorption line intensities will not match precisely with those of the G0 III star. The $v \sin i$ of 31 Com is given as 80 km s^{-1} by Uesugi and Fukuda (1981), implying a comparable value for UZ Lib, in agreement with earlier visual estimates (Bopp 1982). We have confirmed this estimate by generating a series of artificially broadened line profiles for the chromospherically inactive star β Geminorum (K0 IIIb) from observations made with the same equipment. An excellent match with the absorption line profiles of UZ Lib was obtained with $v \sin i = 65 \pm 10$ km s^{-1}. The 4.75 day photometric period and this value for $v \sin i$ then

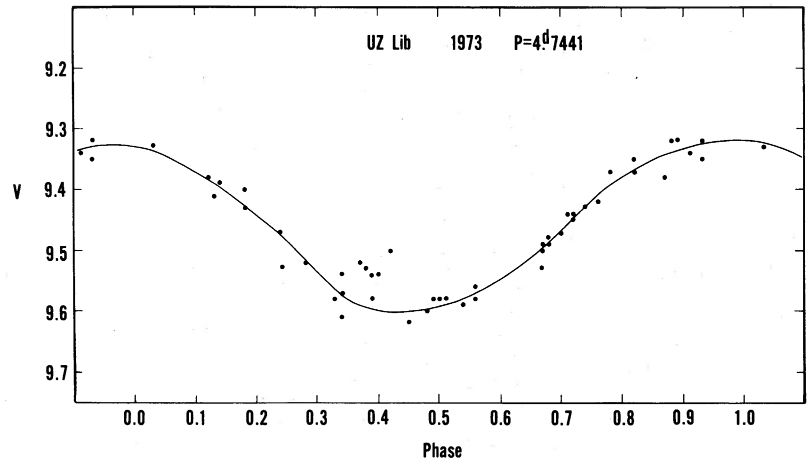

FIG. 2.—The light curve of UZ Lib from the published photometry of Wisniewski (1973). The data have been replotted with a best-fit period of 4.7441 days. Zero phase is taken as J.D. 2441000.

set a lower limit on the stellar radius of $\sim 6\ R_{\odot}$, supporting the classification of UZ Lib as a giant.

The Hα emission profile in UZ Lib is very similar to that of FK Com (Bopp 1982; Ramsey, Nations, and Barden 1981; Walter and Basri 1982). The double-peaked emission varies in violet-to-red emission asymmetry as well as overall intensity (Fig. 4), effects also noted in the spectrum of FK Com. The emission in UZ Lib varies in *antiphase* with the *V* light curve. The weakest Hα emission is seen on 1983 March 30 (phase 0.53) when the star is near maximum brightness (Figs. 1 and 4). Such behavior can be explained by the presence of a dark spot which is also a region of enhanced Hα flux. Identical Hα behavior has been described in the spectrum of the RS CVn binary UX Arietis by Bopp and Talcott (1978).

In the course of measuring the radial velocities of absorption features in the spectrum of UZ Lib (see below) we noticed that these line profiles exhibit varying asymmetries. Figure 5 illustrates the effect. We plot co-added scans of the wavelength region $\lambda\lambda$6420–6480 obtained on the six successive nights of the 1983 March observing run. The strong absorption features visible in this spectral region are due to Ca I (e.g., $\lambda\lambda$6439, 6450) or Fe I (λ6431). The bar in Figure 5 represents 10% of continuum intensity, and the co-added spectra show noise levels ranging from about 3% on March 27 and April 1 to 1–2% on March 31. The noise levels are a function of the total counts per pixel. For example, the March 31 data in Figure 5 represent four co-added scans (total integration time 6000 s) resulting in about 3800 counts per pixel. For comparison, the scan of 31 Com at the top of Figure 5 is a single scan of 200 s, with about 5500 counts per pixel.

The profiles of the absorption lines (note especially Fe I λ6431, Ca I λ6439) show distortions that vary over the six nights of observation. For example, on March 27 and April 1 the lines are asymmetric, with the intensity minima offset to the blue. On March 29 and 31, however, the lines appear symmetric, but with a bump at the bottom of the profile. These effects are admittedly near the noise and resolution limits of our data, but the distortions are seen in *all* the metal lines. Furthermore, we have never seen this behavior in CCD spectra that we have obtained of other, nonchromospherically active stars.

We interpret these effects as due to a dark spot (Fekel 1983; Vogt and Penrod 1983). The data presented by Vogt and Penrod show distortions of $\sim$2–3% in the $\lambda\lambda$6431, 6439 pro-

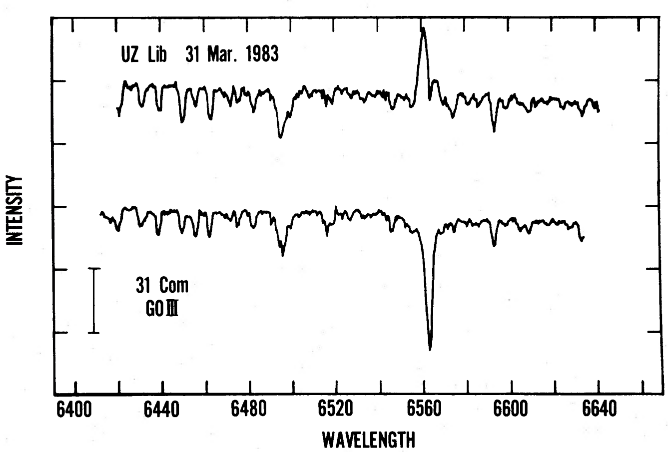

FIG. 3

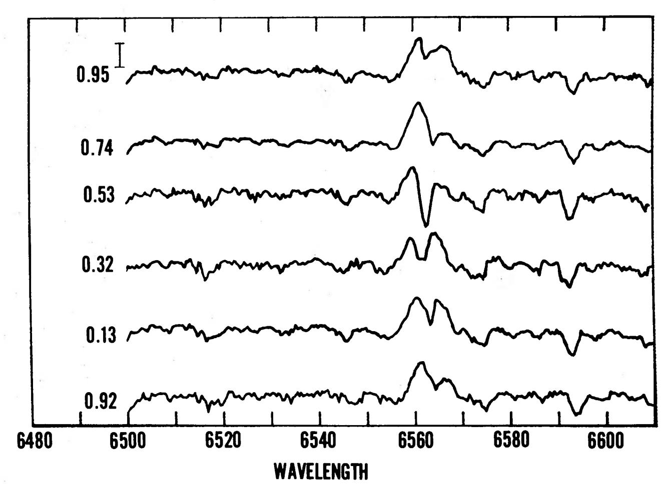

FIG. 4

FIG. 3.—The red spectral regions of UZ Lib and the rapidly rotating (but chromospherically inactive) G giant 31 Com. The bar represents 25% of normalized continuum intensity.

FIG. 4.—Co-added scans of the Hα region of UZ Lib on six successive nights, March 27 (*bottom*) to April 1 (*top*). Photometric phases, as in Fig. 1, are indicated at the left. Note that the weakest Hα emission occurs at $\phi = 0.53$, near *V* maximum.

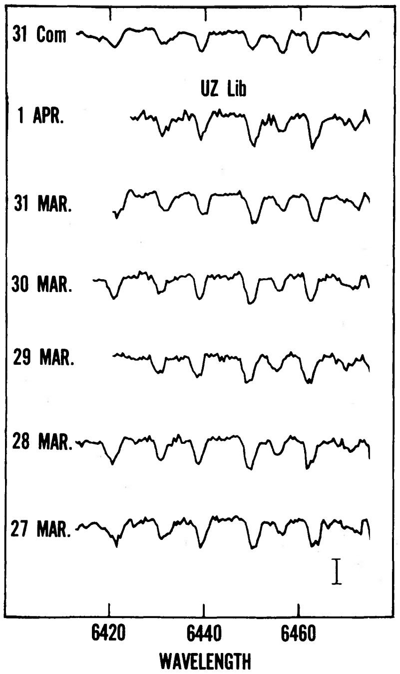

FIG. 5.—Co-added scans of the λ6440 region in UZ Lib on six successive nights, showing the variable absorption line profiles (see text for discussion). The bar represents 10% of normalized continuum intensity.

files in the active RS CVn binary V711 Tauri (= HR 1099). These distortions move across the line profile as the star rotates and may appear as bumps at the bottom of the profile, or as asymmetries in the line wings. Depending on the size and extent of the spot and the inclination of the stellar rotation axis, the distortions may disappear as the spot rotates out of view.

That UZ Lib should exhibit such effects, visible even with our relatively low spectral resolution, is not surprising. The 1983 photometry shows a very large amplitude, implying the presence of a large spot group. We then expect the profile distortions to be correspondingly large. However, any attempt to derive precise information on the location and extent of the spots from our line profiles (Doppler imaging) is hopeless. Vogt and Penrod claim signal to noise ratio of 100:1 and resolution 0.1 Å are necessary for Doppler imaging, and our data fall short of these values. The limitations are mostly those of limited resolution. Even though the $v \sin i$ of UZ Lib is 65 km s^{-1}, we record only 10 pixels across the line profile, whereas 50–100 pixels are probably necessary to reveal the detailed bumps that Vogt and Penrod illustrate in the profiles of HR 1099 and HD 199178.

c) *Radial Velocities and Orbit*

The apparent lack of any large radial velocity variations in any of the FK Com stars is an important aspect of the FK Com phenomenon, with significant evolutionary implications touched on in Paper I. Velocity measurements with precision ± 3 km s^{-1} have failed to find any evidence for a binary companion associated with other FK Com stars (Bopp 1982; Collier 1982; McCarthy and Ramsey 1984), but the velocity data in the literature do not approach this precision for the much fainter star UZ Lib. Accordingly, we devoted special care to the extraction of velocities from our 1983 CCD scans. The profile asymmetry discussed above is an obvious complication to velocity measures. We settled on a measurement technique where the absorption lines in the $\lambda\lambda$6400–6500 region were displayed on a graphics terminal, and a cursor positioned to bisect the line. Because of the bumps at the bottom of the profile, this part of the line was ignored during measurement. Independent measures by two investigators were made of half a dozen strong lines in each scan. The results show a scan-to-scan precision of about ± 5 km s^{-1}. No systematic effects greater than 1 km s^{-1} due to the measurer or to the spectrograph were apparent.

UZ Lib is variable in velocity. The CCD scans show a range in velocity from $+50$ to -10 km s^{-1}. The six nights of CCD data are clearly not adequate to define a velocity curve, but additional data are available. A few photographic spectrograms of UZ Lib had been obtained by one of the authors (B. W. B.) at KPNO and McDonald Observatory in 1974. The McDonald spectrograms are coudé plates of dispersion 18 Å mm^{-1}; those from KPNO are Cassegrain spectrograms (dispersion 39 Å mm^{-1}) obtained at the 2.1 m reflector. The internal errors of these spectrograms are 2–3 km s^{-1}. Lastly, Dr. Steve Vogt brought to our attention the substantial number of velocity measures of UZ Lib made at Kottamia during 1965–1966 (Woolley *et al.* 1981). The Kottamia data are derived from photographic spectrograms of dispersion 66 Å mm^{-1}. The internal errors of these measures are rather high, generally 7–9 km s^{-1}. Nevertheless, these measures also show UZ Lib to vary over a range ~ 60 km s^{-1}. Woolley *et al.* even suggest an orbital period near 4.75 days to fit their data, though no formal orbital computation was performed.

We subjected all the velocity data to standard period finding routines, and obtain a best fit at 4.76783 days. With this period, orbital elements were found by a least squares computer program. The derived elements are given in Table 3 and the velocity curve is plotted as Figure 6. The velocity observations, orbital phases, and residuals are given in Table 4.

Except for the period, the orbital parameters have relatively large errors, and we prefer to classify this orbit as preliminary. The large internal errors, especially those of the Kottamia observations, are most of the problem. This in turn may have been influenced by the profile asymmetries discussed above. At the same time, there is the suggestion of systematic velocity differences between the 1965–1966 Kottamia data (negative O $-$ C residuals) and the 1983 KPNO data (positive residuals). The accuracy of velocity measures is harder to evaluate than internal precision, but deviations as large as the nearly 20 km s^{-1} shown here are unlikely. In the case of both the Kottamia and KPNO observations there were frequent observations of velocity standards, and suitable velocity corrections derived from these observations were applied to the Kottamia measures (Woolley *et al.* 1981). The explanation for the systematic velocity discrepancy may again be the line profile asymmetries, or perhaps motion of the center of mass produced by a third body is the cause.

TABLE 3

PRELIMINARY ORBITAL ELEMENTS OF UZ LIBRAE

P =	4.76783 ± 0.000096 days
T(H.J.D.) =	2445427.48 ± 0.95
γ =	$+15.6 \pm 1.7$ km s^{-1}
K =	33.4 ± 2.3 km s^{-1}
e =	0.05 ± 0.07
ω =	$164 \pm 71°$
$a_1 \sin i$ =	$2.16 \pm 0.17 \times 10^6$ km
$f(M)$ =	$0.018\ M_{\odot}$

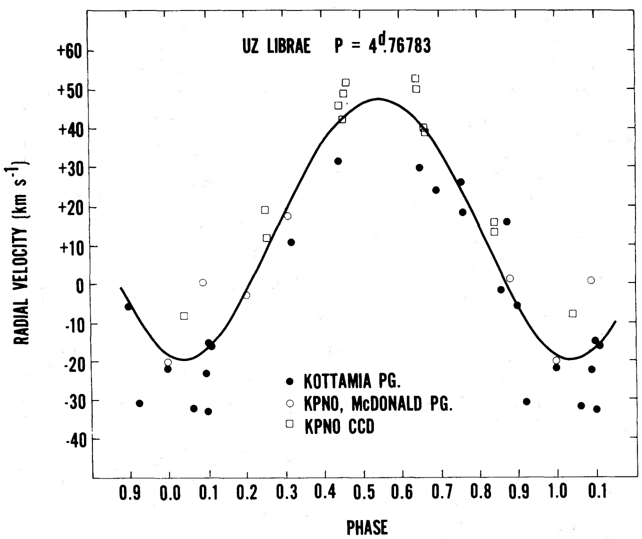

FIG. 6.—The radial velocity curve of UZ Lib.

TABLE 4

VELOCITY MEASURES OF UZ LIBRAE[a]

H.J.D. 2,400,000+	Phase	R.V. (km s^{-1})	O–C (km s^{-1})	Source
38842.498......	0.872	+16	+15.5	Kottamia
38843.564......	0.096	−23	−6.1	Kottamia
38843.590......	0.101	−33	−16.6	Kottamia
38843.622......	0.107	−16	−0.3	Kottamia
38847.494......	0.919	−31	−22.4	Kottamia
38851.504......	0.760	+18	−6.0	Kottamia
39207.567......	0.441	+32	−9.4	Kottamia
39208.560......	0.649	+30	−11.7	Kottamia
39209.581......	0.863	−2	−4.1	Kottamia
39210.535......	0.063	−32	−13.1	Kottamia
39213.521......	0.689	+24	−12.5	Kottamia
39214.542......	0.904	−5	+0.9	Kottamia
39215.501......	0.105	−15	+1.0	Kottamia
39216.510......	0.317	+11	−11.1	Kottamia
39218.581......	0.751	+26	+0.2	Kottamia
39224.507......	0.994	−22	−4.1	Kottamia
42089.978......	0.994	−20.1	−2.2	McDonald coudé
42090.974......	0.203	−2.6	−1.9	McDonald coudé
42227.706......	0.882	+1.3	+3.0	KPNO Cassegrain
42228.730......	0.097	+0.6	+17.4	KPNO Cassegrain
42229.752......	0.311	+17.6	−3.5	KPNO Cassegrain
45420.980......	0.636	+53	+10.0	KPNO CCD
45421.006......	0.642	+50	+7.6	KPNO CCD
45421.936......	0.837	+13	+5.2	KPNO CCD
45421.956......	0.841	+16	+9.1	KPNO CCD
45422.917......	0.042	−8	+11.4	KPNO CCD
45423.909......	0.250	+19	+10.3	KPNO CCD
45423.929......	0.254	+12	+2.5	KPNO CCD
45424.834......	0.445	+46	+4.2	KPNO CCD
45424.853......	0.448	+42	−0.2	KPNO CCD
45424.872......	0.452	+49	+6.4	KPNO CCD
45424.893......	0.457	+52	+9.0	KPNO CCD
45425.851......	0.658	+40	−0.7	KPNO CCD
45425.876......	0.663	+39	−1.1	KPNO CCD

[a] The McDonald coudé and KPNO Cassegrain measures have been given double weight in the orbital solution.

The mass function (Table 3) is small, indicating a companion of low mass. Applying Kepler's third law and assuming the mass of the visible primary to be $\sim 2\ M_{\odot}$, a secondary of $\sim 0.5\ M_{\odot}$ will produce the observed velocity amplitude. Given the uncertain evolutionary status of UZ Lib, it is not clear whether the secondary is a main-sequence M dwarf or an evolved object. White-dwarf companions to evolved, chromospherically active G–K stars are not unknown: 39 Ceti (G5 III + WD) is such an example (Simon, Fekel, and Gibson 1982).

The orbital and rotational periods are nearly identical, implying synchronism. The time scale to achieve synchronism for a star with a convective envelope has been investigated by Zahn (1977). For the values of orbital period and mass-ratio we derive, this time scale is a few $\times\ 10^7$ years. Even if the system was not synchronously rotating when unevolved, synchronism would have been quickly achieved as evolution to the giant branch occurred.

IV. UZ LIBRAE AS AN FK COMAE STAR

We ascribed particular significance in Paper I to the apparent lack of velocity variations among the FK Com stars. It was noted that both the apparent *level* of chromospheric activity, the high rotation velocity, and the lack of any large velocity variations set these objects apart from the RS CVn binaries, and posed an evolutionary puzzle: what are the progenitors of the FK Com stars? The original suggestion (Bopp and Rucinski 1981; Paper I) was that these stars are the coalesced remnants of the W UMa binary systems, following a theoretical evolutionary scenario by Webbink (1976). The observations by Ramsey, Nations, and Barden (1982) explained the broad Hα emission in FK Com as arising in a disk surrounding a single star in the post-coalescence stage (a feature also predicted by Webbink's scenario). However, Walter and Basri (1982) have suggested that FK Com is instead a high mass-ratio binary (thus predicting only a very small velocity amplitude) with the more massive evolved primary accreting material from a low-mass companion. In this model, the Hα emission is produced by the accretion stream; the photometric variations have their origin in a bright spot where the accretion stream hits the stellar surface, rather than in a cool, dark starspot.

It has not been established which of these models is "correct." Recent photometry (Dorren, Guinan, and McCook 1983) show changes in amplitude and phase that appear to weigh heavily against Walter and Basri's bright spot accretion model. Additionally, the observations of McCarthy and Ramsey (1984) have set new limits on the velocity variations that are, they claim, inconsistent with binary accretion models. On the other hand, *IUE* observations reported by Walter *et al.* (1983) show emission asymmetries in Mg II *h* and *k* that are apparently explicable by an accretion stream.

It would appear initially that the binary nature of UZ Lib reported here supports Walter and Basri's model. Admittedly the 4:1 mass ratio we derive for UZ Lib is not as extreme as the 20:1 proposed by Walter and Basri for FK Com (the mass ratio must be greater than 40:1 if we incorporate the new velocity limits by McCarthy and Ramsey), but the resemblances between FK Com and UZ Lib (spectral type, photometric wave, $v \sin i$, Hα profile) are many.

But despite the fact that UZ Lib is a binary, the catalog of similarities between this star and FK Com does not, we believe, support the binary accretion model for FK Com; rather, it argues against this model. None of the unusual characteristics of UZ Lib relies on its binary nature. Certainly the binary companion has induced synchronous rotation and the rotation has in turn driven the dynamo. However, the photometric behavior is unquestionably the effect of a *cool* spot. The Hα emission, whatever the ultimate cause of the bizarre profile, is weakest at light minimum; its behavior depends on rotational, not orbital, phase. The absorption line profile asymmetries are also the result of a cool spot.

Thus the photometric and spectroscopic behavior of UZ Lib is entirely consistent with its being a very chromospherically active star. As many authors have stressed, the clue to such activity lies in stellar rotation and not in stellar duplicity.

Is UZ Lib an FK Com star? If we require such objects to show no detectable velocity variations (part of the Paper I definition), then the answer is no. Rather than feeling a slight sense of disappointment (we have, after all, just eliminated a sizable fraction of all known FK Com stars!), we emphasize that the similarities between UZ Lib and FK Com, especially the Hα emission profile, cannot be overlooked. Like the behavior of UZ Lib, that of FK Com has its origin in extreme chromospheric activity. FK Com may yet prove to be a binary, but a mass accretion mechanism is not the likely origin of its spectroscopic and photometric peculiarities.

We are grateful to Dr. Steve Vogt for leading us to the important set of Kottamia velocity measures of UZ Lib. Dr. Margaret Penston's courtesy in forwarding us a copy of this reference is appreciated. Research on chromospheric activity at the University of Toledo is supported by grants from NSF (AST 81-15098) and NASA (NAGW-229).

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