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Observations of active-chromosphere stars – V. A photometric study of the RS CVn system CF Tuc (HD 5303)

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ABSTRACT

The Wilson–Devinney program is used to model 27 light curves (our own and others) for CF Tuc. We find new parameters for the binary system, and estimate the longitudes and radii of the spots on the cooler secondary star. We also find a strong tendency for spots on the cooler star to appear in a limited range of longitudes, rather than to migrate fairly rapidly as for other RS CVn systems. There is evidence that the mean light level of the cooler star is varying cyclically.

The orbital period clearly changes discontinuously. We discuss this, and the apparently cyclic variations in mean light level, in relation to the model proposed by Applegate.

Key words: stars: activity – binaries: eclipsing – stars: chromospheres – stars: individual: CF Tuc – stars: late-type.

1 INTRODUCTION

The RS CVn stars are binary systems that display starspots and high chromospheric activity. Linsky (1984) provided a classification scheme for these systems, partly based on the tidal synchronization time for stars with convective envelopes. He showed that subgiants with orbital periods less than 20 d should be tidally synchronous, and that the consequent rapid rotation should make them active stars due to the generation of strong magnetic fields by dynamo processes in a convective atmosphere. This idea separates the RS CVn systems (with periods of up to 20 d) from the so-called long-period RS CVn systems with periods longer than 20 d. The short-period cut-off is more difficult to define, but contact binaries with a common coronal envelope are usually excluded.

In addition to evidence of enhanced chromospheric and photospheric activity (strong UV emission lines, radio and X-ray outbursts, starspots and transient Hα emission features), some RS CVn systems show spectroscopic and photometric evidence for intrasystem matter, and undergo changes in orbital period. This paper presents an investigation of the RS CVn system CF Tuc (HD 5303), a relatively bright ($V \sim 7.0$) eclipsing binary with a period of about 2.8 d. The primary eclipse has a depth of about 0.3 mag in *V*. The spectral classification most compatible with the system's properties is G0V/IV + K4V/IV (Cutispoto & Leto 1997). A radial velocity study by Collier, Hearnshaw & Austin (1981) gave an orbital period of 2.798 ± 0.001 d. Eggen (1978) mentioned that the system may be a member of the 61 Cygni moving group.

Thompson, Coates & Anders (1991) were the first to suggest that the orbital period of CF Tuc changes, possibly increasing at a constant rate. While period changes are common for RS CVn systems, a constantly increasing period would be unusual. They pointed out that there are few plausible mechanisms to produce a constantly increasing orbital period for this system. For example, a mass-transfer mechanism is excluded because a very high mass-transfer rate is required from the hotter star (which is far from filling its Roche lobe) to the cooler secondary. At that time it was difficult to decide whether the (O − C) curve (observed minus calculated) would be better fitted by a smooth parabola or by discontinuous line segments. Given the extensive photometry to which we now have access, we can explore these possibilities further.

In this paper we extend the analysis of spots on CF Tuc by Anders, Coates & Thompson (1991), and discuss the results in terms of physical changes in the system, particularly in relation to the mechanism proposed by Applegate (1992) for orbital period modulation in close binaries. Our photometric data concerning longitudes and sizes of spots are similar to those found by Budding & Zeilik (1995); however, we find no support for their suggestion that the ratio of the stars' luminosities is significantly different from that found by previous workers (e.g. Coates et al. 1983, hereafter CHST), nor for their postulate of four quadratically arranged spots on the secondary to depress its luminosity without producing detectable photometric modulation.

2 OBSERVATIONS

Due to CF Tuc's large southerly declination, the system can be

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Table 1. Sources of photometric data and derived times of primary eclipse in cases where the phase coverage permitted.

Source of data	Derived times of primary eclipse HJD - 2400000.0	Data set in Fig. 1
Lloyd Evans & Koen (1987)	43869.524 ± 0.025	a d g
Lloyd Evans & Koen (1987)	44219.270 ± 0.005	a d g
Lloyd Evans & Koen (1987)	44541.013 ± 0.005	a d g
Collier et al. (1981)	44510.227 ± 0.003	b e
Monash data	–	c
Monash data	44513.024 ± 0.003	f
Rucinski (1983)	–	h
Coates, Innis, Thompson (1983)	–	h
Budding & McLaughlin (1987)	45606.914 ± 0.003	j
Monash data	45609.711 ± 0.003	i
Rounthwaite (1988)	46390.265 ± 0.003	k m
Cutispoto (1990)	46801.530 ± 0.003	k m
Monash data	46695.221 ± 0.003	l
Monash data	47000.175 ± 0.002	n
Cutispoto (1991)	47137.272 ± 0.005	p
Rounthwaite (1992)	47168.034 ± 0.006	o s u x
Rounthwaite (1992)	48606.085 ± 0.003	o s u x
Cutispoto (1995)	47878.671 ± 0.003	r
Monash data	47929.030 ± 0.003	q
Cutispoto & Leto (1997)	48141.655 ± 0.005	t
Monash data	48259.154 ± 0.008	v
Monash data	48922.231 ± 0.003	–
Monash data	–	w
Rounthwaite (private communication)	49285.931 ± 0.003	y
Donati et al. (1997)	49347.491 ± 0.001	–
Monash data	49353.077 ± 0.003	–
Rounthwaite et al. (1996)	50351.827 ± 0.003	z aa
Monash data	50388.182 ± 0.003	–
Monash data	50665.152 ± 0.004	–

observed from the southern hemisphere for most of the year. Sources of photometric data used in this paper are given in Table 1. Some data could be used to determine a time of primary eclipse, some yielded well-defined spot waves, and some provided both.

For the Monash data in Table 1, HD 5499 was the primary comparison star, and HD 5210 was the check star. Both stars are within 1° of CF Tuc, resulting in small corrections for differential extinction. In the differential photometry we take $V_{5210} = 8.691$ and $V_{5499} = 6.685$.

Measurements were made with a range of photometers at the Monash Observatory and at the Mount Stromlo and Siding Spring Observatories. Differential photometry was used, and the data were standardized to the Cousins system by calibrating the instruments using standard stars.

3 ANALYSIS AND DISCUSSION

3.1 The light curve and derivation of the spot wave

Budding & McLaughlin (1987) obtained light curves in *U*, *B* and *V*, which they modelled satisfactorily on the assumption that the binary was free of starspots at that epoch (1983 September to 1984 March). They used a revised version of an optimal curve-fitting program described by Budding & Najim (1980). We repeated their analysis using the 1998 version of the Wilson–Devinney program described by Wilson & Devinney (1971, hereafter WD) and Wilson (1979, 1990), and kindly provided by Professor R. Wilson. Our results are similar to those of Budding & McLaughlin, except that we find the effective temperature T_2 of the cooler secondary to be 4310 K rather than 4500 K, and the radius of the hotter primary to be larger than that found by Budding & McLaughlin. Uncertainty regarding the value of T_2 may arise because it actually varies (see Section 3.4 below)

Table 2. Fixed and adjusted parameters for the binary (WD terminology).

Fixed Parameters		Adjusted Parameters	
e	0.00	T_2	4310 K
$a/R_\odot$	11.9	Ω_1	7.1724
q (m_2/m_1)	1.17	Ω_2	4.8457
g_1	0.32	I	69°.3
g_2	0.32	r_1	0.167
A_2	0.50	r_2	0.303
X_1	0.62		
X_2	0.88		
T_1	6100 K		
T_{spot}/T_{star}	0.8		

The limb-darkening coefficients (X_1 and X_2) for the primary and secondary stars were based on the analysis of CF Tuc by Budding & McLaughlin (1987) and on values from Binnendijk (1974). The mass ratio (q) and orbital semimajor axis (a) came from the radial velocity data of Collier et al. (1981). The temperature of the primary star found by Budding & McLaughlin (1987) was approximately 6100 K, in good agreement with the value derived from the colour indices by Collier (1982). This value was therefore used in the modelling process, whereas the less certain temperature of the secondary was allowed to vary. Other parameters adjusted by the program were the orbital inclination (i) and the potentials Ω_1 and Ω_2 which, together with q and the eccentricity (e), define the size, surface gravity and other geometrical properties of the stars. The luminosity (L_1) of the primary star was allowed to vary, whereas the luminosity (L_2) of the secondary was coupled to the stellar temperatures, and was computed by the program from the other parameters using the blackbody law. The basic parameters for the binary are given in Table 2.

Budding & Zeilik (1995) find that $L_1 = L_2$ for the components of CF Tuc, based on deductions from infrared light curves obtained by Antonopolou (1987). To explain the light curves at visible wavelengths, they suggest the presence of four spots on the secondary star, equally spaced in longitude, which produce an almost undetectable modulation of the light curve but depress the overall light level. We believe that our values for the luminosities of the stars are physically more reasonable; in particular, the assumption of four long-lived, equally spaced spots is a little ad hoc, and such spots do not seem to occur in other RS CVn binaries.

In our analysis we followed Schüssler & Solanki (1992) and Budding & Zeilik (1995) by assuming one or two spots, each of temperature 0.8 of the photospheric value, fixed in latitude at +45° and at −45°. Using our derived parameters for the binary, preliminary longitudes and radii were found for each light curve listed in Table 1 for which there was adequate phase coverage so that the spot wave was sufficiently well defined. This was done using the program Binary Maker 2.0 (BINMAKE2) of Bradstreet (1993). The radii and longitudes of the spots were then refined using the routine DC in WD, keeping all other parameters constant.

We subtracted the 'immaculate' light curve from each of the light-curve data sets and from the fitted curves to produce the spot waves shown in Fig. 1 for the 18 years of photometry of CF Tuc. Curve Fig. 1(j) is, of course, the spot wave of the 'immaculate' star.

Table 3. Derived spot data. The longitudes *L* are given in radians (WD convention) and degrees (BINMAK2 convention). Radii are given in radians and degrees. The values of ϕ are the photometric phases at which the centre of the spot is presented towards the Earth.

Data set in Fig. 1	Mean date 1900+	L_1 rad	R_1 rad	L_2 rad	R_2 rad	L_1 deg	R_1 deg	L_2 deg	R_2 deg	ϕ_1	ϕ_2
a	79.0	3.392	0.631	3.227	0.750	166	36	175	43	0.96	0.99
b	79.7	3.226	0.808	5.419	0.606	175	46	50	35	0.99	0.64
c	79.8	3.083	0.828	5.570	0.824	183	47	41	47	0.01	0.61
d	79.8	3.354	0.775	5.211	0.737	168	44	61	42	0.97	0.67
e	80.6	3.257	0.605	5.231	0.644	173	35	60	37	0.98	0.67
f	80.8	3.156	0.447	4.718	0.274	179	26	90	16	1.00	0.75
g	81.7	3.421	0.568	6.226	0.564	164	33	3	32	0.96	0.51
h	82.4	3.185	0.438	–	–	177	25	–	–	0.99	–
i	83.7	2.174	0.392	6.172	0.762	235	22	6	44	0.15	0.52
j	83.9	–	–	–	–	–	–	–	–	–	–
k	85.9	3.139	0.483	5.764	0.705	180	28	30	40	1.00	0.58
l	86.6	3.370	1.145	5.734	1.154	167	66	31	66	0.96	0.59
m	87.1	3.483	0.893	5.663	0.925	160	51	36	53	0.94	0.60
n	87.6	3.368	0.871	5.352	0.955	167	50	53	55	0.96	0.65
o	88.0	3.700	0.583	4.006	0.618	148	33	131	35	0.91	0.86
p	88.0	3.315	0.640	4.616	0.812	170	37	96	47	0.97	0.77
q	89.9	3.158	0.681	0.937	0.447	179	39	306	26	1.00	0.35
r	90.0	3.303	0.729	0.963	0.460	171	42	305	26	0.98	0.35
s	90.0	3.206	0.659	–	–	176	38	–	–	0.99	–
t	90.8	3.768	0.572	1.703	0.402	144	33	262	23	0.90	0.23
u	91.0	3.826	0.607	0.068	0.536	141	35	356	31	0.89	0.49
v	91.0	3.913	0.562	–	–	136	32	–	–	0.88	–
w	91.9	3.652	0.668	5.975	0.922	151	38	18	53	0.92	0.55
x	92.0	3.938	0.408	5.597	0.905	134	23	39	52	0.87	0.61
y	93.9	3.335	0.425	5.929	0.871	169	24	20	50	0.97	0.56
z	95.8	–	–	5.989	0.812	–	–	17	47	–	0.55
aa	96.8	0.670	0.318	2.325	0.467	322	18	227	27	0.39	0.13

In Table 3 we give the derived spot parameters: longitude and radius given in radians for the WD program, in degrees for use in BINMAKE2, and in orbital phase to facilitate comparison with Fig. 1. Spot(1) is in the hemisphere tilted towards us, and so is the dominant spot. Spot(2) in the opposite hemisphere is not so well defined.

The longitudes and radii of the spots are plotted in Figs 2(a) and (b). Our findings confirm those of other workers, including Anders et al. (1991) and Budding & Zeilik (1995), that there is a strong tendency for spots in this system to be found for several years in a narrow range of longitudes just before the phase of primary minimum and just after secondary minimum.

Spot size maxima occurred in 1979 and 1986. At or near these times, abrupt changes occurred in the orbital period of CF Tuc, as will be shown in Section 3.4.

3.2 Changes in mean brightness level

It is now possible to estimate changes in the brightness of the immaculate binary, subject to the usual photometric difficulties. This could not be done from the spot waves alone, since the data were normalized prior to spot fitting. Therefore from each light curve of the original data we estimated the apparent *V* magnitudes at phases 0.25 and 0.75, and from the corresponding spot waves in Figs 1(a) to (aa) we read the flux levels at these phases and at maximum and minimum flux. Using these flux levels and magnitudes we obtained two estimates, which agreed within tolerance, of the *V* magnitude at maximum brightness $V_{\rm bri}$, and two at minimum brightness $V_{\rm dim}$. The difference between these two is the spot-wave peak-to-peak amplitude. This procedure is equivalent to sliding the immaculate *V* light curve up and down the magnitude axis on top of the observed light curve and noting the highest and lowest points of contact. This spot-wave amplitude is plotted in Fig. 3, and follows closely the radius of spot(1).

A new spot cycle clearly began in 1986, and possibly also in 1979 or just before. Significantly, sudden changes in orbital period occurred at 1980 and 1986. We discuss this in Section 3.4 in relation to the theory of Applegate (1992) for the mechanisms causing changes in orbital period for binaries containing active stars.

The mean of each pair $V_{\rm bri}$ and $V_{\rm dim}$ plotted in Fig. 3 can be taken as the average brightness level of the binary, neglecting eclipse effects. The seven points plotted as diamonds are mean light level data $V_{\rm ref}^{(c)}$ from Budding & Zeilik (1994) for comparison. There is not a strong decrease in brightness level when the spot size increased dramatically in 1986, showing that changes in spot-wave amplitude are due as much to *increases* in the brightness of the unspotted regions as to *decreases* in the brightness of the spotted hemisphere of the secondary star. This may be relevant to the so- called missing flux problem of where the energy goes when a spot makes the star dimmer.

Fig. 3 does, however, show that the mean light level varies slowly and systematically. Until 1986 the binary stayed at constant brightness, subsequently dimmed by about 0.065 mag in 1990/91, and then brightened again. This is again relevant to Applegate's theory discussed in Section 3.3.

3.3 The (O−C) diagram

In previous papers (Anders et al. 1991; Thompson et al. 1991), the

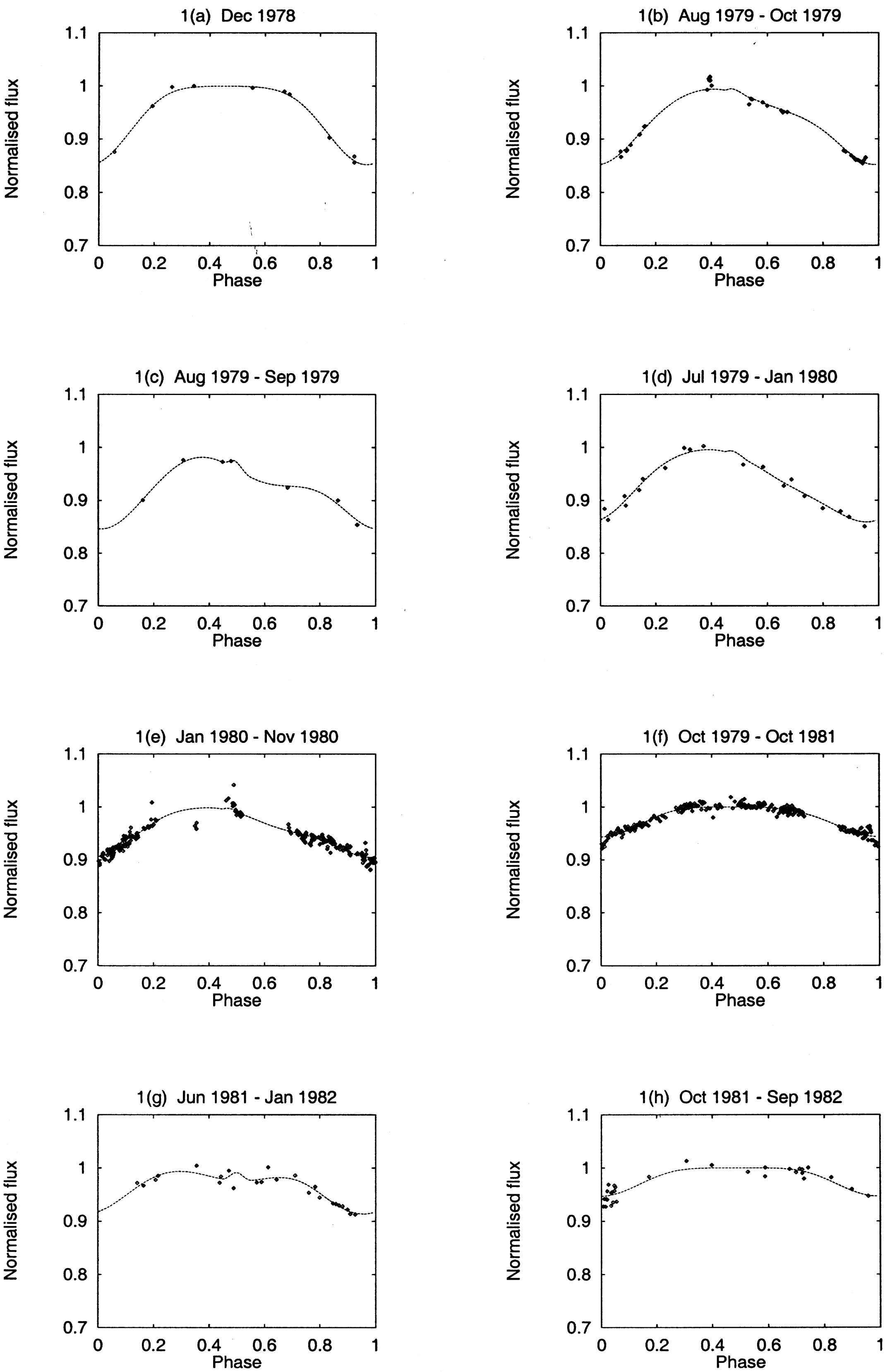

Figure 1. A series of 27 spot waves for CF Tuc derived as described in Section 3.1. Sources of the data are in Table 1.

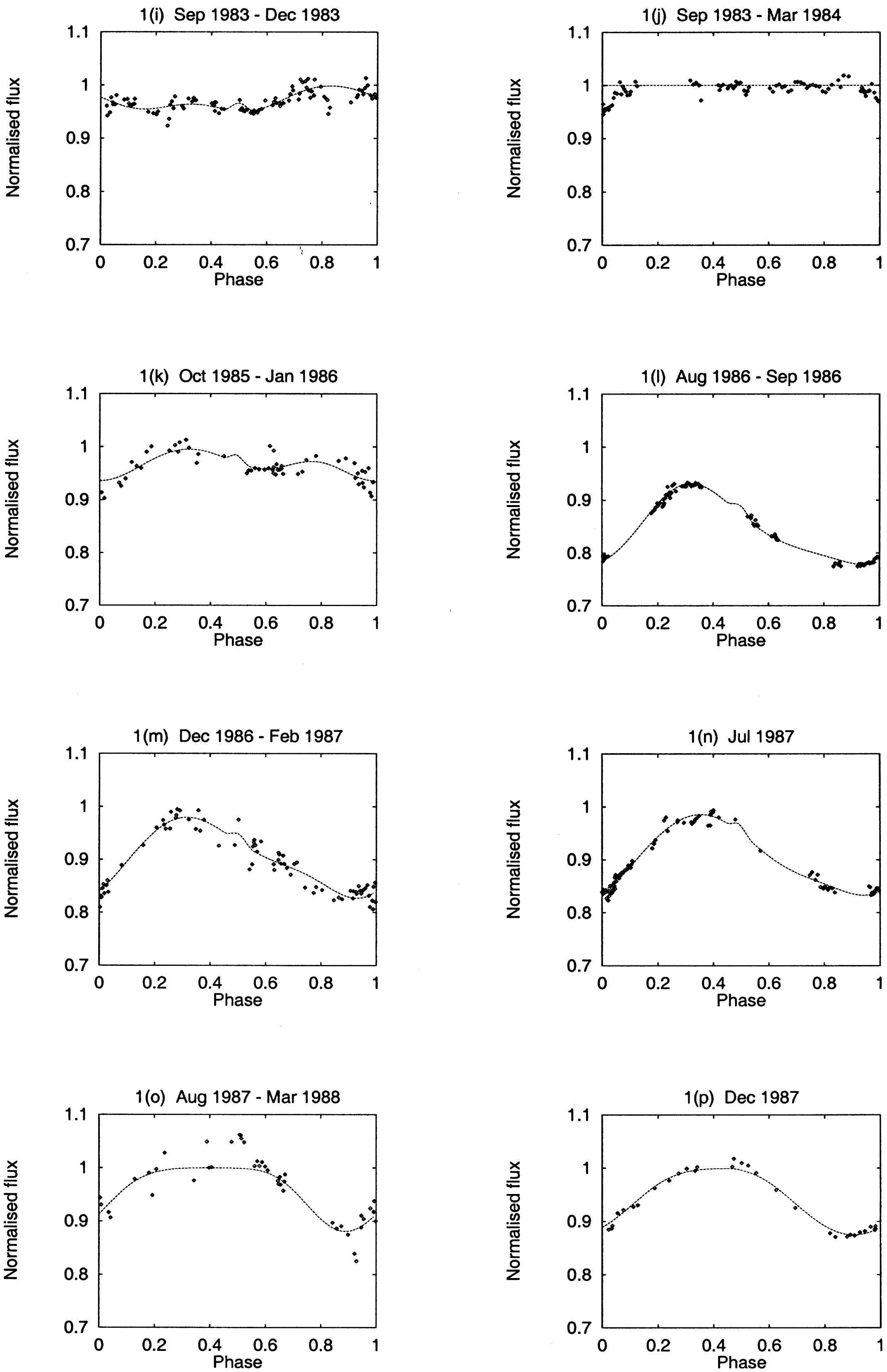

Figure 1 – *continued*

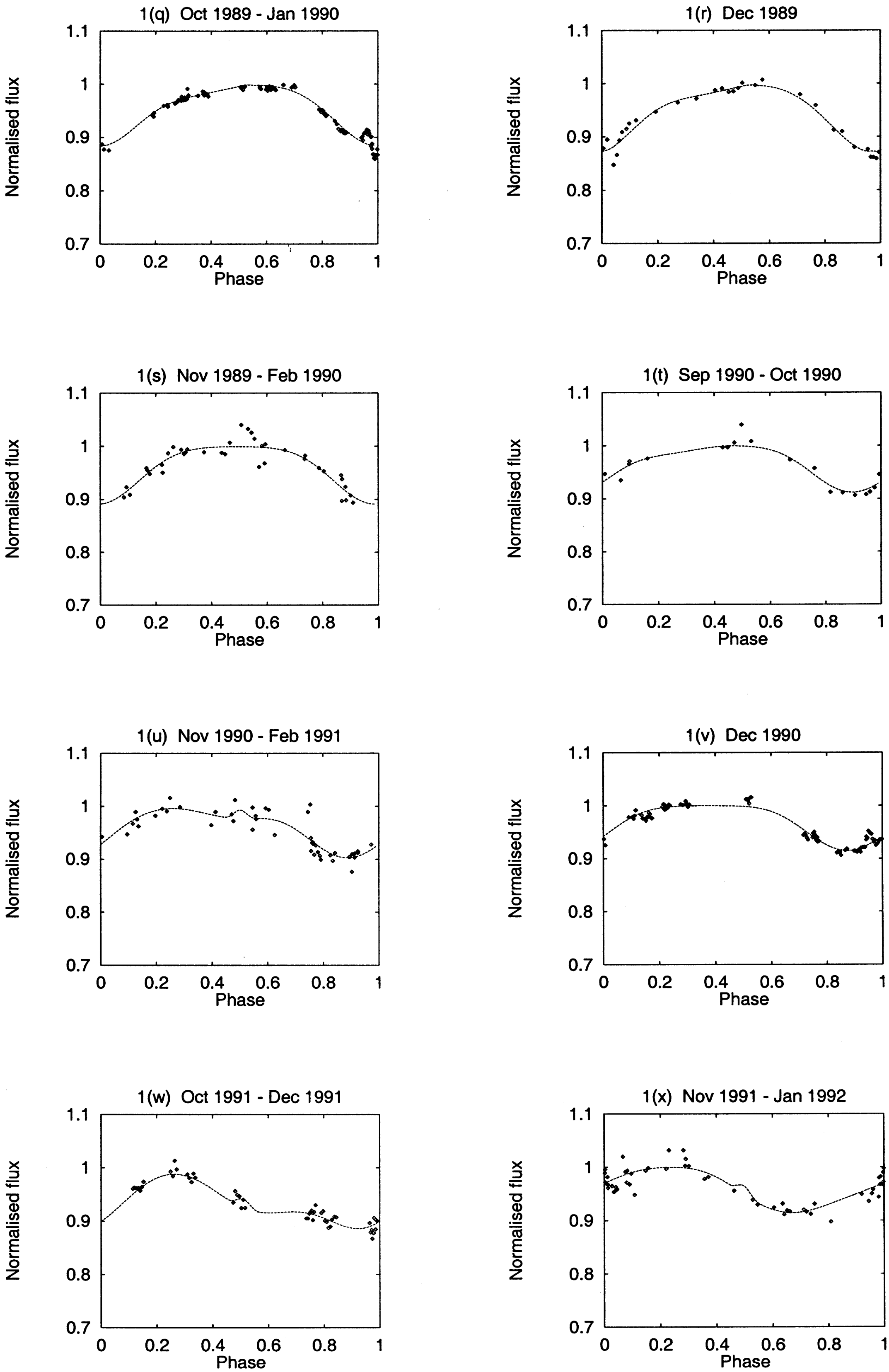

Figure 1 – *continued*

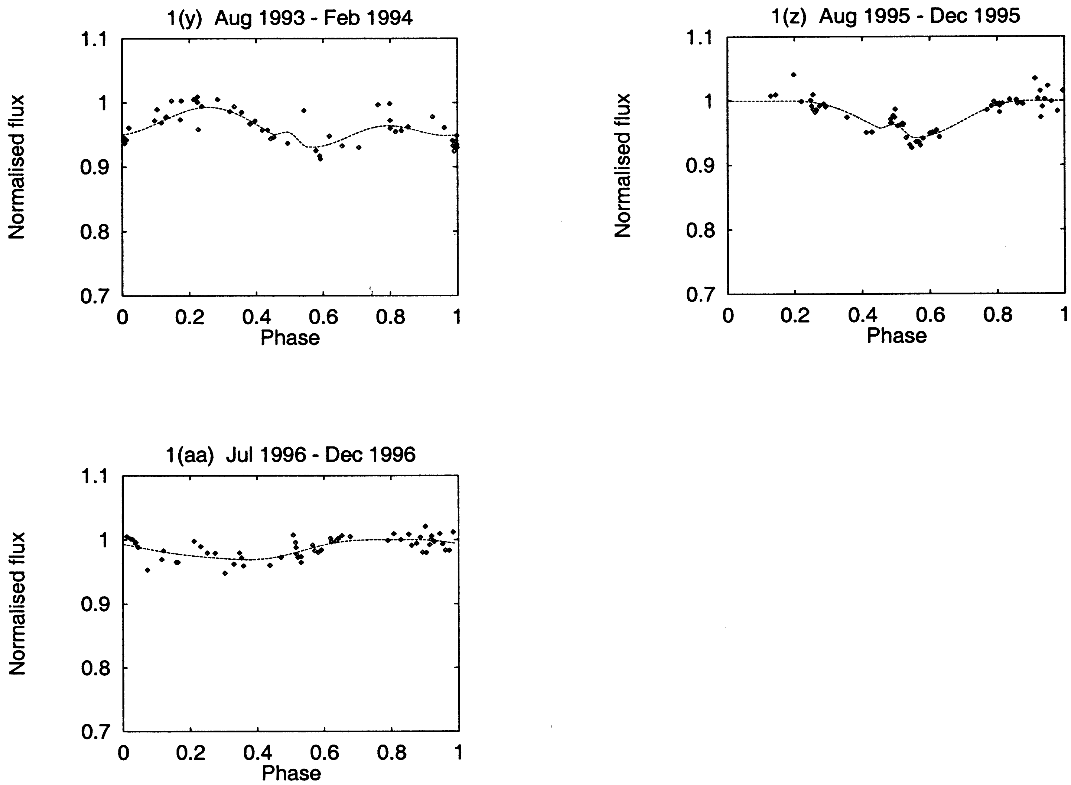

Figure 1 – *continued*

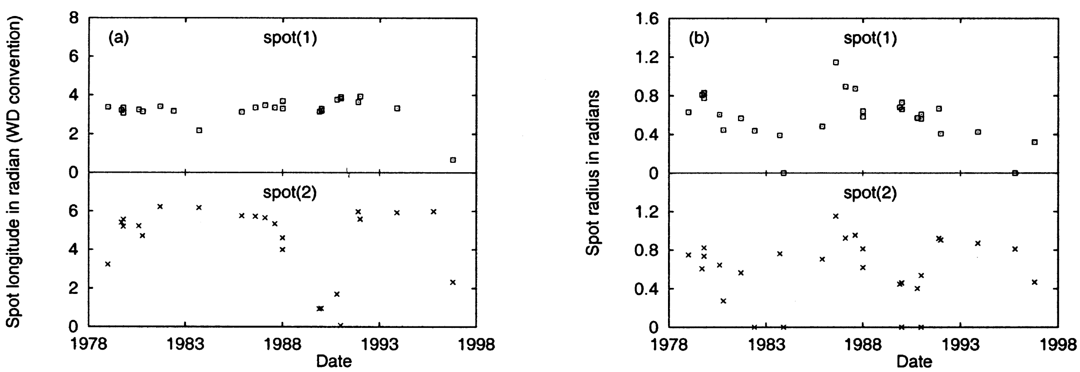

Figure 2. (a) The longitudes of the two spots derived from the curve fitting in Fig. 1, spot(1) is in the nearer hemisphere and spot(2) is in the further hemisphere. In some cases it is not clear which hemisphere the spots are in, particularly around 1996. There are clearly established preferential longitudes around 3 and 6 radians for the first portion, until new spots apparently develop in 1986–88. Thereafter, there seems to be a steady drift which is compatible with differential rotation. (b) The radii of the two spots in radians. There is a strong decay in spot area after 1979, a sudden increase in spot area from 1986 to 1988, and an increase from 1992 to 1996.

(O − C) data for the primary eclipse up to that time were well described by a parabola, and a steady rate of period increase was calculated for the system. However, the more recent data strongly suggest a series of discontinuous period changes. The analysis has therefore been repeated. From the available photometric light curves, 25 times of primary eclipse have been obtained (Table 1). The data near to phase zero were replotted, and the overlay reflection method used to find the time of mid-eclipse. In two cases the data provided only one side of the eclipse, and in these cases a template was overlaid.

The (O − C) data are shown in Fig. 4 according to the ephemeris 244 4219.270 + 2.797 715 × E. There is some evidence that (O − C) varies quasi-periodically, but we reject the hypothesis that this is due to motion about a third star, since a brief analysis assuming an amplitude of 0.015 d and a period of 13 yr gives the third star a minimum of 1 $M_{\odot}$, increasing as the orbital inclination decreases from 90°. The angular separation on the sky would be too small to reveal a visual binary, but no such third star has been needed in previous photometric or spectroscopic analyses.

We have included the point on the extreme left derived from the data of Lloyd-Evans & Koen (1987), even though the uncertainty is large, because of the relative importance of that point in

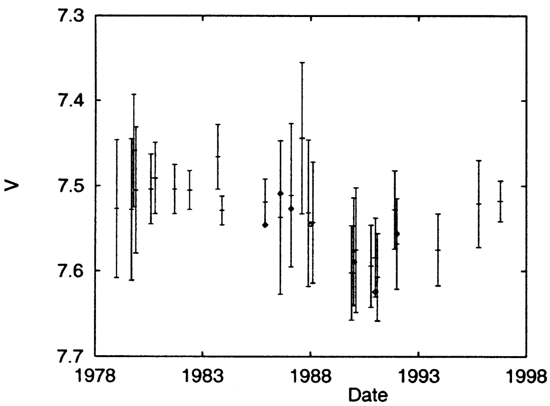

Figure 3. The depth and mean level of the spot wave or the maximum and minimum brightness of the binary, ignoring eclipse and reflection effects. The centre of each vertical bar shows the derived mean level. The extremities of the bar show the brightest (V_{bri}) and dimmest (V_{dim}) levels of the binary. The seven individual points are the mean levels as measured by Budding & Zeilik (1994). The system shows a sinusoidal variation in mean brightness, with a phase lagging approximately 90^0 behind the observed (O − C) diagram. In the period 1986–88 the increased spot-wave amplitude is revealed as due more to an increase in brightness on the brighter side of the secondary than a dimming on the dim side.

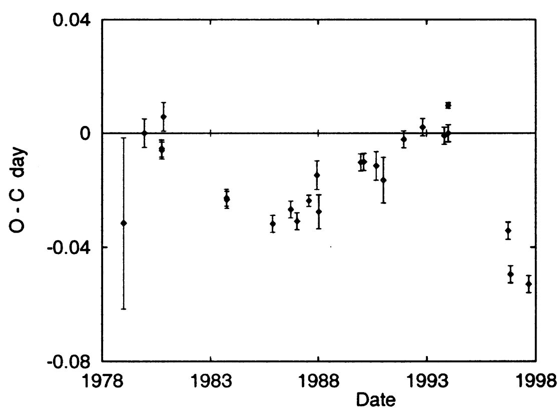

Figure 4. The (O − C) curve for CF Tuc derived from the times of primary eclipse shows period decreases in 1980 and 1993, and an increase in 1986. The value (O − C) = +0.01 d for 1994.0 is derived from high-resolution spectroscopy of Donati et al. (1997). All other data are from Table 1.

establishing a period change around 1980. We have also included a point derived from the high-resolution radial velocity data of Donati et al. (1997).

There is the obvious danger of fitting with a series of straight lines. Nevertheless, by eye, the data suggest a period decrease to a constant period of 2.797 67 d from 1980 to 1986, when there was an abrupt period increase to 2.797 78 d, until about 1994 whereupon the period again decreased to about 2.797 63 d. The changes in period are $\Delta P/P \sim 10^{-5}$ and are not well fitted by a sinusoid. If the periodicity is indeed about 13 yr, then we may expect an abrupt period increase in the next year or two, with a spot-wave amplitude increase.

3.4 The theory of Applegate applied to CF Tuc

Applegate (1992) produced a theory for the orbital period changes observed in active binary stars, which may be summarized as follows. The active star is deeply convective, and has differential rotation with depth and a magnetic dynamo. The internal magnetic field to some extent couples the differentially rotating layers. Changes in field strength at various stages in the magnetic cycle change the degree of magnetic coupling between the inner and outer portions of the star, thus exchanging angular momentum and changing the differential rotation at constant total spin angular momentum. The star's oblateness is determined mainly by the rotation of its outer layers, and so it changes through the cycle as the star's outer layers speed up or slow down. This change in oblateness changes the gravitational coupling to the companion star via the quadrupole moment, and produces changes in the orbital period at constant orbital angular momentum.

As the internal magnetic field rises to the surface and is released we may expect surface activity such as spots. As the differential rotation varies, so does the total kinetic energy of spin rotation, being minimum when the star is closest to solid-body rotation. This variation in kinetic energy is alternately added to or removed from the stellar flux. We may thus expect correlations between orbital period, the spot-wave amplitude and the overall brightness levels and therefore temperature and colour of the secondary star.

Following Applegate (1992), we apply his theory to CF Tuc as he has done to Algol and some other active binaries. The relevant data are taken from CHST: $M_{sec} = 1.205\,M_{\odot}$, $R_{sec} = 3.321\,R_{\odot}$, $L_{sec} = 1.14\,L_{\odot}$, $L_{pri} = 2.15\,L_{\odot}$ and $a(\text{separation})/R_{sec} = 3.307$.

The modulation of the (O − C) diagram with a $P_{mod} \sim 13$ yr and a semi-amplitude of 0.015 d gives $\Delta P/P = 2.0 \times 10^{-5}$. With the binary period 2.80 d, we have $\Omega = 2.6 \times 10^{-5}\,\text{rad}\,\text{s}^{-1}$ and $\Delta P = 4.8$ s.

Applegate's equation (27) gives the amount of angular momentum transferred by the magnetic field as $\Delta J = 4.6 \times 10^{48}\,\text{g}\,\text{cm}^2\,\text{s}^{-1}$. The moment of inertia of the outer shell is estimated as $I_s = 8.7 \times 10^{54}\,\text{g}\,\text{cm}^2$, so the transfer of angular momentum changes the outer shell speed by $\Delta\Omega = 5.3 \times 10^{-7}\,\text{rad}\,\text{s}^{-1}$, or $\Delta\Omega/\Omega = 0.020$.

Using Applegate's equation (28), we find that the kinetic energy change necessary to transfer this angular momentum is

$$\Delta E = 2.5 \times 10^{42} + 1.2 \times 10^{44}(\Omega_{dr}/\Omega)\,\text{erg},$$

where $\Omega_{dr} = \Omega_s - \Omega_*$ is the differential rotation between the outer shell (s) and the inner portion of the star (*), and we note that the first term on the right-hand side is much less than the second-term coefficient. If we assume that this energy is alternately given to and removed from the stellar flux *with no damping in the convective layer*, then using Applegate's equation (30) we may expect luminosity changes of

$$\Delta L_{rms}/L_{\odot} = 4.9 + 240(\Omega_{dr}/\Omega).$$

The observed light changes in Fig. 3 are ±0.065 mag in V for the whole binary (Section 3.2). Since the secondary contributes only 0.35 of the total light, its own brightness changes by ±0.19 mag, and so $\Delta L_{obs}/L_{\odot} = 0.20 = 4.9 + 240\,(\Omega_{dr}/\Omega)$, giving $(\Omega_{dr}/\Omega) = -0.02 = -\Delta\Omega/\Omega$. This identity of the differential rotation with the change in rotation of the outer layers is a result that Applegate obtains for almost all the stars he quotes in his paper. It is a direct consequence of the fact that the observed light level variations are too low compared with the Applegate prediction (Rodono, Lanza & Catalano 1995).

The equating of $(\Omega_{dr}/\Omega) = -(\Delta\Omega/\Omega)$ actually generates the situation where on exchange of the angular momentum the two portions of the rotating star swap roles. The faster becomes the slower and vice versa. Since the moments of inertia are postulated to be the same, there is *no net change in kinetic energy*, which is reflected in ascribing a negligible amount to the observed light variations. However, halfway through the kinetic energy transfer there will be solid-body rotation, so there is a reduced energy exchange at double the frequency. We reject this scenario where the star oscillates about a mean value of zero differential rotation, and prefer to postulate that the star oscillates between negative differential rotation and solid-body rotation, depending on the absence or presence of the subsurface field.

This indicates that the secondary star has a negative differential rotation gradient (the outer portion rotates more slowly) and varies between approximately solid-body rotation (with depth) and the outer portion slowing down by about 2 per cent. This changes Applegate's equation (28) to be

$$\Delta E = (\Delta J)^2/2I_{\rm eff} = 2.5\times10^{42}\,{\rm erg}.$$

From Applegate's equation (33) we deduce the subsurface field to be about 7.5 kG with an energy density of $4.0\times10^6\,{\rm erg\,cm^{-3}}$ which, if it holds over the whole volume of the star, is a total energy of 2×10^{41} erg. In 1987 there was a sudden brightening of the star (Fig. 3) by about 0.08 mag which, if sustained for 2 months, represents an extra energy of 10^{40} erg, which could easily be supplied by the decay of the subsurface field.

The observed magnitude changes, when ascribed to the secondary star only, imply a temperature which varies by ±140 K. This variation may account for the past difficulties in determining the secondary temperature from photometric or spectroscopic data. Such a temperature variation would give a variation in $(B-V)$ for the secondary star which, when diluted with the light of the primary, would produce a total colour change of about 0.015 mag. No significant long-term changes in $(B-V)$ have in fact been observed.

There remains the fact that the observed brightness changes are very much less than any predictions from the kinetic energy changes. We conclude that if the Applegate theory is valid, some allowance must be made for damping in the convective layers. If we represent the outer portion of the star as possessing a thermal capacity H [J deg^{-1}], we may set up the heat balance equations. There is a steady heat influx of $A = 7.8\times10^{26}$ W from the core, being the mean luminosity. There is an oscillating heat input/output from the kinetic energy of 2.5×10^{42} erg with the modulation period of 13 yr. ($\omega_{\rm mod} = 1.53\times10^{-8}\,{\rm rad\,s^{-1}}$.) This gives a term $B\sin(\omega_{\rm mod}t)$ where $B = 1.9\times10^{27}$ W. The heat will be dissipated by the surface of the star according to $A\ (T_{\rm eff}/4100)^4$ W.

The rate of rise in temperature of the outer portion of the star with thermal capacity H is given by

$$H\ {\rm d}T_{\rm eff}/{\rm d}t = A[1-(T_{\rm eff}/4310)^4] + B\sin(\omega_{\rm mod}t).$$

If the temperature and the luminosity lag by ϕ behind the oscillating term, then

$$T_{\rm eff} = 4310 + T_0\sin(\omega_{\rm mod}t-\phi),$$

where $T_0 = 140$ K, and we may approximate:

$$(T_{\rm eff}/4310)^4 = 1 + 4(T_0/4310)\sin(\omega_{\rm mod}t-\phi)$$

so that:

$$H\ T_0\omega_{\rm mod}\cos(\omega_{\rm mod}t-\phi) = -(4AT_0/4310)\sin(\omega_{\rm mod}t-\phi) + B\sin(\omega_{\rm mod}t).$$

This is solved to give $\tan\phi = 18$, or $\phi = 87°$, and $H = 9\times10^{32}\,{\rm J\,deg^{-1}}$.

Such a thermal capacity could arise in a combination of ways, on which we shall not speculate here. We only mention as illustration that the gaseous heat capacity of (1/50) of the stellar mass of monatomic hydrogen is sufficient.

We may sketch the recent history of the active component of CF Tuc: in 1979/80 there was an orbital period decrease, from which we deduce an increase in oblateness and a spin-up of the outer shell of the star. At the same time there was a large spot wave and area of spots in both hemispheres. From 1980 to 1986 the orbital period remained constant at 2.797 670 d. During this time the spots remained at orbital phases of approximately 0.95 and 0.67, and decayed in size. The overall brightness of the star was high, indicating closeness to solid-body rotation. We assume the subsurface field of about 7.5 kG was responsible for holding the star thus. In 1986 the orbital period increased to 2.797 748 d, i.e., $\Delta P/P = 2.8\times10^{-5}$, and there was a sudden brightening of the star, which was noticed on the side opposite the spot as seen in Fig. 3. We interpret this to be the release of the energy from the subsurface magnetic field, and suggest that the surface brightness of the whole star increased, but that this was masked on the dimmer side by the growth of the spot, which increased in area as seen in Fig. 2(b). The increase in orbital period means a decrease in the oblateness of the secondary star and an increase in the differential rotation which would have removed energy from the stellar flux. This is consistent with the observed overall dimming of the star seen after 1986. The star remained dim until about 1991, when it began to brighten, and in 1994 there was a sudden orbital period decrease to about 2.797 59 d. We interpret this to be the beginning of a new spot cycle similar to that begun in 1980.

4 CONCLUSIONS

The (O − C) diagram, the spot-wave amplitude and the overall brightness variations of the star are consistent with the Applegate theory, assuming a negative differential rotation gradient to solid-body rotation and considerable thermal damping in the star's outer layers. The sudden increases in brightness at the time of the spot growth in 1986 could be provided from the release of the magnetic field energy. The predicted $(B-V)$ changes are small enough to escape notice. The temperature variations assumed on the secondary are consistent with difficulties previous workers have had in assigning a temperature.

The overall brightness extrema of the star are not in phase with the (O − C) curve, which is itself not sinusoidal, but lags by about 3 or 4 years. This may in fact be most important, as Applegate says in his penultimate paragraph, 'A measurement of the relative phase between subsurface field strength and surface magnetic activity will be a very important constraint on dynamo models of magnetic activity.'

The constant spot longitudes could be due to the absence of any differential rotation due to the strong internal field. If the field relaxes after 1986, then differential rotation of an amount much smaller than is already observed in the Sun can account for the drifting of the two spots in opposite directions. The changes in surface rotation rate as revealed by the drift rate of the spots are however very much smaller than the 2 per cent predicted by the Applegate model, as was found by Rodono et al. (1995).

CF Tuc clearly needs constant monitoring for eclipse timing, spot-wave amplitude and overall mean brightness level. If colour measurements can be taken, then they are more likely to reveal any long-term changes if taken at primary eclipse.

We strongly suspect that there will be a period shift and an increase in the spot-wave amplitude sometime in the next two years.

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