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CHROMOSPHERICALLY ACTIVE STARS. VII. 39 CETI = AY CETI, HD 185151 = V1764 CYGNI, AND BINARY SYNCHRONIZATION

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ABSTRACT

Improved orbital elements have been determined for 39 Ceti and HD 185151. 39 Cet has a circular orbit with an orbital period of 56.82 days, which differs substantially from its rotational period of 75–78 days. An observation of the lithium region of 39 Cet shows that the G5 III component has almost no lithium in its outer atmosphere. HD 185151 has a circular orbit with an orbital period of 40.142 days and has a nearly identical rotational period. The large mass function suggests that the secondary is a late A to mid F type star whose continuum should be visible at ultraviolet wavelengths. The orbital inclination is estimated to be $62° \pm 12°$, while the distance is about 390 pc. Orbital and rotational periods are compared for 114 chromospherically active binaries. Only 7%–11% of the 94 systems with a period of 30 days or less are asynchronously rotating. About 50% of the 13 systems between 30 and 70 days are asynchronously rotating suggesting that there is still a tendency toward synchronization in this period range. The seven systems with periods greater than 70 days are nearly all asynchronously rotating.

I. INTRODUCTION

The spectroscopic characteristics of the chromospherically active binaries 39 Ceti = HR 373 = AY Ceti ($\alpha = 1^h14^m03\overset{s}{.}8$, $\delta = -02° 45' 46''$ (1950), $V = 5.47$, WD + G5 III) and HD 185151 = V1764 Cygni ($\alpha = 19^h34^m41\overset{s}{.}0$, $\delta = 27° 46' 17''$ (1950), $V = 7.69$ K1 III) have been discussed by Simon, Fekel, and Gibson (1985) and Bopp *et al.* (1982), respectively. 39 Cet is a late-type giant and single-lined spectroscopic binary. Ultraviolet observations showed that the secondary is a DA white dwarf with an effective temperature of about 18 000 K. The preliminary orbital period of 56.80 days found by Simon, Fekel, and Gibson (1985) is substantially shorter than the rotational period of 77.65 days determined from photometry (Eaton *et al.* 1983). Strassmeier *et al.* (1989) found a slightly different rotational period of 75.12 days from photometry obtained between 1983 and 1986. These slightly different rotational periods are presumably due to the latitudinal migraton of starspots. 39 Cet is one of a small number of chromospherically active binaries that is not synchronously rotating.

HD 185151 = V1764 Cyg is also a late-type giant and single-lined spectroscopic binary. The preliminary orbital period of 40.13 days found by Bopp *et al.* (1982) is twice as long as the period of the photometric light variations. They suggested that the light variations were caused by two starspots almost exactly 180° apart. Morris (1985) identified it as a possible ellipsoidal variable in his catalog of such stars. Lines *et al.* (1987) showed that the light variations were due primarily to the ellipticity effect that has a period of one-half the orbital period. In addition, they found light variations due to spots with a period of 39.9 days and a third possibly nonperiodic variation of unknown cause.

In this paper, we provide substantially improved orbital elements for each system and further discuss their properties.

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II. OBSERVATIONS AND REDUCTIONS

High-dispersion coudé spectroscopic observations were obtained at Erwin W. Fick Observatory, McDonald Observatory, and Kitt Peak National Observatory (KPNO). At Fick Observatory, the observations were obtained with a radial-velocity spectrometer. The telescope–spectrometer system and reduction procedures are described by Beavers and Eitter (1986).

Table I lists the telescope–detector combinations for the McDonald and KPNO observations. The photographic spectrograms obtained with the McDonald 2.1 m Struve reflector cover the wavelength region 3800–4600 Å. For each spectrogram, the radial velocities of about 20 lines were measured with the Grant-type measuring engine at Johnson Space Center, Houston, TX. A correction of -0.7 km s^{-1} (Fekel 1981) has been added to the McDonald photographic velocities to place them on the International Astronomical Union (IAU) velocity system (Pearce 1955). IAU Commission 30 is currently undertaking a major review of this velocity system to determine the zero point of the system as well as more accurate velocities of appropriate standard stars.

Almost all of the spectra obtained with solid-state Reticon detectors and charge coupled devices (CCDs) at McDonald Observatory and KPNO covered the wavelength region 6390–6470 Å. One spectrum of 39 Cet was obtained of the lithium region (6650–6740 Å). The McDonald and KPNO radial velocities were determined with a cross-correlation procedure described by Fekel, Bopp, and Lacy (1978). For 39 Cet, these radial velocities were determined relative to the IAU radial-velocity standards α Ari, β Gem, and ι Psc, for which the velocities are -14.3, 3.3, and 5.3 km s^{-1}, respectively (Pearce 1955). For HD 185151, the vast majority of the radial velocities were determined relative to μ Her for which we assumed a velocity of -15.0 km s^{-1} (Beavers and Eitter 1986). Although not an IAU velocity standard,

TABLE I. Telescope–detector combinations.

Telescope	Detector	Dispersion (Å mm⁻¹)	Resolution Å	Wavelength Range (Å)	Source Code
McDonald 2.1 m	IIaO plates	8.9	0.17	800	MP
McDonald 2.7 m	Reticon	4.4	0.24 or 0.36	110	MR1
McDonald 2.1 m	Reticon	9.5	0.56	235	MR2
Kitt Peak coudé feed	Fairchild CCD	14.8	0.45	165	KF
Kitt Peak coudé feed	RCA CCD	4.2	0.30	65	KR
Kitt Peak coudé feed	Texas Instruments CCD (TCCD)	4.2	0.21	50	KT1
Kitt Peak coudé feed	TCCD	7.6	0.23	90	KT2
Kitt Peak coude feed	TCCD	7.0	0.19	82	KT3

the assumed velocity appears to differ from the IAU standards used in this paper by less than 1 km s^{-1} (Beavers and Eitter 1986). Several velocities were determined relative to the IAU standards β Oph and α Boo, which have velocities of -12.0 and -5.3 km s^{-1}, respectively (Pearce 1955). One velocity was measured relative to HR 6469 Å, which was assumed to have a velocity of -1.2 km s^{-1} (Fekel unpublished) for this observation.

III. 39 CETI

a) Orbit

Table II lists 18 velocities from Fick Observatory, 15 from McDonald Observatory, and 23 from KPNO obtained between 1977 and 1987. Initially, an orbital element solution was computed for only the Fick velocities and a separate solution was computed for the combined McDonald and KPNO velocities. From a comparison of the center-of-mass velocities of the two solutions, -0.4 km s^{-1} was added to the Fick velocities. Then a combined solution with all velocities appropriately weighted was obtained. All but two of the McDonald and KPNO velocities were given unit weight. Those two observations, noted in Table II, were obtained through heavy cloud cover and the spectra had substantially lower signal-to-noise ratios than other similar observations and were given zero weight. The Fick observations listed by Beavers and Eitter (1986) were given weights of 0.3–1.0, appropriate to their quality classification, while more recent velocities were weighted according to their reciprocal variances. Four old Mount Wilson Observatory velocities (Abt 1970) were of no use in improving the period and were not included in the final solution. The solution of the spectroscopic orbit for the McDonald and KPNO velocities alone gave a value for the eccentricity of 0.016 ± 0.017. Inclusion of the generally lower weighted Fick velocities increased the eccentricity of 0.036 ± 0.018. According to the precepts of Lucy and Sweeney (1971), an $e = 0$ solution has been adopted (Table III). The standard error of an observation of unit weight is 0.4 km s^{-1}, the best of any star in this series so far. The observed radial velocities and the computed radial-velocity curve are plotted in Fig. 1. The phases of the observations in Table II and Fig. 1 are computed from the time of maximum positive radial velocity, T_0 in Table III. Simon, Fekel, and Gibson (1985) gave preliminary orbital elements from a subset of the current velocity data. The most notable differences between the two solutions are the assumption of a circular orbit for the present orbit and the reduction of the semiamplitude by almost 1 km s^{-1}. The orbital elements in this paper supercede those listed by Strassmeier *et al.* (1988).

b) Discussion

Cowley and Bidelman (1979) classified 39 Ceti as a G5 III having Ca II H and K emission. Simon, Fekel, and Gibson (1985) detected an 18 000 K DA white dwarf companion. Although the trigonometric parallax is of low weight 0"016 ± 0"007 (p.e.) (Jenkins 1962), Simon, Fekel, and Gibson (1985) find it consistent with the radius, surface

TABLE II. Radial velocities of 39 Ceti.

HJD 2440000+	Phase	V (km s^{-1})	O-C (km s^{-1})	Source	Standard
3389.942	0.151	-25.6	0.4	MP	
3390.974	0.170	-25.9	0.8	MP	
3391.799	0.184	-27.5	-0.3	MP	
3447.700	0.168	-26.7	-0.1	MP	
3448.741	0.186	-27.6	-0.3	MP	
3449.624	0.202	-25.0[a]	3.0	MP	
3450.788	0.222	-28.9	-0.0	MP	
3541.595	0.820	-26.6	0.5	MP	
4518.772	0.017	-23.9	-0.9	FICK	
4530.762	0.228	-29.4	-0.3	MR1	ιPsc
4627.557	0.931	-24.2	-0.6	MR1	ιPsc
4829.848	0.491	-39.4[a]	-2.2	MR1	αAri
4885.710	0.474	-37.7	-0.6	FICK	
4888.699	0.527	-38.7	-1.6	FICK	
4894.761	0.633	-35.6	-0.7	MR1	αAri
4896.715	0.668	-34.8	-1.2	FICK	
4896.790	0.669	-32.9	0.7	MR1	αAri
4920.694	0.090	-24.6	-0.5	FICK	
4943.554	0.492	-37.5	-0.3	FICK	
4958.577	0.756	-28.5	1.3	FICK	
4977.567	0.091	-23.4	0.7	FICK	
4983.563	0.196	-27.0	0.7	FICK	
4995.512	0.406	-35.6	0.4	FICK	
5006.522	0.600	-36.1	-0.2	FICK	
5187.992	0.794	-28.0	0.2	MR1	αAri
5269.862	0.234	-29.8	-0.4	MR1	αAri
5291.632	0.618	-34.4	1.0	FICK	
5298.645	0.741	-30.0	0.5	FICK	
5356.656	0.762	-29.9	-0.3	KR	αAri
5357.607	0.779	-28.0	0.8	KR	αAri
5358.623	0.796	-28.0	0.1	KR	αAri
5360.661	0.832	-25.8	0.8	KR	βGem
5361.650	0.850	-25.5	0.4	KR	βGem
5525.952	0.741	-30.9	-0.4	KT1	ιPsc
5594.968	0.956	-23.2	-0.0	KT2	αAri
5596.980	0.992	-23.9	-0.9	KT2	βGem
5598.929	0.025	-22.8	0.3	KT2	αAri
5718.684	0.133	-25.0	0.3	KT2	βGem
5853.982	0.514	-37.5	-0.3	KT2	ιPsc
5941.941	0.062	-23.5	0.0	KT2	ιPsc
5958.849	0.359	-33.6	1.0	FICK	
5971.892	0.589	-36.2	-0.0	KT2	αAri
5972.903	0.607	-35.7	0.0	KT2	αAri
5973.896	0.624	-35.1	0.1	KT2	αAri
5974.853	0.641	-34.4	0.3	KT2	αAri
6010.697	0.272	-30.6	0.5	FICK	
6041.649	0.816	-27.1	0.1	FICK	
6076.579	0.431	-36.8	-0.2	KT2	αAri
6077.627	0.450	-37.0	-0.1	KT2	αAri
6315.854	0.642	-34.7	-0.1	FICK	
6363.736	0.484	-37.3	-0.1	FICK	
6582.983	0.343	-34.5	-0.5	KT2	ιPsc
6584.983	0.378	-35.2	0.0	KT2	ιPsc
6585.983	0.396	-35.7	0.1	KT2	ιPsc
6586.988	0.413	-35.9	0.3	KT2	ιPsc
7098.901	0.422	-35.9	0.5	KT2	αAri

[a] Velocity given 0 weight

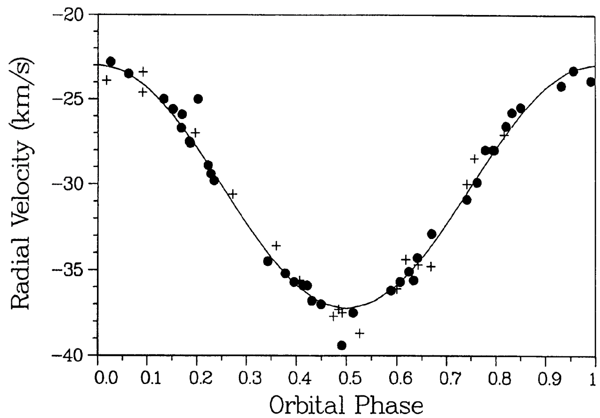

FIG. 1. Observations and computed radial-velocity curve for 39 Ceti. Dots are KPNO or McDonald Observatory velocities. + 's are Fick Observatory velocities. Phase 0 is the time of maximum positive velocity T_0 in Table III.

gravity, and mass of the white dwarf. From the assumed range in parallax, 0."0138–0."026, they derived physical parameters for both components. A parallax of 0."015 resulted in typical values for the white dwarf's mass and radius and a mass of $2.09\mathscr{M}_\odot$ for the G5 III. Our new value of 0.0021 ± 0.0001 $\mathscr{M}_\odot$ for the mass function results in a slightly smaller value of 26° for the orbital inclination in this case.

Fekel (1988) has found a moderate strength or strong lithium line in some chromospherically active G and K giants. Such stars were probably early-type B or A main-sequence stars which have just recently become convective late-type giants. Convection in these stars has not yet had time to deplete lithium substantially in the outer atmosphere because of their relatively rapid crossing of the Hertzsprung–Russell gap. Lower mass F stars that become giants would take longer to cross the Hertzsprung–Russell gap, causing the lithium to be depleted at earlier spectral types. On Julian Date 2447098.9, an observation of the lithium spectral region was obtained at KPNO for 39 Cet. At best, there appears to be a very weak lithium feature, having an equivalent width of only 2 mÅ, which is partially blended with the Fe I line at 6707.44 Å. This line strength is similar to many of the inactive G giants observed by Lambert, Dominy, and Sivertsen (1980). Thus, it appears that 39 Cet has been a late-type star long enough to almost completely deplete its atmospheric lithium abundance.

Fekel, Moffett, and Henry (1986) found $v \sin i = 6 \pm 2$ km s^{-1} for the primary. Measurement of weak lines in the lithium region leads to a revised value of 3 ± 2 km s^{-1}, while Gray (1988) has determined a value of 4.3 ± 0.6 km s^{-1}. Determinations of the rotational period from light variations range from 75.12 days (Strassmeier *et al.* 1989) to 77.65 days (Eaton *et al.* 1983). Assuming a rotational period

TABLE III. Orbital elements for 39 Cet.

$P = 56.824 \pm 0.011$ days (m.e.)
$T_0 = 2446336.205$ HJD
$\gamma = -30.107 \pm 0.084$ km s^{-1}
$K_1 = 7.13 \pm 0.13$ km s^{-1}
$e = 0.0$ (assumed)
$a_1 \sin i = 5.57 \pm 0.10 \times 10^6$ km
$f(m) = 0.0021 \pm 0.0001$ $\mathscr{M}_\odot$
Standard error of an observation of unit weight = 0.4 km s^{-1}

of 76 days and $v \sin i$ value of Gray, the minimum radius $R \sin i = 6.5 \pm 1$ $R_\odot$. If the orbital and spin inclination are the same and assumed to be 26°, then the rotational velocity is 9.8 ± 1.4 km s^{-1} and the radius is 15 ± 1 $R_\odot$. This radius is twice as large as the radius derived from flux relations by Simon, Fekel, and Gibson (1985).

Synchronization timescales are substantially shorter than circularization timescales by several orders of magnitude (Zahn 1977; Tassoul 1988). Why, then, is the orbit of 39 Cet circular, but the rotational velocity of the giant not synchronized with the orbital period? Simon, Fekel, and Gibson (1985) suggested that differential rotation, the change of rotational period with latitude, might be the cause.

The angular-momentum evolution of a star as it evolves across the Hertzsprung–Russell gap is still somewhat uncertain (Gray and Endal 1982). Their models assume conservation of angular momentum, which is probably not the case here. The 39 Cet system has relatively recently undergone substantial evolutionary change. The former more massive star is a white dwarf with a presumed past history of mass loss and mass transfer. Thus, the current orbital period is expected to be longer than it was when both stars were on the main sequence.

The giant star evolved off of the main-sequence roughly 10^8 yr ago and has been increasing its raidus during that time. Perhaps the combination of radius increase, mass transfer and loss, and changing orbital period have resulted in the current nonsynchronous situation.

IV. HD 185151

a) Orbit

Table IV lists 25 velocities from Fick Observatory, eight from McDonald, and 24 from KPNO obtained between 1980 and 1988. A separate orbital element solution was determined for the Fick velocities and a combined solution was determined for the McDonald and KPNO velocities. From the variances of the two solutions the Fick velocities were given weights of 0.15, while each McDonald and KPNO velocity was given a weight of 1.0. A single solution with all velocities included produced an orbital eccentricity of 0.013 ± 0.010, so according to the precepts of Lucy and Sweeney (1971), an $e = 0$ solution has been adopted (Table V). These orbital elements supercede those listed by Strassmeier *et al.* (1988). The standard error of an observation of unit weight is 0.9 km s^{-1}, quite good for a star whose features have a rotational broadening of almost 30 km s^{-1}. The observed radial velocities and the computed radial-velocity curve are plotted in Fig. 2. The phases of the observations in Table IV and Fig. 2 are computed from the time of maximum positive radial velocity T_0 in Table V.

b) Discussion

Heard (1956) gives a spectral type of K1 III for HD 185151. Moffett (Fekel, Moffett, and Henry 1986) observed HD 185151 on two nights and found $V = 7.69$, $B - V = 1.25$, $V - R = 1.05$, and $R - I = 0.67$. The $B - V$ color is consistent with a K2 III–K3 III spectral type according to the color–spectral-type relation of Johnson (1966).

Since the system is not double lined, it is more difficult to determine the properties of the system such as the orbital inclination and the nature of the secondary. Yet some limits

TABLE IV. Radial velocities of HD 185151.

HJD 2440000+	Phase	V (km s^{-1})	O-C (km s^{-1})	Source	Standard
4355.932	0.852	1.0	-2.0	MR1	αBoo
4356.959	0.878	8.3	0.4	MR1	μHer
4474.633	0.809	-8.1	-1.4	MR1	μHer
4475.730	0.837	-0.7	-0.4	MR1	μHer
4476.674	0.860	5.3	0.7	MR1	μHer
4480.710	0.961	18.5	0.3	MR2	μHer
4489.660	0.184	- 2.0	3.0	FICK	
4490.606	0.207	-14.5	-3.8	FICK	
4505.580	0.580	-56.8	0.7	FICK	
4520.579	0.954	16.6	-1.1	FICK	
4865.602	0.549	-61.5	-0.9	FICK	
4894.551	0.270	-27.5	-0.8	MR1	μHer
4895.596	0.296	-34.6	-1.3	MR1	μHer
5075.971	0.790	-11.8	0.3	KF	μHer
5077.970	0.839	0.6	0.3	KF	μHer
5143.844	0.480	-63.4	-1.2	FICK	
5149.803	0.629	-50.8	-1.0	FICK	
5158.831	0.854	1.7	-1.6	FICK	
5170.756	0.151	4.1	1.8	FICK	
5174.744	0.250	-21.3	0.3	FICK	
5175.734	0.275	-26.9	1.1	FICK	
5183.743	0.474	-58.4	3.6	FICK	
5189.711	0.623	-48.0	2.9	FICK	
5190.705	0.648	-44.8	1.3	FICK	
5202.681	0.946	15.1	-2.0	FICK	
5203.682	0.971	17.3	-1.4	FICK	
5216.629	0.294	-30.6	2.1	FICK	
5242.574	0.940	-17.3	2.0	FICK	
5250.594	0.140	4.3	-0.3	FICK	
5264.527	0.487	-63.1	-0.7	FICK	
5447.962	0.056	15.4	-1.4	KR	μHer
5525.864	0.997	18.8	-0.6	KT1	μHer
5528.793	0.070	18.8	3.3	FICK	
5537.759	0.294	-33.1	-0.5	FICK	
5566.699	0.014	24.8	5.6	FICK	
5571.644	0.138	1.4	-3.6	FICK	
5594.701	0.712	-30.8	0.5	KT2	μHer
5595.781	0.739	-27.1	-2.7	KT2	μHer
5783.981	0.427	-58.5	-0.1	KT2	HR6469A
5939.658	0.306	-35.4	0.2	KT2	βOph
5941.824	0.359	-48.6	-1.0	KT2	βOph
5960.601	0.827	- 5.5	-3.0	FICK	
6389.596	0.514	-62.2	0.2	KT2	μHer
6392.602	0.589	-55.8	0.5	Kt2	μHer
6530.976	0.036	19.2	0.8	KT2	μHer
6533.015	0.087	14.0	0.6	KT2	μHer
6534.990	0.136	7.2	1.9	KT2	μHer
6583.913	0.355	-48.0	-1.3	KT2	μHer
6586.837	0.428	-58.2	0.2	KT2	μHer
6717.654	0.687	-37.6	-0.1	KT2	μHer
6718.709	0.713	-30.4	0.6	KT2	μHer
6720.677	0.762	-18.3	0.2	KT2	μHer
6721.655	0.786	-12.8	-0.5	KT2	μHer
6868.025	0.433	-59.5	-0.6	KT2	μHer
7248.999	0.923	15.3	0.6	KT3	μHer
7308.881	0.415	-56.4	0.5	KT3	μHer
7310.913	0.466	-60.7	0.9	KT3	μHer

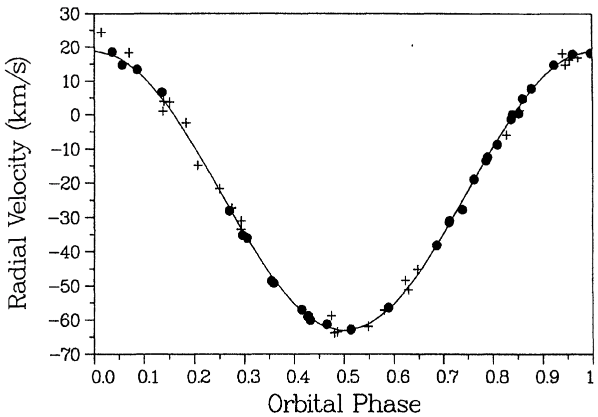

FIG. 2. Observations and computed raidal-velocity curve for HD 185151. Dots are KPNO or McDonald Observatory velocities. + 's are Fick Observatory velocities. Phase 0 is the time of maximum positive velocity T_0 in Table V.

can be determined with reasonable assumptions and the available information.

Most of the masses of the active stars in subgiant eclipsing RS CVn binaries range from 1.2 to 1.8 $\mathscr{M}_\odot$ (Popper 1980). There are indications (Fekel 1988) that many chromospherically active giants may be somewhat more massive than these subgiants.

At red wavelengths the lines of an early F type star are seen in HD 155638 (Fekel, Moffett, and Henry 1986) and HD 158393 (Lloyd Evans, Balona, and Fekel 1987). No lines of the secondary have been detected in the spectrum of HD 185151. However, the mass function $= 0.287 \mathscr{M}_\odot$ (Table V) is quite large.

Table VI lists various mass combinations and inclination limits. The mass of the late-type giant is assumed to range from 1.2 to 2.5 $\mathscr{M}_\odot$. A primary mass larger than 2.5 results in a secondary mass greater than 1.8$\mathscr{M}_\odot$, corresponding to a mid to late A star, whose luminosity should substantially affect the $B-V$ color of the observed system. Since the observed $B-V$ is consistent with the K III spectral type, there is no evidence for a star hotter than mid to late A in the system. Combining the mass function with each assumed primary mass results in a corresponding minimum value of the secondary mass (for $i = 90°$) and a maximum mass ratio $\mathscr{M}_1/\mathscr{M}_2$. Assuming that the secondary is a single star that is less massive than the primary results in the minimum orbital inclination for each primary mass. Since there is no photometric evidence for eclipses (Lines *et al.* 1987), $R_1 + R_2 < a \cos i$ where R_1 and R_2 are the radii of the primary and secondary, respectively, and a is the semimajor axis of the relative orbit. This produces the maximum inclination limits. Our best estimate for the inclination is $62° \pm 12°$.

TABLE V. Orbital elements of HD 185151.

$P = 40.1418 \pm 0.0033$ days (m.e.)
$T_0 = 2445927.395$ HJD
$\gamma = 22.78 \pm 0.31$ km s^{-1}
$K_1 = 40.99 \pm 0.44$ km s^{-1}
$e = 0.0$ (assumed)
$a_1 \sin i = 2.262 \pm 0.024 \times 10^7$ km
$f(m) = 0.287 \pm 0.009 \mathscr{M}_\odot$
Standard error of an observation of unit weight = 0.9 km s^{-1}

TABLE VI. Mass and inclination limits for HD 185151.

$\mathscr{M}_1$ ($\mathscr{M}_\odot$)	$\mathscr{M}_2(i=90°)$ ($\mathscr{M}_\odot$)	max $\mathscr{M}_1/\mathscr{M}_2$	min i (°)	max i (°)
1.2	1.17	1.03	77	72
1.5	1.31	1.14	61	73
2.0	1.53	1.31	50	74
2.5	1.72	1.45	43	75

The secondary may be a rapidly ($V_{rot} \gtrsim 15$ km s^{-1}), and therefore asynchronously, rotating late A or early F star whose very weak lines might escape detection at red wavelengths. Alternatively, the star may be a mid F star whose luminosity is not great enough for its absorption features to be detectable. At short ultraviolet wavelengths (1200–2000 Å) the continuum of such a secondary should be detectable. Identification of the spectral type of the secondary would produce substantially improved mass and inclination limits.

The $v \sin i$ value of 28 ± 2 km s^{-1} (Fekel, Moffett, and Henry 1986) results in a minimum radius of $22.2 \pm 1.6 R_\odot$ for the K III primary. Thus, the Roche lobe of the primary is 63%–82% filled depending on the mass ratio of the stars.

Assuming a radius of $25R_\odot$ and a temperature of 4300 K, the luminosity of HD 185151 is about 190 times the Sun's. From this, $\mathscr{M}_v = -0.25$ mag, which is consistent with the giant luminosity classification and a distance of 390 pc.

V. SYNCHRONOUS AND ASYNCHRONOUS ROTATION OF CHROMOSPHERICALLY ACTIVE BINARIES

In his seminal work on chromospherically active stars, Hall (1976) proposed that the RS CVn group, nearly all of which were double-lined eclipsing systems, had periods between 1 and 14 days, while active G–K IV–II stars with orbital periods greater than 14 days were called the long-period group. Bopp *et al.* (1979) argued that the division into two groups was artificial and the result of selection effects. Nevertheless, Linsky (1984), in his review of RS CVn binaries, suggested that a natural division between the two groups of binaries is about 20 days. This period limit was based on the theoretical tidal friction synchronization timescale of Zahn (1977).

In this paper, we have two binaries whose orbital periods are substantially longer than this 3 week cutoff. One system, HD 185151, is both synchronized and circularized. The other, 39 Cet, is circularized but not synchronized. These two contrasting systems lead us to examine the status of synchronization in chromospherically active binaries.

Recently, Tassoul (1987) has proposed a purely hydrodynamic mechanism for synchronization and circularization of binaries, which appears to be more efficient than the tidal friction theory of Zahn (1977). Tassoul (1987) asserts that his spin-down mechanism explains why the RS CVn binaries exhibit a statistical tendency toward synchronization for orbital periods up to 100 days. He cites the work of Tan and Liu (1986, 1987) on $v \sin i$ values for observational confirmation. From an examination of photometric and spectroscopic catalog data, Hall (1987) found about 15 of 168 chromospherically active binaries to be substantially asynchronously rotating. However, he cautioned that the orbital period is not the best parameter with which to study synchronization.

According to Eqs. (9) and (10) of Tassoul (1987), the synchronization timescale t_s depends on either $(d/R)^{33/8}$, where d is the mean separation of the components and R is the radius of the primary, or on $P^{11/4}$ where P is the orbital period. Unfortunately, the total semimajor axis of a binary, particularly for a noneclipsing single-lined system, and the primary star's radius, particularly if it is a subgiant or giant, are much more difficult to determine than its orbital period. Because such data for d and R are lacking, we have chosen to examine the relation between period and synchronization.

The recent compilation of data for 168 chromospherically active binaries (Strassmeier *et al.* 1988) provides an extensive orbital- and rotational-period dataset. This dataset was updated with information from Balona (1987), Lloyd Evans and Koen (1987), and Strassmeier *et al.* (1989), many of whose preliminary values were used in the catalog. A new value for the rotational period of Capella (Krisciunas 1988) is also included. Of the 168 systems, 114 have both an orbital period from spectroscopy and a rotational period from photometry. Three of these (Hall 1986) are pseudosynchronously rotating (Hut 1981), while 86 are synchronously rotating. Table VII lists 19 definitely asynchronous systems. The six possibly asynchronous systems are listed in parentheses. Photometric and spectroscopic periods and orbital eccentricities are given for each of the 25 systems. An uncertain quantity is followed by a colon.

Table VIII gives the orbital period distribution of the 114 systems, dividing them into synchronous, asynchronous, and possibly asynchronous rotators. For the 94 systems with periods less than or equal to 30 days there is a strong tendency for synchronization. Only 7%–11% are asynchronously rotating. The statistical sample for periods greater than 30 days is much smaller. Of the 13 systems between 30 and 70 days, between 46% and 62% are asynchronously rotating. In this period range, there is a significant tendency toward synchronization; about 50% of the systems are synchronously rotating. Of the seven systems with orbital periods greater than 70 days, between 86% and 100% are asynchronously rotating. The current statistics support the general claim of Tassoul (1987) concerning synchronization of late-type binaries, although the upper period limit is still not well determined. Additional long-period systems need to be investigated to improve the statistics.

The referee has pointed out that if the synchronization timescale is conservatively estimated to be 10 times the spin-down timescale, $N = 4$ to simulate some turbulence in the surface layers, the mass ratio is 1, and typical values of the luminosity, mass, and radius ($L = 100L_\odot$, $\mathscr{M} = 2\mathscr{M}_\odot$, $R = 10R_\odot$) are used, then Tassoul's (1987) Eq. (10) gives a synchronization time of 10^5 yr for a period of 70 days. This theoretical value is directly applicable only to static stars, It does not take into account the gradually increasing radius which would act against synchronization. Since 10^5 yr is several orders of magnitude less than the evolutionary time-

TABLE VII. Asynchronous rotators.

System	Variable Name	P_{phot} (days)	P_{spec} (days)	e
39 Cet	AY Cet	75.1	56.8	0.00
HD 10909		32.5	15.0	0.39
(HD 17433	VY Ari	20.0:	13.2	0.08)
(HD 19754		48.2	48.3	0.10:)
HD 30050	RZ Eri	31.4	39.3	0.36
HDE 283882	V808 Tau	6.8	11.9	0.51
12 Cam	BM Cam	84.9	80.2	0.35
α Aur	NSV 1897	40.0	104.0	0.00
HD 42504		43.8	106.7	0.32
HD 45088	OU Gem	7.4	7.0	0.15
HD 71071		32.9	16.5	0.13
HR 3385		19.3	45.1	0.00
(HD 83442		55.0	52.3	0.13:)
(HD 91816	LR Hya	4.9:	6.8	0.01)
93 Leo	DQ Leo	55.0	71.7	0.00
HD 137164		45.0	49.4	0.5
HR 6469	V819 Her	81.9	2018.0	0.68
29 Dra	DR Dra	28.8	915.0	0.00
(o Dra		138.4:	138.4	0.11)
HD 181809		61.0	13.0	0.00
HD 185510		25.6	20.7	0.09
HD 202134		61.0	63.1	0.52
(HD 204128		22.4	22.3	0.12:)
HD 205249		57.9	49.1	0.08
λ And	λ And	54.0	20.5	0.04

TABLE VIII. Distribution of asynchronous rotators for chromospherically active binaries.

Orbital Period (days)	Total number	asynchronous	%	possibly asynchronous	Total %
0-10	59	1	2	1	4
10.01-20	22	4	18	1	23
20.01-30	13	2	15	1	23
30.01-40	2	1	50	0	50
40.01-50	6	3	50	1	67
50.01-60	3	1	33	1	67
60.01-70	2	1	50	0	50
70.01-80	1	1	100	0	100
80.01-90	1	1	100	0	100
90.01-100	0	0	0	0	0
≥ 100.01	5	4	80	1	100

scale of these stars as giants, it suggests that the hydrodynamic mechanism can synchronize late-type binaries in the subgiant and giant stages of evolution.

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