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CHROMOSPHERICALLY ACTIVE STARS. XIII. HD 30957: A DOUBLE LINED K DWARF BINARY

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ABSTRACT

HD 30957 is a double-lined spectroscopic binary with a period of 44.395 days and a modest eccentricity of 0.09. The spectral types of the components are K2–3 V and K5 V. The measured $v \sin i$ for both components is $\leqslant 3$ km s^{-1} and the orbital inclination is estimated to be 69°. The system is relatively nearby with a parallax of 0.025″ or a distance of 40 pc. Space motions of the system indicate that it does not belong to any of the known moving groups. Absolute surface fluxes of the Ca II H and K lines have been recomputed and indicate only modest chromospheric activity. If the stars are rotating pseudosynchronously, the lack of light variability is consistent with the value of the critical Rossby number for starspot activity.

1. INTRODUCTION

HD 30957=BD+64°487 [α=4^{h}56^m 25.7^s, δ=64°24′13″ (2000), V=8.8] was one of 445 late-type stars listed as having Ca II H and K emission by Joy & Wilson (1949). That survey of calcium emission contained a compilation of published results as well as previously unpublished information about stellar spectrograms in the Mount Wilson collection. Compared to some of the other chromospherically active stars, the relative emission intensity of HD 30957 was rather weak. Nevertheless, the hope of the compilers "that the data may be sufficient to open up the field and induce further study on calcium atmospheres of the stars," was realized for this system. Some years later, Young (1974), searching for counterparts to BD+16°516 obtained a moderate dispersion spectrum of HD 30957, confirmed the Ca II H and K emission, found rotationally broadened lines, and suggested that the star was a possible spectroscopic binary. After an additional hiatus this suggestion precipitated our interest in this star and led to its inclusion as a candidate in the first chromospherically active binary star catalog of Strassmeier *et al.* (1988). That HD 30957 had significant Ca II H and K emission features was shown by Strassmeier *et al.* (1990). The star appears in the main list of Strassmeier *et al.*'s (1993) second-edition catalog where our preliminary results are given. Hooten & Hall (1990) analyzed photometric observations of HD 30957, obtained from 1988 September through 1989 March, for possible variability but found no periodicity. This chromospherically active system was one of 24 null detections in the *ROSAT* All-Sky Survey of active binary coronae (Dempsey *et al.* 1993). The results in the present paper supersede those listed in the second catalog (Strassmeier *et al.* 1993).

2. OBSERVATIONS AND REDUCTIONS

From 1986 through 1993, 22 observations of HD 30957 were obtained at the Kitt Peak National Observatory (KPNO) with the coudé feed telescope, coudé spectrograph, and a Texas Instruments charge-coupled device (CCD). All observations were centered at 6430 Å. The spectrograms cover a wavelength range of about 80 Å and have a resolution of about 0.2 Å. Many of the spectra have signal-to-noise ratios of 100:1 or better.

The radial velocities were determined relative to several International Astronomical Union radial-velocity standard stars (Pearce 1957); primarily 10 Tau or β Gem but β Vir and α Ari also were used on occasion. The velocities of these four stars have been assumed from the work of Scarfe *et al.* (1990). Fekel *et al.* (1978) discussed the details of the velocity-reduction procedure and the velocities of HD 30957 are listed in Table 1.

A second set of observations (Table 1), 16 of the primary, 17 of the secondary, and 5 at times when the lines of the two components were blended, was obtained from 1990 to 1993 with the photoelectric speedometer CORAVEL (Tokovinin 1987) attached to the 1 m telescope at Maidanak, Uzbeki-

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TABLE 1. Velocity observations of HD 30957.

HJD – 2400000	Phase	V_A (km s^{-1})	$(O-C)_A$ (km s^{-1})	V_B (km s^{-1})	$(O-C)_B$ (km s^{-1})	Source
46717.949	0.479	−15.6	0.4	30.5	−0.2	KPNO
46869.629	0.896	17.0	0.2	−5.2	−0.3	KPNO
47096.987	0.017	37.4	0.0	−26.5	0.8	KPNO
47151.935	0.255	18.4	−0.3	−7.5	−0.5	KPNO
47456.019	0.104	39.6	0.6	−28.9	0.1	KPNO
47457.008	0.127	37.8	0.4	−26.5	0.8	KPNO
47459.020	0.172	32.2	−0.1	−22.3	−0.6	KPNO
47556.855	0.376	−2.8	−0.3	16.2	0.1	KPNO
47811.024	0.101	38.8	−0.4	−28.9	0.3	KPNO
47811.981	0.122	37.6	−0.2	−27.8	−0.1	KPNO
47812.993	0.145	35.5	−0.1	−25.7	−0.4	KPNO
47814.032	0.169	33.4	0.6	−22.2	0.0	KPNO
47816.018	0.213	26.2	0.2	−14.1	0.8	KPNO
47917.704	0.504	−18.5	−0.3	33.1	0.0	KPNO
47932.120	0.828	3.8[a]	1.5	--	--	CORAVEL
47937.194	0.943	26.5	0.0	−12.2	3.2	CORAVEL
47940.250	0.012	37.4	0.5	−26.4	0.3	CORAVEL
47941.125	0.031	38.7	0.2	−30.1	−1.6	CORAVEL
47947.152	0.167	31.4	−1.6	−22.4	0.0	CORAVEL
47950.199	0.236	23.1	1.0	−8.6	2.1	CORAVEL
48166.543	0.109	39.5	0.7	--	--	CORAVEL
48166.546	0.109	--	--	−27.1	1.6	CORAVEL
48167.958	0.141	35.5	−0.6	−26.6	−0.8	KPNO
48169.560	0.177	31.1	−0.5	--	--	CORAVEL
48169.563	0.177	--	--	−19.8	1.2	CORAVEL
48172.503	0.243	21.3	0.5	--	--	CORAVEL
48172.509	0.243	--	--	−9.5	−0.2	CORAVEL
48174.489	0.288	8.2[a]	−4.5	--	--	CORAVEL
48210.491	0.099	40.1	0.8	--	--	CORAVEL
48210.496	0.099	--	--	−29.0	0.3	CORAVEL
48253.378	0.065	41.0	1.1	--	--	CORAVEL
48253.384	0.065	--	--	−27.4	2.5	CORAVEL
48310.228	0.345	6.6[a]	4.1	--	--	CORAVEL
48314.210	0.435	−11.2	−0.2	25.2	−0.1	CORAVEL
48319.223	0.548	−20.5	0.5	36.6	0.5	CORAVEL
48321.214	0.593	−21.9	0.3	38.5	1.1	CORAVEL
48329.121	0.771	−8.7	−0.3	--	--	CORAVEL
48329.129	0.771	--	--	21.1	−1.3	CORAVEL
48334.141	0.884	8.6[a]	−5.6	--	--	CORAVEL
48346.679	0.166	32.2	−0.9	−23.1	−0.5	KPNO
48348.687	0.212	25.1	−1.2	−16.1	−0.9	KPNO
48605.886	0.005	35.3	−0.8	−26.2	−0.3	KPNO
48915.892	0.988	33.6	−0.4	−23.4	0.1	KPNO
49038.178	0.742	−11.7	1.0	--	--	CORAVEL
49038.182	0.742	--	--	24.9	−2.2	CORAVEL
49038.185	0.742	--	--	27.2	0.1	CORAVEL
49042.202	0.833	3.0[a]	−0.2	--	--	CORAVEL
49050.162	0.012	--	--	−26.9	−0.2	CORAVEL
49050.168	0.012	37.1	0.2	--	--	CORAVEL
49251.011	0.536	−20.7	−0.3	35.1	−0.4	KPNO
49302.022	0.685	−19.4	−0.5	34.9	1.1	KPNO

Notes to TABLE 1

[a] Blended, given zero weight

stan. This CORAVEL determines a radial velocity by cross correlation between the stellar spectrum and a mask that selects about 2000 lines in the 3900–6900 Å region. For most of the CORAVEL observations the radial-velocity dips of the two components were observed simultaneously but for a few observations the dips were observed separately.

3. ORBITAL ELEMENTS

Astronomers at Mt. Wilson Observatory obtained 3 moderate-dispersion observations in the 1940s (Wilson & Joy 1950) and found an average velocity of -6.7 km s^{-1}. The individual velocities were published by Abt (1970) and indicate that the spectra were single lined and within 20 km s^{-1} of our center-of-mass velocity. When combined with our two sets of velocities, the old velocities can be forced to fit the primary's velocity curve if the period is 44.4072 days. However, because of the lower quality, dispersion, probable line blending, and uncertain zero point of the old observations, we have chosen to use only our two sets of new observations.

From the KPNO velocities for the primary, the initial value of the period was determined with the period-finding program of Deeming (Bopp *et al.* 1970). Preliminary orbital elements for this data set were determined with a slightly modified version of the Wilsing–Russell method (Wolfe *et al.* 1967). These elements were refined with a differential corrections computer program of Barker *et al.* (1967). Separate solutions of the KPNO velocities of the secondary as well as the CORAVEL velocities of the primary and secondary were made with this program to check for possible zero point shifts between the KPNO and CORAVEL data and to determine the relative weights for the individual components of the data sets. For the final double-lined solution, no zero-point correction was applied and all velocities were given unit weight except for the CORAVEL secondary velocities, which were given a weight of 0.15, and the blended velocities, which were given zero weight. Table 1 lists the orbital phases of the velocities and the velocity residuals. The final orbital elements are listed in Table 2 and the velocities are compared with the computed velocity curves in Fig. 1.

TABLE 2. Orbital elements of HD 30957.

P	44.3955 ± 0.0016 days
T	2448161.713 ± 0.289 JD
γ	6.40 ± 0.09 km s^{-1}
K_A	31.06 ± 0.13 km s^{-1}
K_B	33.73 ± 0.17 km s^{-1}
e	0.0916 ± 0.0036
ω_A	329°.3 ± 2°.5
ω_B	149°.3 ± 2°.5
$a_A \sin i$	18.88 ± 0.08 x 10^6 km
$a_B \sin i$	20.50 ± 0.10 x 10^6 km
$M_A \sin^3 i$	0.645 ± 0.007 $M_\odot$
$M_B \sin^3 i$	0.594 ± 0.005 $M_\odot$
M_A/M_B	1.086 ± 0.007

Standard error of an observation of unit weight = 0.56 km s^{-1}

4. SPECTRUM AND $v \sin i$

Joy (Wilson & Joy 1950) classified the spectrum as dK0. Preliminary spectral types of K2 V for both components from a visual examination of our spectra appeared in Strassmeier *et al.* (1993). In this paper we have determined the spectral types of the components with the spectrum addition technique of Strassmeier & Fekel (1990). They identified several luminosity-sensitive and temperature-sensitive line ratios in the 6430 Å region and used them along with general appearance of the spectrum, as spectral type criteria. In addition, for K dwarfs the strength of the line wings of the

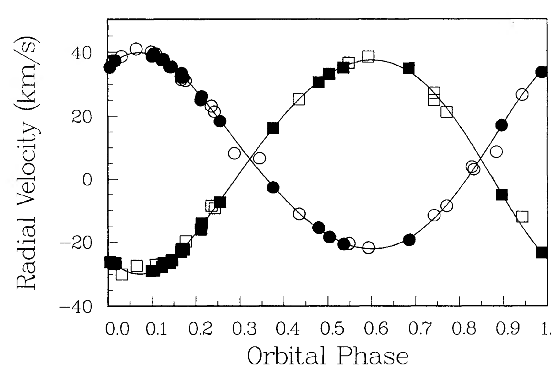

FIG. 1. A plot of the computed radial velocity curves of HD 30957 compared with the observations. For component A filled circles are KPNO velocities and open circles are CORAVEL velocities. The five blended CORAVEL velocities are also shown as open circles. For component B filled squares are KPNO velocities and open squares are CORAVEL velocities.

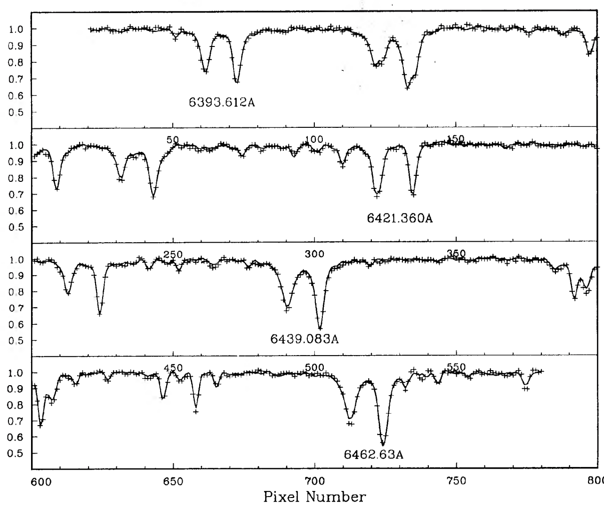

FIG. 2. A portion of the spectrum of HD 30957 in the red region obtained at KPNO on 1992 October 20 is shown as plusses. The weighted spectra of ϵ Eri (K2 V) and HD 156026 (K5 V) are superposed as a continuous curve. Red shifted lines are of component A, the K2–3 V star. The vertical axis is relative intensity. The rest wavelengths of several line pairs are identified.

saturated lines in this wavelength region is a very useful criterion. Combinations of reference stars with spectral types from K0 V to K5 V were tried. The best fit (Fig. 2) occurs with ϵ Eri (K2 V; Keenan & McNeil 1989) and HD 156026 (K5 V; Houk 1982) although a fit with HR 8832 (K3 V; Keenan & McNeil 1989) and HD 156026 (K5 V) is nearly as good. Thus, we classify the primary and secondary components of the system as K2–3 V and K5 V, respectively.

Analysis of the CORAVEL observations results in $v \sin i = 7\pm1$ km s^{-1} for each component. From our spectra Strassmeier *et al.* (1990) determined similar values of 6 ± 2 km s^{-1} for both components. The $v \sin i$ values of Strassmeier *et al.* as well as the values discussed below were determined with the procedure used by Fekel *et al.* (1986). The full width at half maximum of several lines in the 6430 Å region was measured and averaged. Instrumental broadening was taken into account and then the remaining linewidth was converted into a velocity and multiplied by an empirical constant of 0.591. A macroturbulence of 2 km s^{-1} (Marcy & Basri 1989) was assumed to obtain the final $v \sin i$ values.

A reexamination of our spectra of HD 30957 shows that relatively strong lines in the 6430 Å region such as the Fe I lines at 6393, 6421, and 6430 Å give similar $v \sin i$ values of 6 km s^{-1} for both components. However, an examination of the spectra of the single stars ϵ Eri (K2 V) and HR 8832 (K3 V) indicates that these lines have begun to saturate and have significant wings making them unsuitable for line broadening measurements. In the single-star spectra the linewidths of two weaker lines, the Ca I line at 6456 Å and the Fe I line at 6469 Å, give smaller linewidths that are consistent with the results of Marcy & Basri (1989).

The widths of these weaker lines in HD 30957 result in $v \sin i$ values at the limit of measurement, about 3 km s^{-1} or less for both components. For $v \sin i \leq 5$ km s^{-1}, the instrumental profile becomes a very large fraction of the total width of the lines. Nevertheless, the two weaker features are clearly narrower than the three moderately strong lines mentioned above. Thus, we have assumed these revised $v \sin i$ values in the discussion below. Spectroscopic observations obtained with higher resolution would be useful to confirm such small $v \sin i$ values.

5. DISCUSSION

Work over the past 15 years (e.g., Griffin & Gunn 1978; Griffin *et al.* 1982; Fekel & Beavers 1984; Griffin *et al.* 1985; Popper 1993) has shown that the masses of early K dwarfs are somewhat greater than the canonical values listed in Allen (1973). Allen's masses for K5 V and K0 V stars are $0.69\mathcal{M}_\odot$ and $0.78\mathcal{M}_\odot$, respectively. While Griffin (e.g., Griffin *et al.* 1985) has suggested increasing Allen's masses in this spectral type range by about 15%, we assume a more modest increase of about one-half this amount. However, the uncertainty estimated for our assumed mass of the primary results in the full amount of the increase suggested by Griffin *et al.* (1985). For HD 30957 the minimum mass of the primary is $0.645\mathcal{M}_\odot$. With an assumed mass of $0.80\pm0.05\mathcal{M}_\odot$ for this component, the mass of the secondary is $0.74\pm0.04\mathcal{M}_\odot$ and the inclination of the system is $69°\pm3°$.

The central wavelength of our spectra is about 0.6 of the way between the effective wavelengths of the Johnson V and R bandpasses. A magnitude difference of 0.45 is estimated from the average line depth ratio in our two best spectra and a nearly identical value comes from our two best spectrum addition fits. This results in a V mag difference of about 0.55. No modern V magnitude has been determined. However, from his photometric observations Henry (1994) has provided us with differential magnitudes for HD 30957 minus the comparison star and the comparison star minus the check star. The check star is HR 1440 for which Oja (1991) obtained a V magnitude of 5.91. The resulting V magnitude for HD 30957 is 8.82. This value combined with the magnitude difference of the components and an absolute visual magnitude of 6.3 (Corbally & Garrison 1984) for the primary gives a parallax of 0.025″ or a distance of 40 pc. This distance is about 50% larger than the value assumed in Strassmeier *et al.* (1993).

With the proper motions from the PPM catalog (Röser & Bastian 1991) the U, V, W space velocities in a right handed coordinate system are -13, -7, 0 km s^{-1}, respectively. These velocities do not identify HD 30957 with any of the moving groups listed by Soderblom & Mayor (1993).

Strassmeier *et al.* (1990) computed absolute surface fluxes of the Ca II H and K lines. Their relatively large fluxes resulted from the assumption that the primary was a G subgiant. In addition, their spectrum did not show resolved H or K emission lines of the two stars. To revise the surface fluxes we have assumed a mean spectral type of K3 V and $V-R = 0.82$, resulting in $\log F(\mathrm{H_1}) = 5.88$ and $\log F(\mathrm{K_1}) = 6.04$ for the mean absolute surface fluxes of the system. When subtracted from these values, the underlying photospheric fluxes calculated for such a star (Linsky *et al.* 1979) do not significantly change these values. The revised position of the system in Figs. 5(a) and 6(a) of Strassmeier *et al.* (1990) indicates that the system has modest H and K surface fluxes.

Hooten & Hall (1990) found no evidence for photometric variability during the 1988–89 observing season. Is this lack of variability to be expected? Although the orbit is not circular, the eccentricity is quite modest, 0.092 ± 0.004. Thus, the pseudosynchronous period for rotation (Hut 1981) is only about 5% less than the orbital period, 42.2 days versus 44.4 days. The pseudosynchronous period and a radius of, say, $0.8 R_{\odot}$ result in a rotational velocity of 1 km s^{-1}. This result is quite consistent with the measured $v \sin i \leqslant 3$ km s^{-1}. Both values are below the cutoff value of 5 km s^{-1} proposed by Bopp & Fekel (1977) for enhanced activity. However, more recent work has shown that the convective turnover time is an equally important parameter. From Gilliland (1985) the convective turnover time for a K2 V star is 38.5 days. Hall (1991) found that the Rossby number, the ratio of rotation period to convective turnover time, must be less than 0.67 for spot activity to be expected. If the pseudosynchronous rotation period is assumed, the Rossby number for the primary of HD 30957 is about 1.1, significantly greater than Hall's limit, and no variability would be expected, in agreement with the results of Hooten & Hall (1990).

While the above results are consistent, they assume that the primary is rotating with the pseudosynchronous period. Although the various proposed theories (e.g., Zahn 1977; Tassoul & Tassoul 1992) significantly disagree on the time scale for synchronization, the theories do agree that synchronization will take place much more quickly than circularization. That the orbit of HD 30957 is nearly circular suggests that the rotation should be pseudosynchronous but this assumption can not be taken for granted. What period and rotational velocity would be necessary for variability to be expected? To obtain a Rossby number less than 0.67, the rotation period must be about 25 days or less for the same convective turnover time. Such a period would result in a rotational velocity of less than 2 km s^{-1}, also consistent with our observed upper limit. A rotational velocity of 6 km s^{-1}, as previously determined, would result in a rotational period of about 7 days and would certainly produce starspot activity. Finally we note that starspot activity would be more likely to occur on the later type secondary but because of the magnitude difference of the components, any such variability would be more difficult to detect. Since the components are both K dwarfs, the system, should it ever be found to have light variability, would be more appropriately classified as a BY Dra system (Bopp & Fekel 1977) than a RS CVn binary.

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