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CHROMOSPHERICALLY ACTIVE STARS. XXV. HD 144110 = EV DRACONIS, A DOUBLE-LINED DWARF BINARY

Francis C. Fekel,[1,2] Gregory W. Henry,[2] and Ceteka Lewis
Center of Excellence in Information Systems, Tennessee State University, 330 10th Avenue North, Nashville, TN 37203;
fekel@evans.tsuniv.edu, henry@schwab.tsuniv.edu
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ABSTRACT

New spectroscopic and photometric observations of HD 144110 have been used to obtain an improved orbital element solution and determine some basic properties of the system. This chromospherically active, double-lined spectroscopic binary has an orbital period of 1.6714012 days and a circular orbit. We classify the components as G5 V and K0 V and suggest that they are slightly metal-rich. The photometric observations indicate that the rotation of HD 144110 is synchronous with the orbital period. Despite the short orbital period, no evidence of eclipses is seen in our photometry.

Key words: binaries: spectroscopic — stars: late-type — stars: spots — stars: variables: other

Online material: machine-readable table

1. INTRODUCTION

In 1991, *ROSAT* with its Wide-Field Camera completed the first all-sky survey of extreme ultraviolet (EUV) wavelengths. The satellite results led to follow-up optical observations from which numerous late-type stars were identified as optical counterparts. In their initial catalog of objects, Pounds et al. (1993) identified HD 144110 ($\alpha = 16^{h}01^{m}47\overset{s}{.}5$, $\delta = 51°20'52\overset{''}{.}0$ [J2000.0], $V = 8.5$ mag) as one such star. Mulliss & Bopp (1994) discovered HD 144110 to be a chromospherically active, double-lined binary. Jeffries et al. (1994) determined an orbital period of 1.671 days, while Jeffries et al. (1995) presented a complete set of orbital elements and briefly discussed the likely properties of the system. Henry et al. (1995) conducted a photometric survey for light variability in 66 potential or known chromospherically active stars. For HD 144110 they detected V-band variations of 0.06 mag with a period of 1.651 days, essentially identical to the orbital period. As a result, Kazarovets & Samus (1997) assigned it the variable star name EV Draconis. Henry et al. (1995) classified the primary as G8 V and the secondary as K1 V. Fekel (1997) determined rotational velocities of 31 and 27 km s^{-1} for the G and K dwarf components, respectively.

Because the spectroscopic observations of Jeffries et al. (1995) were acquired over only a 6 day period, we have obtained additional high-resolution spectrograms of HD 144110 to improve its orbital period and other elements and to determine better its properties. We also have obtained and analyzed additional photometric observations to improve the determination of the rotation period and check for eclipses.

2. SPECTROSCOPIC OBSERVATIONS AND REDUCTIONS

From 1995 April to 2004 June we obtained 21 high-resolution spectrograms of HD 144110 (Table 1) with the Kitt Peak National Observatory (KPNO) coudé feed telescope, coudé spectrograph, and a TI CCD detector. All of the spectrograms are centered in the red at 6430 Å, cover a wavelength range of about 80 Å, and have a resolution of 0.21 Å. Typical signal-to-noise ratios are 150–200. A sample spectrum is shown in Figure 1 with several lines of the primary (component A) and the secondary (component B) identified.

We determined radial velocities with the IRAF cross-correlation program FXCOR (Fitzpatrick 1993), using β Aquilae as the cross-correlation reference star. Its velocity of -40.2 km s^{-1}, measured relative to the IAU velocity standard HR 7560 (Scarfe et al. 1990), was adopted from our unpublished results. Lines of the primary and secondary of HD 144110 are partially blended in two spectrograms. In those cases the resulting cross-correlation functions were fitted simultaneously with two Gaussians.

3. PHOTOMETRIC OBSERVATIONS AND REDUCTIONS

We obtained our photometry of HD 144110 with the T3 0.4 m automatic photoelectric telescope (APT) at Fairborn Observatory in the Patagonia Mountains of southern Arizona. This APT uses a temperature-stabilized EMI 9924B bi-alkali photomultiplier tube to acquire data through Johnson B and V filters. The APT is programmed to measure stars in the following sequence, termed a group observation: K, sky, C, V, C, V, C, V, C, sky, K, where K is a check star, C is the comparison star, and V is the program star. A total of 328 group observations of HD 144110 were obtained with the APT during three observing seasons between 1994 and 1996 with HD 143595 ($V = 7.84$, $B - V = 1.18$, K2 III) as the comparison star and HD 144204 ($V = 5.93$, $B - V = 1.50$, K5 III) as the check star.

To create group means for each group observation, three variable-minus-comparison ($V - C$) and two check-minus-comparison ($K - C$) differential magnitudes in each photometric band were computed and averaged. The group means were then corrected for differential extinction with nightly extinction coefficients, transformed to the Johnson system with yearly mean transformation coefficients, and treated as single observations thereafter. The external precision of the group means, based on standard deviations for pairs of constant stars, is typically ~0.004 mag on good nights with this telescope. Group

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] Also Senior Research Associate, Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235.

TABLE 1
Radial Velocities of HD 144110

Hel. Julian Date (HJD − 2,400,000)	Phase	V_A (km s^{-1})	$(O-C)_A$ (km s^{-1})	V_B (km s^{-1})	$(O-C)_B$ (km s^{-1})
49835.908	0.319	−33.1	0.0	48.0	−0.3
49836.936	0.934	86.1	−0.1	−91.9	−0.1
50201.924	0.306	−27.0	−0.4	40.0	−0.7
50263.844	0.353	−50.5	−0.9	67.8	0.1
50361.597	0.839	52.1	0.4	−51.3	−0.1
50578.806	0.795	28.2[a]	−1.0	−25.8[a]	−0.9
50927.972	0.701	−21.0[a]	1.8	35.3[a]	−0.9
51308.828	0.567	−77.2	0.1	99.6	−0.6
51349.792	0.076	83.8	0.0	−88.5	0.5
51657.945	0.444	−79.3	0.4	103.3	0.3
51658.928	0.032	90.8	−1.2	−98.9	−0.3
51731.731	0.590	−71.2	−0.1	92.7	−0.3
52013.984	0.462	−82.7	0.0	106.8	0.3
52014.873	0.994	93.9	0.1	−101.9	−1.2
52180.602	0.150	57.8	0.9	−57.3	0.1
52392.852	0.139	61.9	0.2	−62.6	0.4
52538.619	0.352	−48.8	0.3	67.7	0.6
52539.598	0.938	87.3	0.3	−92.2	0.6
52540.597	0.535	−82.5	0.5	107.4	0.5
53123.928	0.542	−82.3	−0.3	105.3	−0.4
53169.879	0.035	92.3	0.6	−98.3	−0.1

[a] Blended component, velocity given zero weight.

mean differential magnitudes with internal standard deviations greater than 0.01 mag were discarded, leaving 317 and 310 good group means in *B* and *V*, respectively. The individual differential magnitudes are given in Table 2. Further details of telescope operations and data reduction procedures can be found in Henry (1995a, 1995b).

4. ORBIT

An initial spectroscopic period of 1.6714 days was determined by fitting a sine curve to the 21 KPNO velocities of the primary, component A, for trial periods between 0.4 and 4.0 days with a step size of 0.0001 days. For each period, the sum of the squared residuals was computed and the period with the smallest value of that sum was identified as the preliminary value of the orbital period. This analysis clearly excluded possible alias periods near 0.6 and 2.5 days and confirmed the orbital period determined by Jeffries et al. (1995).

Velocities from the two spectra having blended components were not included in our initial analyses. Thus, preliminary orbital elements for 19 primary velocities were computed with BISP (Wolfe et al. 1967), a computer program that implements a slightly modified version of the Wilsing-Russell method. The orbit was then refined with SB1 (Barker et al. 1967), a program that uses differential corrections. An orbit for the 19 KPNO velocities of the secondary, component B, also was computed. The variances of the solutions for the primary and secondary resulted in weights of 1.0 for the secondary velocities relative to those of the primary. Then the spectroscopic orbits of the primary and secondary were refined with a modified version of SB1 that uses differential corrections to determine simultaneously the elements of the two components. Since the eccentricity of this solution is extremely small, a circular orbit solution was computed with SB2C (D. Barlow 1998, private communication), which also uses differential corrections to determine the elements. The tests of Lucy & Sweeney (1971) indicate that the circular orbit solution is to be preferred, and so its elements and their standard deviations are given in Table 3. For a circular orbit, the element *T*, a time of periastron passage, is undefined. Thus, as recommended by Batten et al. (1989), T_0, a time of maximum velocity for the primary, is given instead. Velocities of the two KPNO spectra that have blended lines were included in the final circular orbit solution but were given weights of zero.

We also computed several orbital solutions for the velocities of Jeffries et al. (1995). With no available velocity ephemeris and only a short, 1 week observing run, Jeffries et al. (1995) obtained nearly half of their 16 observations at times when the lines of the two components were blended. Because of the substantially greater velocity uncertainties, uncertain velocity zero point, and somewhat poor distribution in phase, none of their velocities have been included in our analysis.

The phases of the 21 KPNO observations and the velocity residuals to the computed curves are included in Table 1. The

TABLE 2
Photometric Observations of HD 144110

Hel. Julian Date (HJD −2,400,000)	Var. *B* (mag)	Var. *V* (mag)	Check *B* (mag)	Check *V* (mag)
49481.8951	0.268	0.749	−1.615	−1.918
49482.9097	0.310	0.789	−1.613	−1.911
49485.8793	0.294	0.774	−1.615	−1.907
49486.8008	0.284	0.766	−1.616	−1.910
49487.8081	0.305	0.780	−1.613	−1.914

Note.—Table 2 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

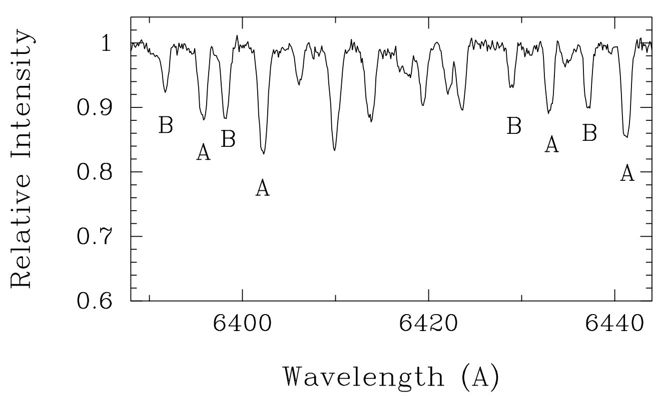

Fig. 1.—Spectrum of HD 144110 in the 6430 Å region. Several lines of components A and B are identified.

TABLE 3
Orbital Elements of HD 144110

Parameter	Value
P (days)	1.67140121 ± 0.00000065
T_0 (HJD)	2452182.0226 ± 0.0006
γ (km s^{-1})	4.341 ± 0.083
K_A (km s^{-1})	89.52 ± 0.15
K_B (km s^{-1})	105.10 ± 0.15
e	0.0 adopted
$a_A \sin i$ (km)	$(2.0574 \pm 0.0034) \times 10^6$
$a_B \sin i$ (km)	$(2.4155 \pm 0.0034) \times 10^6$
$m_A \sin^3 i$ ($M_\odot$)	0.6909 ± 0.0023
$m_B \sin^3 i$ ($M_\odot$)	0.5885 ± 0.0021
Standard error of an observation of unit weight (km s^{-1})	0.5

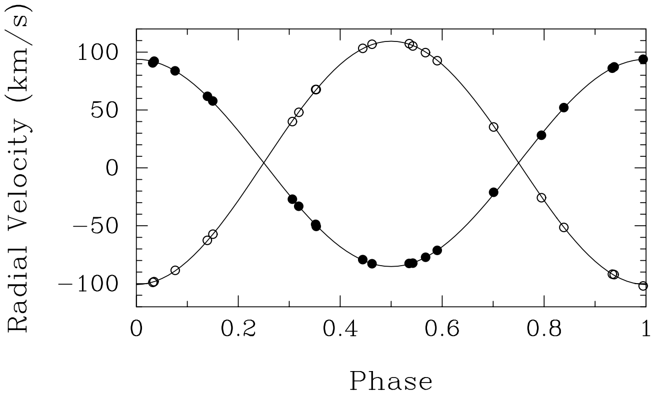

FIG. 2.—Computed radial velocity curves of HD 144110 compared with the KPNO radial velocities. Filled circles represent component A, and open circles represent component B. Zero phase is a time of maximum radial velocity of the primary.

21 KPNO velocities of each component and the two computed velocity curves are compared in Figure 2, where zero phase is a time of maximum velocity of the primary component.

5. PHOTOMETRIC ANALYSIS

The 310 Johnson V photometric observations from all three observing seasons are plotted in the top panel of Figure 3; only the first cluster of 38 observations was available to Henry et al. (1995). We divided the photometric data into the three separate observing seasons, separated by vertical lines in Figure 3, and searched for periodicities in the three seasons using the method of Vaniĉek (1971), as described in Henry et al. (2001). The gaps in the first and second season data sets arise from the annual shutdown of our APT operation during the summer rainy season in Arizona. The results of our period analysis are described below and summarized in Table 4.

We analyzed the check star–minus–comparison star ($K - C$) data in B and V over the period range 0.5–200 days and found no clear evidence for periodicity. The standard deviations of the $K - C$ observations for the three observing seasons range between 0.007 and 0.009 mag (Table 4, col. [10]), slightly larger than the nominal precision of 0.004 mag for this telescope. Similarly, the seasonal means of the $K - C$ differential magnitudes (Table 4, col. [9]) scatter slightly more (but less than 0.005 mag rms) than would be expected for constant stars. The comparison and check stars are K2 and K5 giants, respectively. Henry et al. (2000) have shown that most K giants exhibit low-amplitude photometric variability that increases with later spectral subclass. Thus, most of the variability in the $K - C$ observations probably emanates from the check star. Possible subtle variability in the comparison star should not significantly affect our analysis of the $V - C$ observations because of the much larger variability (up to 0.08 mag) in HD 144110.

The standard deviations of the $V - C$ observations are given in column (6) of Table 4 and range between 0.016 and 0.031 mag, indicating clear photometric variability in HD 144110. The seasonal means in column (5) also show that HD 144110 varies by at least 0.04 mag on longer timescales as well. The results of our period search of the $V - C$ observations are given in column (7). The power spectrum of the third-season V observations, which has the largest amplitude, is shown in the middle panel of Figure 3 and yields a period of 1.672 ± 0.001 days, which is identical to the orbital period (Table 3) within the uncertainties. The alias frequency at 0.40 day^{-1}, corresponding to a period of 2.5 days, is also found in the period search of the radial velocities (see § 4). The photometric observations from the third season are replotted in the bottom panel of Figure 3, phased with the 1.672 photometric period and the epoch of maximum radial velocity (T_0) of the primary from Table 3. We take the photometric periods listed in column (7) of Table 4 to be measures of the stellar rotation period, made apparent by rotational modulation in the visibility of photospheric star spots, so the rotation in HD 144110 is synchronous with the orbital period.

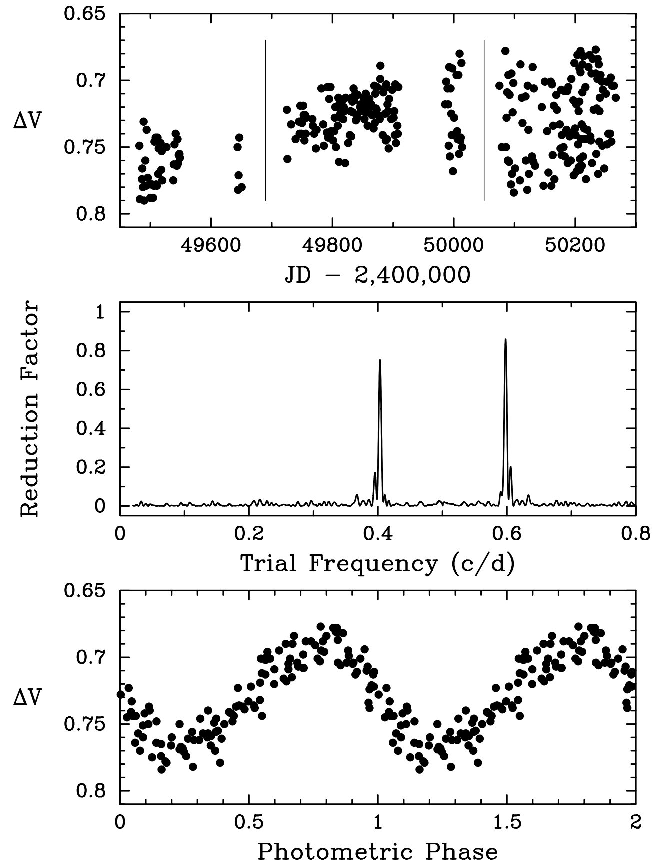

FIG. 3.—*Top:* Complete set of Johnson V photometric observations acquired in three separate observing seasons (separated by vertical lines) plotted against Julian Date. *Middle:* Power spectrum of the data from the third season, which had the largest amplitude. The best frequency is 0.5980 day^{-1}, corresponding to a period of 1.672 ± 0.001 days. *Bottom:* Photometric observations from the third observing season plotted modulo the 1.672 day period reveal a rotational amplitude of 0.078 mag.

6. SPECTRAL TYPES AND MAGNITUDE DIFFERENCE

Strassmeier & Fekel (1990) identified several luminosity-sensitive and temperature-sensitive line ratios in the 6430–6465 Å region. Those critical line ratios and the general appearance of the spectrum were employed as spectral-type criteria. Comparing stars with well-determined spectral types to a spectrum of HD 144110, Henry et al. (1995) classified its components as G8 V and K1 V. Since that time, we have obtained additional reference star spectra for comparison, which cover a wider range of iron abundances. Thus, we have reexamined the spectral classification of the components of HD 144110. Its spectrum was compared with those of G and early-K dwarfs and subgiants from the lists of Keenan & McNeil (1989), Fekel (1997), and Gray et al. (2003). Spectra of the reference stars were obtained at KPNO with the same telescope, spectrograph, and detector as our spectra of HD 144110. With a computer program developed by

TABLE 4
Results from Photometric Analysis of HD 144110

Season (1)	Photometric Band (2)	HJD Range (HJD −2,400,000) (3)	N_{obs} (4)	$\langle(V-C)\rangle$ (mag) (5)	σ_{V-C} (mag) (6)	Photometric Period (days) (7)	Peak-to-Peak Amplitude (mag) (8)	$\langle(K-C)\rangle$ (mag) (9)	σ_{K-C} (mag) (10)
1............	V	49481–49650	43	0.7635	0.0163	1.645 ± 0.001	0.038	−1.9084	0.0068
1............	B	49481–49646	43	0.2833	0.0209	1.646 ± 0.002	0.049	−1.6149	0.0084
2............	V	49724–50013	138	0.7258	0.0169	1.674 ± 0.001	0.034	−1.9060	0.0087
2............	B	49724–50015	142	0.2424	0.0198	1.674 ± 0.001	0.038	−1.6056	0.0091
3............	V	50075–50266	129	0.7291	0.0294	1.672 ± 0.001	0.078	−1.9064	0.0092
3............	B	50075–50266	132	0.2408	0.0314	1.672 ± 0.001	0.081	−1.6081	0.0092

Huenemoerder & Barden (1984) and Barden (1985), various combinations of reference star spectra were rotationally broadened, shifted in radial velocity, appropriately weighted, and added together in an attempt to reproduce the spectrum of HD 144110 in the 6430 Å region. The prominent features in this wavelength region are primarily iron lines, although there are also several calcium lines. The best fit to our spectrum of HD 144110 was found with a combination of κ Ceti, G5 V (Keenan & McNeil 1989), and mean [Fe/H] = 0.08 (Taylor 2003), plus HR 511, K0 V (Wilson 1962), and mean [Fe/H] = 0.10 (Taylor 2003). These spectral types are slightly earlier than the G8 V and K1 V types of Henry et al. (1995). Such a comparison provides an indication of our classification uncertainty. The iron abundances of the reference stars suggest that HD 144110 is slightly metal-rich relative to the Sun.

In the 6430 Å region the reference stars were added together in various proportions to match the spectrum of HD 144110. The best fit results in a continuum-intensity ratio of 0.49 for component B relative to component A. To determine the luminosity ratio of the two components, the intrinsic line-strength ratio must be taken into account, since the actual line strength of the cooler secondary is greater than that of the hotter primary. In the 6430 Å region, the average of the Fe I line depths in κ Cet relative to those in HR 511 results in a line-strength ratio of 1.16, which we adopt as the B/A ratio for the components of HD 144110. This produces a luminosity ratio of 0.42 for HD 144110, corresponding to a magnitude difference of 0.94 mag in the 6430 Å region. This central wavelength is about 0.6 of the way between the effective wavelengths of the Johnson V and R bandpasses. Thus, from the mean colors of G5 and K0 dwarfs (Johnson 1966), for HD 144110 we adopt $\Delta V = 1.0$ mag and estimate an uncertainty of 0.2 mag from the various reference star combinations that were examined.

TABLE 5
Fundamental Properties of HD 144110

Parameter	Value	References
V (mag)	8.53	1
$B-V$ (mag)..............................	0.68	1
π (arcsec)	0.01681 ± 0.00075	2
Spectral type of A......................	G5 V	1
Spectral type of B......................	K0 V	1
$v_A \sin i$ (km s^{-1})	31 ± 2	3
$v_B \sin i$ (km s^{-1})	27 ± 3	3
M_v(A) (mag)	5.02 ± 0.11	1
M_v(B) (mag)..............................	6.02 ± 0.18	1
L_A ($L_\odot$)......................................	0.86 ± 0.09	1
L_B ($L_\odot$)......................................	0.38 ± 0.06	1
R_A ($R_\odot$)	0.96 ± 0.06	1
R_A ($R_\odot$)	0.75 ± 0.07	1

References.—(1) This paper; (2) Perryman et al. 1997; (3) Fekel 1997.

7. BASIC PROPERTIES

We searched the literature and examined our APT data for the brightest visual magnitude and corresponding $B-V$ of HD 144110. From Figure 3, HD 144110 is brightest in season 3 with a peak differential V magnitude of 0.69. To convert this to an apparent V magnitude, we adopted $V = 7.84$ mag (Perryman et al. 1997) for our comparison star, HD 143595. This resulted in a maximum V magnitude of 8.53 for HD 144110. In a similar manner we obtained $B-V = 0.68$. O'Neal et al. (1996) showed that on some heavily spotted stars, the observed maximum V magnitude underestimates the brightness of the unspotted star by 0.3–0.4 mag. However, most chromospherically active dwarfs have small photometric amplitudes, typically less than 0.1 mag, and are not believed to be heavily spotted (e.g., Henry et al. 1995). Because we are unable to determine a specific correction to the observed maximum V magnitude, we have adopted $V = 8.53$ as the unspotted magnitude for the combined system.

The *Hipparcos* parallax of 0.″01681 ± 0.″00075 (Perryman et al. 1997) corresponds to a distance of 59.5 ± 2.7 pc, and so we assume no interstellar reddening. As a result, the parallax, the adopted V magnitude, and the magnitude difference of the components were combined to obtain absolute magnitudes $M_V = 5.02 \pm 0.11$ and 6.02 ± 0.18 mag for components A and B, respectively. From Johnson (1966), $B-V$ colors of 0.66 and 0.82 were adopted for the G5 V and K0 V components, respectively. Those colors were used in conjunction with Table 3 of Flower (1996) to obtain the bolometric corrections and effective temperatures of components A and B. The resulting luminosities are $L_A = 0.86 \pm 0.09\ L_\odot$ and $L_B = 0.38 \pm 0.06\ L_\odot$, while the radii are $R_A = 0.96 \pm 0.06\ R_\odot$ and $R_B = 0.75 \pm 0.07\ R_\odot$. The uncertainties in the computed quantities are dominated by the parallax and magnitude difference uncertainties plus, to a lesser extent, the effective temperature uncertainty, which is estimated to be ±100 K. Values for these basic properties of components A and B and their standard deviations are summarized in Table 5.

8. DISCUSSION

Comparison with the solar abundance evolutionary tracks of Charbonnel et al. (1996) indicates that both components are close to the zero-age main sequence. However, Figure 1 of Jeffries et al. (1995) shows no obvious lithium line near 6708 Å. This line would be easily visible in the G5 V component (Soderblom et al. 1993) if the system were as young as the Pleiades, which has an age of only ~100–125 Myr (Meynet et al. 1993; Stauffer et al. 1998). Thus, HD 144110 is not extremely young.

Despite the rather short orbital period of 1.6714 days, the results of Jeffries et al. (1995) indicated that the system is probably not eclipsing. Nevertheless, because of the paucity of well-determined masses for G and K dwarfs less massive than the Sun, we examined our photometry but found no evidence of eclipses.

The minimum inclination for eclipses to occur is computed from

$$a \cos i < R_{\rm A} + R_{\rm B},$$

where a is the semimajor axis of the binary, i is the orbital inclination, and R is the component radius. From Table B1 of Gray (1992), we adopt masses of 0.98 $M_\odot$ for the G5 V primary and 0.82 $M_\odot$ for the K0 V secondary. Those values plus the orbital period produce the binary semimajor axis from Kepler's third law. The radii of components A and B are listed in Table 5. With these quantities, the orbital inclination must be $\geq 76°$ for eclipses to occur. The masses we adopted from Gray (1992), compared with our minimum masses (Table 3), result in an orbital inclination of 63°, which is less than the value of 76° and consistent with our lack of detection of eclipses.

The two main theories of orbital circularization and rotational synchronization (e.g., Zahn 1977; Tassoul & Tassoul, 1992) disagree significantly on absolute timescales but do agree that synchronization should occur first. With a short orbital period of 1.6714 days, it is not surprising that the orbit is circular. Given their identical ages and similar spectral types, both components of the binary should be chromospherically active. We found in § 5 that the photometric period is essentially identical to the orbital period. Thus, we assume that both components are synchronously rotating.

The minimum radii of components A and B, computed from $v \sin i = 31 \pm 2$ and 27 ± 3 km s^{-1} (Fekel 1997), respectively, and a rotation period of 1.672 days, are 1.02 ± 0.07 $R_\odot$ for component A and 0.89 ± 0.10 $R_\odot$ for component B. If the orbital and rotational axes are parallel, as would be expected in such a short-period system, then an inclination of 63° results in radii of 1.14 and 1.00 $R_\odot$ for A and B, respectively. These radii are larger than those computed from the Stefan–Boltzmann law in § 7, and the uncertainties of the determinations do not overlap.

Fekel et al. (1999) have found other chromospherically active stars with this inconsistency. They pointed out that in such situations part of the discrepancy between the values of the radii determined with the two methods can be attributed to the assumption that the brightest known magnitude of the star is equal to its unspotted magnitude. This assumption is useful and necessary in the absence of other information. However, it is often false, since a flat maximum light level, which, if present, is indicative of an unspotted surface, is rarely seen in the light curves of chromospherically active stars (e.g., Henry et al. 1995).

For HD 144110, our adopted maximum V magnitude is likely a significant part of the radii discrepancy problem. The bottom panel of Figure 3 shows a light curve that does not have a flat maximum level. The light curve of HD 144110, however, is complicated by the fact that both components are presumably chromospherically active and contributing to the variability. Another indication that we have not seen the unspotted surface of this binary is found in the top panel of Figure 3, which shows that in just three seasons of monitoring, the maximum light level increased by 0.06 mag. A much longer time span of observation might well result in a significantly brighter maximum V magnitude. If the true unspotted V magnitude were 0.1 mag brighter than our adopted value, the luminosity would be increased by 10% and the radius by 5%, improving the agreement between the different determinations of the radii.

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