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CHROMOSPHERICALLY ACTIVE STARS. XVIII. SORTING OUT THE VARIABILITY OF HD 95559 AND GLIESE 410 = DS LEONIS

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ABSTRACT

We have obtained spectroscopy and photometry of HD 95559 and photometry of Gliese 410 = DS Leonis. HD 95559 consists of a pair of essentially identical K1 V stars, whose orbital period we refine to $1.52599775 \pm 0.00000104$ days. The system is photometrically variable with a mean period of 1.5264 ± 0.0003 days. Despite minimum masses greater than 0.8 $M_\odot$ for each component, a search for eclipses proved negative. The lithium abundances of the components of HD 95559 indicate that the system is younger than the Hyades cluster, and its components may even have just arrived on the zero-age main sequence. Gl 410 = DS Leo is also a photometric variable, but we conclude that the photometric period originally ascribed to this star is an alias of the period for HD 95559. We find periods of 13.99 and 15.71 days for the first and second seasons of observation, respectively. Both HD 95559 and Gl 410 are BY Draconis variables, with variability resulting from the rotational modulation of starspots. We also find HR 4269, the check star for our photometry of HD 95559 and Gl 410, to be a variable K4 III with a photometric period of 26.4 days in the first season of observation and periods of 13.96 and 83 days in the second. We suggest that its variability mechanism is radial pulsation, the same as that for M giant semiregular variables.

Key words: binaries: spectroscopic — stars: spots — stars: variables: other

1. INTRODUCTION

The story of variability in the stars HD 95559 = BD +23°2297 ($\alpha = 11^{\rm h}02^{\rm m}02\overset{\rm s}{.}3$, $\delta = 22°35'45''$ [2000.0], $V = 8.96$) and HD 95650 = Gl 410 = DS Leo ($\alpha = 11^{\rm h}02^{\rm m}38\overset{\rm s}{.}3$, $\delta = 21°58'02''$ [2000], $V = 9.57$) is one with several subplots. Bopp et al. (1983) made differential photometric observations of Gl 410. After noting that their first comparison star, HD 95467 = BD +23°2293, was variable, they used their second, HD 95559, to determine that Gl 410 is a variable with a period of 2.935 days.

Young et al. (1989) obtained a red wavelength spectrum of GL 410 that showed Hα to be almost completely filled in by emission. Strassmeier et al. (1990) found that Gl 410 has strong Ca II H and K emission and variable Hα emission. With a spectral type of dM1 (Joy & Abt 1974), Gl 410 is clearly a chromospherically active star.

Jeffries, Bertram, & Spurgeon (1994) compared the Hα and Ca II H and K lines of Gl 410 with those of other dwarfs having similar spectral types and photometric periods. They concluded that if the photometric period found by Bopp et al. for Gl 410 is correct, its activity level is anomalously low. However, their examination of the properties of HD 95559, the comparison star observed by Bopp et al. (1983), led them to an alternative explanation. HD 95559 has been identified as the optical counterpart to an EUV source (Mason et al. 1995), and the spectroscopic observations of Jeffries et al. (1994) showed it to be a late-type double-lined spectroscopic binary with a period of 1.528 days. With such a short orbital period, the components are presumably synchronously rotating, and so Jeffries et al. (1994) predicted that HD 95559 should show photometric variability. They also noted that the one-day alias of a 1.528 day period is 2.89 days, very similar to the period found by Bopp et al. (1983) for Gl 410. Thus, they suggested that HD 95559 might be the true source of the variability observed in Gl 410 by Bopp et al. (1983). Jeffries et al. (1994) urged that additional photometric observations be made to resolve the issue.

Recently, Strassmeier et al. (2000) included HD 95559 in an extensive search for Doppler-imaging candidates. Their blue and red wavelength spectra of HD 95559 show the typical signatures of a chromospherically active binary. From their photometric observations they determined a period of 2.944 days, essentially identical to the period assigned by Bopp et al. (1983) to Gl 410. However, in their Table A3, Strassmeier et al. (2000) noted that a period of 1.514 days was a possibility, in agreement with the period anticipated by Jeffries et al. (1994).

Popper (1996) estimated a K2 spectral class for HD 95559 and suggested that the system might well be evolved. However, he also noted that if the system is a main-sequence pair, its minimum masses are large, and so eclipses might be detected.

As a result of the suggestions of Jeffries et al. (1994) and Popper (1996), we obtained photometry of HD 95559 and Gl 410 to sort out the photometric variability questions. We also have made additional spectroscopic observations of HD 95559 to improve its orbital elements, in anticipation of its discovery as a late-type dwarf eclipsing system. Our elements and additional spectroscopic and photometric information are used to discuss the fundamental properties of this chromospherically active binary system. Our photometric check star, HR 4269, turned out to be variable as well, adding yet another subplot to the entwined variability story of Gl 410 and HD 95559.

2. SPECTROSCOPIC OBSERVATIONS AND REDUCTIONS

We made nine high-dispersion spectroscopic observations of HD 95559, all but one of them obtained at

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double-lined phases, from 1996 April to 2000 April with the Kitt Peak National Observatory (KPNO) coudé feed telescope, coudé spectrograph, and a Texas Instruments CCD detector. All the observations made at double-lined phases are centered in the red at 6430 Å, cover a wavelength range of about 80 Å, and have a resolution of 0.21 Å. We obtained a single observation at 6707 Å with the same wavelength range and resolution when the lines of the two components were significantly blended. During the 2000 April observing run, single observations of the photometric check and comparison stars, HR 4269 and HD 95242, respectively, also were acquired at 6430 Å.

We determined radial velocities of the stars with the IRAF cross-correlation program FXCOR (Fitzpatrick 1993). The velocity standard for HD 95559 was β Vir, while for HR 4269 and HD 95242 it was HR 4695. Both are IAU radial velocity standard stars (Pearce 1957), whose velocities we adopted from the work of Scarfe, Batten, & Fletcher (1990). Because of the relatively large projected rotational velocities of HD 95559, we used only the least blended two or three lines of each star in the cross-correlation.

3. PHOTOMETRIC OBSERVATIONS AND REDUCTIONS

We obtained our photometry of HD 95559 and Gl 410 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. Each of the two program stars was measured in the following sequence, termed a group observation: K, sky, C, V, C, V, C, V, C, sky, and K, where K is a check star, C is the comparison star, and V is the program star. A total of 216 group observations of HD 95559 and 235 group observations of Gl 410 were obtained with the APT during the 1995–1996 and 1996–1997 observing seasons.

For each group observation, three $V-C$ and two $K-C$ differential magnitudes were computed and averaged together to create group means. 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. For this telescope external precision of the group means, based on standard deviations for pairs of constant stars, is about 0.004 mag on good nights. Group mean differential magnitudes with internal standard deviations greater than 0.01 mag were discarded. Further details of telescope operations and data reduction procedures can be found in Henry (1995a, 1995b).

Since HD 95559 and Gl 410 are close together on the sky, we used the same check star and comparison star for both group observing sequences. The check and comparison stars were HR 4269 ($V = 6.17$, $B-V = 1.55$, K2) and HD 95242 ($V = 7.29$, $B-V = 1.122$, K0), respectively. The $K-C$ differential magnitudes have a scatter of about 0.015 mag (standard deviation), indicating that at least one of these two stars is a low-amplitude variable. We demonstrate in § 7 that the comparison star HD 95242 is constant to 0.006 mag or better, implicating the check star HR 4269 as a new variable, which we discuss briefly in § 6. Therefore, all differential magnitudes analyzed in this paper use HD 95242 as a known constant comparison star. All of the individual photometric observations are available on the Tennessee State University Automated Astronomy Group web site.[2]

4. HD 95559

4.1. *Spectroscopic Orbit*

The two components of HD 95559 have nearly equal line strengths. Nevertheless, with the help of the preliminary period determined by Jeffries et al. (1994), we obtained a consistent set of component identifications. For one of the components, a period search of the Jeffries, Bertram, & Spurgeon (1995) velocities and our velocities identified a period of 1.526 days. The observations of Jeffries et al. (1995) span only 5 days, but because they usually obtained two or three observations per night, the one-day alias problem encountered in the photometric data (see below) is not present in our combined set of velocities. For identification purposes we call the star with the slightly greater minimum mass, as judged from the results of our new orbital elements, the primary or component A, while the less massive star is called the secondary or component B.

To compute the orbital elements, we used several different computer programs. For single- and double-lined circular orbits, we analyzed the velocities with SB1C and SB2C (D. Barlow 1998, private communication), respectively, both of which use differential corrections to determine the elements. For eccentric-orbit solutions we used a slightly modified version of the program developed by Barker, Evans, & Laing (1967), which likewise uses differential corrections.

Because of the short orbital period, a circular orbit was initially adopted. With the revised period of 1.526 days assumed as a starting value, four sets of orbital elements were computed, one each for the primary and secondary from our KPNO velocities and two more solutions from the data of Jeffries et al. (1995). The center-of-mass velocities of the solutions were nearly identical, so no zero-point adjustment was made to any of the sets of velocities. Next, the primary and secondary velocities were analyzed simultaneously in two additional circular-orbit solutions, one for the KPNO velocities and one for the velocities of Jeffries et al. (1995). After the variances of the two solutions were compared, weights of 1.0 were assigned to the KPNO velocities, while weights of 0.15 were given to the velocities of Jeffries et al. (1995). Then, a double-lined circular-orbit solution of all those data was computed. The velocity of our KPNO observation having significantly blended lines also was included, but with zero weight.

For comparison, a double-lined eccentric-orbit solution with the same data was obtained. The eccentricity of this solution is 0.0046 ± 0.0018. According to the second test of Lucy & Sweeney (1971), the circular-orbit solution is to be preferred, but this result is close to the test's dividing line. We have chosen the circular-orbit solution as our final one because of the result of this test, the very small value of the eccentricity, and because tidal forces would be expected to circularize such a short-period orbit during the Hayashi-track phase (Zahn & Bouchet 1989). Table 1 lists our KPNO velocities and the unblended velocities of Jeffries et al. (1995). It also lists the velocities of the two components from the lone red wavelength observation of Strassmeier et al. (2000), which were not included in our analysis. Our final

[2] See http://schwab.tsuniv.edu/papers/aj/castars18/castars18.html.

TABLE 1

RADIAL VELOCITIES OF HD 95559

HJD (−2,400,000+)	Phase	RV_A (km s^{-1})	$O-C_A$ (km s^{-1})	RV_B (km s^{-1})	$O-C_B$ (km s^{-1})	Source[a]
49,052.571......	0.574	−92.8	1.0	101.9	−0.3	J95
49,052.664......	0.635	−68.5	0.0	78.5	1.8	J95
49,052.757......	0.696	−32.2	0.5	40.9	0.3	J95
49,054.600......	0.903	95.4	1.9	−87.2	−0.7	J95
49,054.644......	0.932	104.2	1.0	−95.9	0.4	J95
49,055.389......	0.420	−93.2	−1.2	100.7	0.4	J95
49,055.435......	0.451	−99.4	0.7	106.8	−1.7	J95
49,055.611......	0.566	−94.5	1.6	106.2	1.7	J95
49,055.679......	0.610	−86.9	−6.8	88.7	−0.4	J95
49,055.727......	0.642	−65.5	0.8	72.8	−0.1	J95
50,200.709......	0.959	109.1	−0.2	−103.4	−0.9	KPNO
50,400.035......	0.579	−92.3	0.1	101.0	0.5	KPNO
50,401.049......	0.243	5.4[b]	−2.9	5.4[b]	6.1	KPNO
50,576.681......	0.337	−52.9	−0.1	60.9	0.1	KPNO
50,632.664......	0.023	111.4	−0.4	−103.9	1.1	KPNO
50,831.054......	0.030	111.6	0.5	−104.0	0.3	KPNO
50,831.947......	0.615	−78.6	−0.5	86.4	0.0	KPNO
50,927.773......	0.410	−88.6	0.1	96.4	−0.4	KPNO
51,240.763......	0.516	−103.7[c]	1.1	110.2[c]	−3.0	S00
51,659.696......	0.046	107.7	−0.7	−101.6	0.0	KPNO

[a] (J95) Jeffries et al. 1995; (KPNO) this paper; (S00) Strassmeier et al. 2000.

[b] Blended velocity given zero weight.

[c] Uncertain velocity zero point, velocity given zero weight.

orbital elements are presented in Table 2. The mass ratio, $M_A/M_B = 1.0075 \pm 0.0024$, differs from unity by only 3 σ. Thus, whether star A is really more massive than star B is problematic. We note that our results reverse the component identification given by Jeffries et al. (1995) as a result of his preliminary orbit. In Figure 1 the velocities we used are compared with the computed velocity curves. Zero phase is computed from T_0, a time of maximum velocity.

For their red wavelength observation, Strassmeier et al. (2000) listed velocities for components A and B, as well as a third velocity near the system's center-of-mass velocity. In their Table 3, they noted that HD 95559 is possibly a triple system. However, we find no evidence for a third component in our spectra.

4.2. *Photometric Variability*

The differential V magnitudes of HD 95559 in the sense HD 95559 minus the comparison star HD 95242 for the two observing seasons are plotted against Julian date in Figure 2. The light curve changed little during the first season, but significant changes in amplitude and mean light level occurred during the second season. The light curve of the B data is essentially identical to the V observations.

We list our analysis results of these photometric data in Table 3. The seasonal mean magnitudes of each of the four data sets are listed in column (5), while the standard deviations of a single observation from its seasonal mean are listed in column (6). Separate periodogram analyses of the four data sets resulted in the periods listed in column (7). The weighted mean of these four period determinations is 1.5264 ± 0.0003 days, which is 1 σ agreement with our spectroscopically determined orbital period. We interpret the light variations as due to rotational modulation of a spotted stellar surface (see § 4.6), so rotation in HD 95559 is tightly synchronized to the orbital motion. All our periodogram analyses also revealed a strong alias at 2.89 days. This is very close to the period of Gl 410 reported by Bopp et al. (1983), when they used HD 95559 as their comparison star.

TABLE 2

ORBITAL ELEMENTS OF HD 95559

Parameter	Value
P (days)	$1.52599775 \pm 0.00000104$
T_0 (HJD)	$2{,}450{,}359.4755 \pm 0.0005$
γ (km s^{-1})	3.81 ± 0.11
K_A (km s^{-1})	109.14 ± 0.18
K_B (km s^{-1})	109.96 ± 0.18
e	0.0 (assumed)
$a_A \sin i$ (km)	$22.962 \pm 0.039 \times 10^5$
$a_B \sin i$ (km)	$23.074 \pm 0.038 \times 10^5$
M_A/M_B	1.0075 ± 0.0024
$M_A \sin^3 i$ ($M_\odot$)	0.8365 ± 0.0031
$M_B \sin^3 i$ ($M_\odot$)	0.8303 ± 0.0031
Standard error of an observation of unit weight	0.48 km s^{-1}

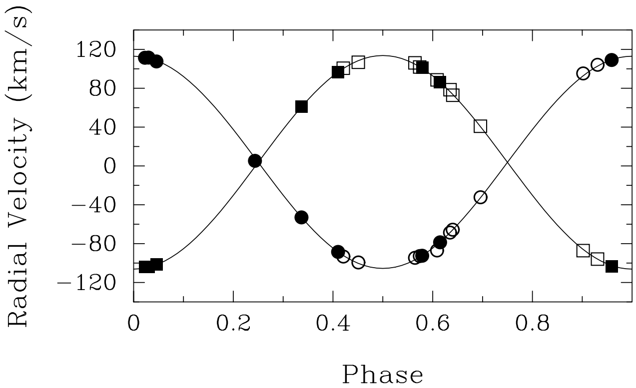

FIG. 1.—Plot of the computed radial velocity curves of HD 95559 compared with the observations. For component A, filled circles represent data from KPNO; open circles represent data from Jeffries, Bertram, & Spurgeon (1995). For component B, filled squares represent data from KPNO; open squares represent data from Jeffries et al. (1995). Phase is computed from a time of maximum velocity.

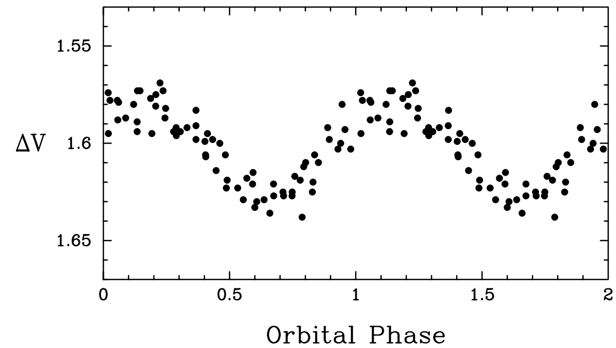

FIG. 3.—Differential V magnitudes of HD 95559 from the 1995–1996 observing season replotted against orbital phase computed with the ephemeris in eq. (1). Eclipses are not detected at the phases of conjunction.

The V observations from the first observing season are replotted in Figure 3 against spectroscopic orbital phase computed with the ephemeris

$$JD_{conj} = 2{,}450{,}359.094 + 1.52599775E \, , \qquad (1)$$

where the epoch corresponds to a time when the more massive star is in front of the less massive star and the period is our spectroscopic orbital period. The figure clearly shows that the possible eclipses predicted by Popper (1996) do not occur. Sine curve fits to the resulting phase curves of each of the four data sets were computed by the method of least squares. The resulting full amplitudes and phases of minimum light (θ_{min}) are listed in columns (8) and (9), respectively, of Table 3. These amplitudes suggest little change from the first to the second season, although Figure 2 shows there is significant change in amplitude *within* the second season. A small change in the phase of minimum is evident between the two seasons. The rms residuals of the observations from the sine curve fits are listed in column (10) of Table 3. The changing light curve of the second season is reflected in the higher residuals for that season.

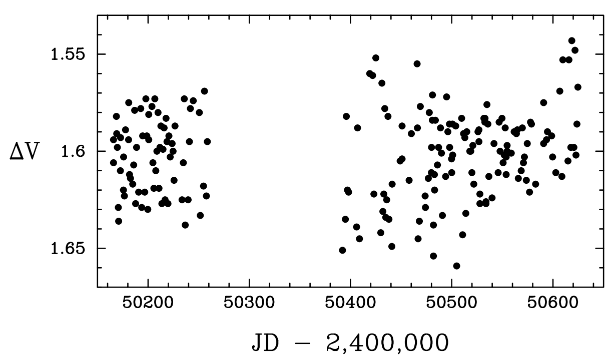

FIG. 2.—Differential V magnitudes of HD 95559 plotted against Julian date for the 1995–1996 and 1996–1997 observing seasons. The light curve is changing throughout the second season.

4.3. *v sin i, Spectral Types, and Magnitude Difference*

With the procedure of Fekel (1997), we determined the projected rotational velocities for the two components of HD 95559 from seven KPNO red wavelength spectra. For each spectrum the FWHM of the one or two least blended lines was measured and, if appropriate, the results were averaged for each component. The instrumental broadening was removed, and the calibration polynomial of Fekel (1997) was used to convert the resulting broadening in angstroms into a total line broadening in kilometers per second. We assumed a macroturbulence of 2 km s^{-1}, appropriate for a K dwarf (Marcy & Basri 1989). The resulting $v \sin i$ values are 32.4 and 31.6 km s^{-1} for components A and B, respectively, with an estimated error of 2 km s^{-1} (Table 4). These values, based on seven spectra, supersede the ones determined by Fekel (1997), and a comparison shows that the component identification has been reversed and the new values are slightly smaller.

The late spectral type of the components produces significant line crowding even at red wavelengths, and there are really no unblended lines in the observed wavelength region. In addition, starspots cause the lines to be shallower than in an unspotted star, making the measured FWHM a bit larger. Thus, our latest $v \sin i$ results may be slightly too large. Nevertheless, they are in reasonable agreement with

TABLE 3
PHOTOMETRIC ANALYSIS RESULTS FOR HD 95559

Season (1)	Filter (2)	Date Range (JD − 2,400,000) (3)	N_{obs} (4)	Mean Brightness (mag) (5)	σ (mag) (6)	Period (days) (7)	Full Amplitude (mag) (8)	θ_{min} (phase) (9)	rms (mag) (10)
1995–1996......	V	50,165–50,258	69	1.6021	0.019	1.5269 ± 0.0008	0.048 ± 0.003	0.655 ± 0.009	0.007
1995–1996......	B	50,165–50,258	66	1.3752	0.019	1.5269 ± 0.0007	0.052 ± 0.002	0.632 ± 0.007	0.006
1996–1997......	V	50,392–50,624	133	1.6014	0.024	1.5259 ± 0.0006	0.045 ± 0.004	0.513 ± 0.015	0.016
1996–1997......	B	50,392–50,624	133	1.3725	0.025	1.5261 ± 0.0007	0.044 ± 0.005	0.504 ± 0.017	0.017

TABLE 4

FUNDAMENTAL PROPERTIES OF HD 95559

Parameter	Value	Reference
V (mag)	8.96	ESA 1997
$B-V$ (mag)	0.872	ESA 1997
π (arcsec)	0.001843 ± 0.00119	ESA 1997
Spectral Type of A, B	K1 V	This paper
$V_A \sin i$ (km s^{-1})	32.4 ± 0.2	This paper
$V_B \sin i$ (km s^{-1})	31.6 ± 0.2	This paper
$V_{\rm A,B}$ (mag)	9.71 ± 0.10	This paper
$M_{V({\rm A,B})}$ (mag)	6.04 ± 0.17	This paper
$L_{\rm A,B}$ ($L_\odot$)	0.373 ± 0.067	This paper
$R_{\rm A,B}$ ($R_\odot$)	0.778 ± 0.083	This paper
$M_A(i = 75°)$ ($M_\odot$)	0.93	This paper
$M_B(i = 75°)$ ($M_\odot$)	0.92	This paper

the values of 27 km s^{-1} for each component found by Jeffries et al. (1995) and 31 and 26 km s^{-1}, determined by Strassmeier et al. (2000).

We determined the spectral types of the components of HD 95559 with a spectrum-addition technique used by Strassmeier & Fekel (1990). They identified several luminosity-sensitive and temperature-sensitive line ratios in the 6430–6465 Å region and used them, along with the general appearance of the spectrum, as spectral-type criteria. The spectra of K dwarf and subgiant reference stars from the list of Fekel (1997) were obtained at KPNO with the same telescope, spectrograph, and detector as our spectra of HD 95559 were. Comparison spectra were created with a computer program developed by 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 best reproduce the spectrum of HD 95559 in the 6430 Å region.

The starting point for this determination was the spectral class of Popper (1996). Very good fits to the spectrum of HD 95559 were found with reference stars of spectral type K0 V and K2 V, while a fit with the spectrum of a K3 V star was not as good. Fits with the spectra of early K subgiants did not produce the correct line ratios for luminosity-sensitive line pairs. As noted above, the lines of the two components are nearly identical, and so we classify both stars as K1 V (Table 4). Abundance values, found in the literature for the K dwarf reference stars, indicate that the [Fe/H] value for HD 95559 is equal to or slightly greater than the Sun's.

The resulting continuum-intensity ratio $I_B/I_A = 0.96$. Since the same reference-star spectrum provided a good fit to both components, this intensity ratio is assumed to be the luminosity ratio and results in a magnitude difference at 6430 Å of 0.05 ± 0.10 mag. The uncertainty has been estimated from the various best-fit combinations. The components have identical spectral types, and so the magnitude difference of the components does not change with wavelength. Although the slightly more massive star may be slightly brighter, given the 0.1 mag uncertainty, we adopt $\Delta V = 0.0$ mag.

4.4. *Fundamental Parameters*

With the help of the *Hipparcos* parallax, V magnitude, and $B-V$ color (ESA 1997), we determined fundamental parameters of the components of HD 95559. The distance to the system is 54 pc, and so we have assumed that interstellar extinction is not significant. Thus, the components have $M_V = 6.04 \pm 0.17$ mag. The canonical M_V value of a K1 V star listed by Gray (1992) is 6.2 mag, in good agreement with our result. A bolometric correction of -0.261 (Flower 1996) and an assumed $M_{\rm bol}$ for the Sun of 4.71 mag result in $L = 0.373 \pm 0.067$ $L_\odot$. From Flower's (1996) $(B-V)-T_{\rm eff}$ relation, we assume an effective temperature of 5120 K. The luminosity and temperature combine to produce a radius $R = 0.778 \pm 0.083$ $R_\odot$.

The radii of the components of HD 95559 can be estimated in a second way. From the mean of our $v \sin i$ values for A and B and the photometrically determined rotation period, the mean $R \sin i = 0.965 \pm 0.087$ $R_\odot$. This minimum value is 0.18 $R_\odot$ larger than the radius computed from the luminosity and effective temperature, although the uncertainties of the two determinations are nearly 0.1 $R_\odot$ each.

The radius from the Stefan-Boltzmann law is in accord with the canonical value 0.78 $R_\odot$ (Gray 1992), but the minimum value computed from the $v \sin i$ and rotation period is nearly 0.2 $R_\odot$ larger. However, the uncertainties in our two determinations have not taken into account two factors that systematically affect the computed radii. Fekel et al. (1999) pointed out that for a chromospherically active star the true radius can be somewhat larger than the value computed from its assumed effective temperature plus its luminosity via its parallax and V magnitude. The mean brightness of an active star varies, and such stars rarely, if ever, have an unspotted hemisphere. For HD 95559 we have adopted its mean V magnitude as the magnitude of its unspotted surface. If the V magnitude were 0.1 mag brighter than our adopted value, the radius would increase by 0.04 $R_\odot$, or 5%. With regard to the minimum radius, because of blending problems our $v \sin i$ value is likely a bit too large. If the measured mean $v \sin i$ were 2 km s^{-1} smaller, the minimum radius would be reduced by 0.06 $R_\odot$. Thus, accounting for such effects would bring the radius values closer together.

From the minimum masses, orbital period, and derived radii, we estimate that the system should have an inclination less than 76° for no eclipses to occur. An inclination of 75° results in masses of 0.93 and 0.92 $M_\odot$ for the components. Such masses are more than 0.1 $M_\odot$ larger than the canonical value of Gray (1992), suggesting that the actual inclination must be very close to the above limit. Thus, we adopt a value of 75° for the orbital inclination. The disparity of our mass and minimum radius values with canonical values may be the result of unknown problems associated with our determination of those quantities. However, there currently are almost no K dwarf eclipsing binaries from which to determine accurate masses and radii (Popper 1996). Thus, canonical masses and radii for such stars also may have significant uncertainties. Our results for HD 95559 emphasize the need for accurate determinations of fundamental parameters for K dwarfs.

A summary of the basic parameters of HD 95559 is given in Table 4. Some of the values are similar to the initial results determined by Jeffries et al. (1995).

4.5. *Lithium Abundances*

Lithium abundances have previously been determined by Strassmeier et al. (2000). They found nearly identical equivalent widths of $\sim$60 mÅ for both components. Our single spectrum of the lithium region was obtained at an orbital phase when the components were severely blended. Nevertheless, because the components are essentially identical in spectral class, mass, and luminosity, we have assumed that the blended lithium line represents the abundance for each component. Our measured equivalent width is 63 Å, in excellent agreement with the mean value of the two components found by Strassmeier et al. (2000). We assume their lithium abundance result of log ϵ(Li) = 1.9.

4.6. *Discussion*

Our photometric and spectroscopic investigation of HD 95559 has confirmed the prediction of Jeffries et al. (1994) that HD 95559 is a photometric variable with a period nearly identical to its orbital period. Since both components are K1 dwarfs, the system belongs to the BY Draconis class of variables. In such late-type dwarfs, convection and rapid rotation generate a dynamo, resulting in chromospheric activity and starspots. As the latter rotate in and out of view, photometric variations of a few percent with typical periods of a few days are detected. Hall (1994) has shown that main-sequence stars with Rossby numbers less than a threshold value of about 0.65 exhibit enhanced photometric variability ($\gtrsim$0.01 mag) due to starspot activity. (The Rossby number is defined as the ratio of a star's rotation period to its convective turnover time.) Taking our observed rotation period of 1.526 days and a convective turnover time of 37 days (Gilliland 1985), we compute the Rossby number for HD 95559 to be 0.04. This confirms that HD 95559 should possess a dynamo strong enough to produce the observed photometric variability.

Lithium is very rapidly depleted in late-type dwarfs. By the age of the Hyades cluster (800 Myr), the equivalent width of the 6708 Å lithium line in single, early dwarfs is 5 mÅ, corresponding to a lithium abundance of log $\epsilon(Li) \lesssim$ 0.6 (Thorburn et al. 1993). However, Thorburn et al. (1993) found two K dwarf Hyades binaries with periods of about 2 days whose lithium abundances were enhanced relative to those of the single stars. (The larger logarithm of lithium abundance value was 0.9). They suggested that lithium depletion was significantly inhibited in such short-period, tidally locked binaries. Recently, however, using spectrum synthesis, S. Balachandran (2000, private communication) reanalyzed the lithium abundances of the two K dwarf Hyades binaries observed by Thorburn et al. (1993). She found lower values and concluded that the new results do not support theoretical models that predict tidally locked binaries have higher lithium abundances than single stars.

As shown above, HD 95559 is a short-period, tidally locked, K dwarf binary with large lithium abundances. However, the abundances of its two components are about an order of magnitude greater than that of the two Hyades binaries. By correcting for the continuum contribution of the secondary stars, Barrado y Navascués & Stauffer (1996) refined the lithium abundances of many Hyades binaries. Their Figure 4 is a plot of the logarithm of the lithium abundance versus effective temperature for Hyades and Pleiades stars. Using the values from Strassmeier et al. (2000), we find that the position of HD 95559 in that figure indicates HD 95559 is younger than the Hyades cluster and may approach the age of the Pleiades (70 Myr). Soderblom et al. (1995) noted that K dwarfs of the Pleiades have just arrived on the zero-age main sequence. Thus, HD 95559 is a very young system, perhaps even consisting of a pair of zero-age main-sequence stars.

5. GLIESE 410 = DS LEO

5.1. *Photometric Variability*

The differential V magnitudes of Gl 410 in the sense Gl 410 − HD 95242 for the two observing seasons are plotted against Julian date in Figure 4. The light curve of the B data is essentially identical. The variability amplitude increased in the second observing season, while the mean brightness changed very little.

The results of our analysis of the Gl 410 photometry are listed in Table 5, in the same format as in Table 3. Periodogram analyses of the four data sets give periods of about 2 weeks, with the periods in the first observing season being somewhat longer and considerably weaker. The weighted mean of the V and B periods is 15.71 ± 0.18 days for the first season and 13.99 ± 0.02 days for the second season. Least-squares sine curve fits to the four data sets with the period fixed to the weighted-mean period of each season give the results shown in columns (8)–(10). The standard deviations in column (6) and the full amplitudes in column (8) both show the smaller photometric variability in the first

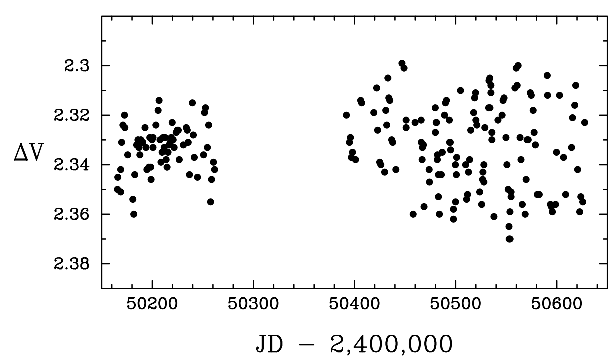

FIG. 4.—Differential V magnitudes of Gl 410 plotted against Julian date for the 1995–1996 and 1996–1997 observing seasons. The amplitude is somewhat higher in the second season.

TABLE 5

PHOTOMETRIC ANALYSIS RESULTS FOR GLIESE 410

Season (1)	Filter (2)	Date Range (JD − 2,400,000) (3)	N_{obs} (4)	Mean Brightness (mag) (5)	σ (mag) (6)	Period (days) (7)	Full Amplitude (mag) (8)	θ_{min} (phase) (9)	rms (mag) (10)
1995–1996......	V	50,165–50,261	68	2.3335	0.010	15.75 ± 0.2[a]	0.017 ± 0.003	0.388 ± 0.024	0.007
1995–1996......	B	50,165–50,255	60	2.6563	0.011	15.54 ± 0.4[a]	0.014 ± 0.004	0.408 ± 0.043	0.009
1996–1997......	V	50,392–50,627	138	2.3324	0.018	14.00 ± 0.02	0.044 ± 0.002	0.993 ± 0.007	0.007
1996–1997......	B	50,392–50,625	121	2.6568	0.019	13.98 ± 0.02	0.048 ± 0.002	0.997 ± 0.007	0.007

[a] An additional periodicity was also present at 6.85 ± 0.06 days.

season, which explains the relative weakness of the 15.71 day period. In addition to this 15.71 day period, we found another weak period of 6.85 ± 0.06 days in the first season only.

As in the case of HD 95559, we interpret these photometric variations as rotational modulation of a spotted stellar surface; therefore, the 15.71 and 13.99 day periods are stellar rotation periods. The difference in these two periods can be understood in terms of differential rotation of the star combined with a latitude change in the most prominent spot features from the first season to the second. Since there is very little difference in mean brightness of Gl 410 in the two observing seasons, the smaller level of variability in the first season must be due to a more uniform distribution of starspots during that season. This is also very likely to be the explanation of the 6.85 day secondary period in the first season since spot groups on opposite hemispheres of the star would result in a photometric period of half the stellar rotation period.

The V observations from the second observing season are replotted in Figure 5 against photometric phase computed with the ephemeris

$$\mathrm{JD} = 2{,}450{,}400.0 + 13.99E\ , \qquad (2)$$

where the epoch is arbitrary and the period is the weighted mean photometric period for the second season. The binning of the observations in phase results because the period is almost precisely an integral number of days. This light curve is typical of many chromospherically active stars with low amplitudes (see, e.g., Henry, Fekel, & Hall 1995).

5.2. *Discussion*

As a result of our photometric investigation of Gl 410, we have determined that it does indeed deserve its variable star designation of DS Leo even though the variability originally attributed to it by Bopp et al. (1983) actually belongs to HD 95559. Since our photometric observations of both Gl 410 and HD 95559 reveal intervals of low-amplitude variability (0.01 mag or so; see Figs. 2 and 4), corresponding to times when spot distributions are nearly uniform, it is likely that variability in HD 95559 dominated that in Gl 410 during the epoch of the observations by Bopp et al. (1983). Like HD 95559, Gl 410 belongs to the BY Draconis class of variables.

A search of the literature indicates that the 14.0 day period of Gl 410 is the longest photometrically determined rotation period so far found for an M dwarf. From a sample of 17 BY Draconis variables, the vast majority of which had late K or early M spectral classes, Bopp & Fekel (1977) suggested that a rotational velocity $\gtrsim 5$ km s^{-1} is necessary for photometric variations. Assuming that our photometric period is the rotation period of Gl 410 and that, appropriate for its spectral type, it has a radius of 0.58 $R_\odot$ (Gray 1992), we compute an equatorial rotational velocity of 2.1 km s^{-1}. A radius of nearly 1.4 $R_\odot$ would be required for a rotational velocity of 5 km s^{-1}. The derived rotational velocity of 2.1 km s^{-1} is consistent with the results of Delfosse et al. (1998). They observed a volume-limited sample of 118 field M dwarfs that included both old-disk and young-disk stars. Able to determine $v \sin i$ values as low as ~ 2 km s^{-1}, they found that, for dwarfs earlier than M3, no star had a measurable rotational velocity.

At least one other active late-type dwarf, HD 216803 = TW PsA (K4 V, $P_{\rm rot} = 10.3$ days) has been found to rotate more slowly (Vogt, Soderblom, & Penrod 1983) than the proposed trigger velocity. Thus, the true rotational velocity limit is likely lower than the value suggested by Bopp & Fekel (1977), who based their result on the limited number of BY Draconis variables known at that time. Taking our rotation period of 14 days for Gl 410 and a convective turnover time of about 92 days (Gilliland 1985), we compute a Rossby number of 0.15. Hence, according to Hall (1994), Gl 410 is expected to have an enhanced magnetic dynamo capable of producing the observed photometric variability in spite of its small rotational velocity.

Stauffer & Hartmann (1986) and Herbst & Layden (1987) have identified K and M dwarfs with weak Hα absorption. It is probable that a photometric survey of such stars, which have activity levels similar to that of Gl 410, would result in the discovery of additional dwarfs with rotation periods greater than 10 days.

6. CHECK STAR HR 4269 = HD 94720

6.1. *Photometric Variability*

The differential B magnitudes of HR 4269 in the sense HR 4269 minus the comparison star HD 95242 are plotted against Julian date in Figure 6 for the 1995–1996 observing season and in Figure 7 for 1996–1997. Light curves of the V observations are essentially identical except that the amplitudes are slightly smaller. The results of our photometric analysis of these data are listed in Table 6 in a format similar to Tables 3 and 5. Since HR 4269 served as the check star and HD 95242 served as the comparison star for our group observations of both HD 95559 and Gl 410, we have twice the number of observations of HR 4269 as we do

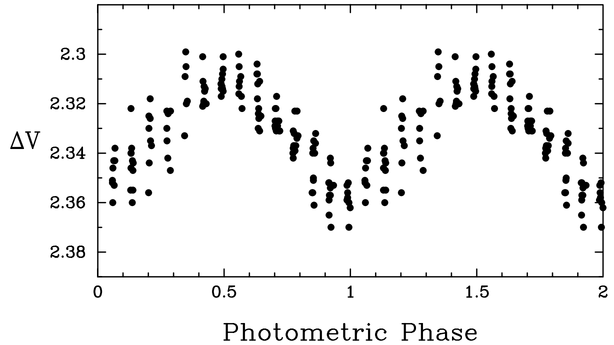

FIG. 5.—Differential V magnitudes of Gl 410 from the 1996–1997 observing season replotted against photometric phase computed with the ephemeris in eq. (2).

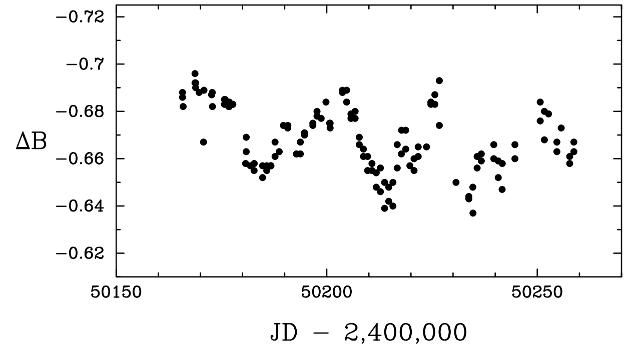

FIG. 6.—Differential B magnitudes of HR 4269 plotted against Julian date for the 1995–1996 observing season.

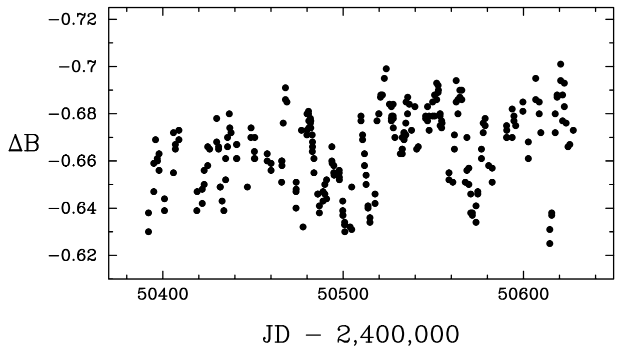

FIG. 7.—Differential *B* magnitudes of HR 4269 plotted against Julian date for the 1996–1997 observing season.

for HD 95559 and Gl 410. Periodogram analysis of these observations finds periods of 26.4 and 13.96 days for the first and second seasons, respectively. An additional weaker period of about 83 days was detected in the second season's observations, which span a longer interval of time than the first season. The amplitudes in column (8) of Table 6 are total brightness ranges estimated from the light curves.

6.2. *Spectroscopic Results*

We obtained a single spectrum of HR 4269 from which we determined its spectral type, projected rotational velocity, and radial velocity. Its spectrum in the 6430 Å region was visually compared with similarly obtained standard-star spectra from the list of Keenan & McNeil (1989). Critical line ratios and the general appearance of the spectrum were used as spectral-type criteria. We classified HR 4269 as K4 III. Its $v \sin i$ value was determined in the same manner as that of HD 95559. Following Fekel (1997), we adopted a macroturbulent velocity of 3.0 km s^{-1}, which resulted in $v \sin i = 3.6 \pm 1.0$ km s^{-1}. Its radial velocity for JD 2,451,654.772 is 26.1 ± 0.5 km s^{-1}.

6.3. *Discussion*

HR 4269 was included in a radial velocity survey of 681 stars made at the David Dunlap Observatory (DDO). Young (1945) reported a mean radial velocity of 26.7 ± 1.6 (p.e.) km s^{-1}, measured from four moderate-dispersion plates, and a DDO spectral type of K5. Those results are in excellent agreement with ours.

Henry et al. (2000) made a photometric and spectroscopic survey of 187 G, K, and a few M giants. They found photometric variability on timescales of days or weeks in 43% of the giants. The vast majority of giants had low projected rotational velocities, $\lesssim 3$ km s^{-1}, ruling out rotational modulation of starspots. As a result, Henry et al. (2000) concluded that the radial pulsation mechanism operating in M giants extends into the K giants up to about spectral class K2. With a spectral type of K4 III, a low $v \sin i$ value, and photometric variability with a period as short as two weeks, HR 4269 is another member of this class of variable stars.

7. COMPARISON STAR HD 95242

7.1. *Photometric Constancy*

In § 3 above, we noted that the scatter in our *K–C* differential magnitudes suggested that either the check star HR 4269 or the comparison star HD 95242 is variable. Since we know unambiguously from our spectroscopic orbital elements of HD 95559 that the 1.526 day variation in the HD 95559 − HD 95242 differential magnitudes comes from HD 95559, we can use the rms residuals of these observations from a sinusoidal 1.526 day variation to estimate the variability in our comparison star. These residuals result from the combination of our measurement errors (typically ∼0.004 mag), cycle-to-cycle variability in the shape and amplitude of the light curve of HD 95559, deviations in the shape of the light curve from a purely sinusoidal form, and variations in the comparison star itself. The *B* light curve from the first observing season gives the smallest residuals, 0.006 mag. We conclude that any variability in our comparison star cannot be larger than this and so cannot significantly exceed our measurement precision of 0.004 mag. Thus, HD 95242 *is* a suitable comparison star for the measurement of the much larger photometric variations in HD 95559, Gl 410, and HD 4269 reported in this paper.

7.2. *Spectroscopic Results*

We obtained a single spectrum of HD 95242 on JD 2,451,654.765, from which we determined its spectral type, projected rotational velocity, and radial velocity. As with HR 4269, the spectrum of HD 95242 was visually compared with similarly obtained standard-star spectra from the list of Keenan & McNeil (1989). From this comparison we classified it as a K1 III. Its $v \sin i$ value was determined in the same manner as that of HD 95559. Following Fekel (1997), we adopted a macroturbulent velocity of 3.0 km s^{-1}, which resulted in $v \sin i = 2.8 \pm 1.0$ km s^{-1}. Its radial velocity was 19.9 ± 0.5 km s^{-1}. A check of the SIMBAD data base indicates that these data provide new information about the star.

7.3. *Discussion*

In their photometric and spectroscopic survey of 187 late-type giants with spectral classes ranging from G0 to M0, Henry et al. (2000) found that the percentage of photometrically variable giants was a minimum for late G and early K classes. Since most of the comparison stars used to

TABLE 6

PHOTOMETRIC ANALYSIS RESULTS FOR HR 4269

Season (1)	Filter (2)	Date Range (JD − 2,400,000) (3)	N_{obs} (4)	Mean Brightness (mag) (5)	σ (mag) (6)	Period (days) (7)	Full Amplitude (mag) (8)
1995–1996......	*V*	50,165–50,261	126	−1.1320	0.013	26.4 ± 0.4	0.04
1995–1996......	*B*	50,165–50,258	130	−0.6684	0.014	26.4 ± 0.4	0.05
1996–1997......	*V*	50,392–50,627	257	−1.1296	0.014	13.96 ± 0.05[a]	0.06
1996–1997......	*B*	50,392–50,627	264	−0.6653	0.017	13.95 ± 0.05[a]	0.07

[a] An additional periodicity was also present at 83 ± 3 days.

examine the variability of Gl 410 have turned out to be variable themselves, it was fortunate that HD 95242 is a K1 III with little or no variability, making it quite adequate for its intended purpose.

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