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HD 166181 = V815 HERCULIS, A SINGLE-LINED SPECTROSCOPIC MULTIPLE SYSTEM

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ABSTRACT

We have obtained extensive spectroscopic and velocity spectrometer observations of HD 166181, a previously known single-lined spectroscopic binary. Our improved orbit for the G6 V primary has a period of 1.8098343 days and is circular. Although the lines of additional components have not been detected, radial velocity measurements confirm that the system has additional velocity variations with a period of 2092 days, or 5.73 yr. This long-period orbit has an eccentricity of 0.76. An analysis of the *Hipparcos* observations produces a well-determined astrometric orbit for the long-period system that has an inclination of 78°. Mass estimates of the components in this zero-age main-sequence multiple system indicate that the unseen secondary in the 5.73 yr orbit may also be a binary. Thus, HD 166181 is at least a triple system and possibly quadruple.

Key words: binaries: spectroscopic — stars: fundamental parameters — stars: variables: other

1. INTRODUCTION

HD 166181 = V815 Herculis = HIP 88848 ($\alpha = 18^{\rm h}08^{\rm m}15\overset{\rm s}{.}7$, $\delta = 29°42'36\overset{''}{.}3$ [J2000], $V = 7.56$ mag) was included in a radial velocity survey of over 1000 late-type stars conducted at the David Dunlap Observatory (DDO). From five observations Heard (1956) found a velocity range of 87 km $\rm s^{-1}$ and thus identified it as a single-lined spectroscopic binary. Almost two decades later, Nadal et al. (1974) acquired 18 additional spectroscopic observations at the Haute-Provence Observatory (OHP). Those radial velocities, combined with the ones from the DDO, resulted in an orbital period of 1.809837 days. Nadal et al. (1974) also found that this G5 V star (Heard 1956) had strong, narrow Ca II H and K emission lines and suggested that the unseen secondary is an early M dwarf. Fekel et al. (1986) discovered that the G dwarf possesses a very strong lithium line at 6708 Å, indicating that HD 166181 is a young system.

Eggen (1978) noted that in 1962 HD 166181 had light variations of about 0.1 mag. Soon after this report Mekkadan et al. (1980) collected seven nights of photometry and found variability of about 0.1 mag in *V* that had a period consistent with the orbital one. Like other chromospherically active stars, the variability was attributed to starspots rotating in and out of view. Kholopov et al. (1985) assigned HD 166181 the variable star name V815 Her. More recently, Jetsu et al. (2000) analyzed 14 yr of *BV* photometry and concluded that the G dwarf maintained a constant period of 1.7924 days over that time span. The mean brightness changes seen to date have not produced a regular activity cycle.

As expected for a chromospherically active star, HD 166181 has emission and variability in other wavelength regions. Drake et al. (1986) found HD 166181 to be a radio source at 6 cm. Fekel et al. (1986) observed HD 166181 as part of a survey of chromospherically active stars. Their low-dispersion ultraviolet spectra showed strong emission lines but no evidence of a hot companion. The system was detected in the extreme ultraviolet by the *Extreme Ultraviolet Explorer* satellite (Malina et al. 1994) and as an X-ray source in the *ROSAT* Wide Field Camera all-sky survey (Pounds et al. 1993). Makarov (2003) listed it as one of the 100 brightest X-ray stars within 50 pc of the Sun.

Dempsey et al. (1996) discussed nearly simultaneous ultraviolet and visual spectroscopy, as well as contemporaneous photometry. From 13 KPNO coudé feed telescope, red-wavelength spectra, they measured radial velocities and used them to determine new orbital elements. Comparing their orbit with that of Nadal et al. (1974), Dempsey et al. (1996) found agreement within the uncertainties for all elements except for the center-of-mass velocity, which differed by 11 km $\rm s^{-1}$. Such a large difference led them to propose that the system is most likely triple. That conclusion caused us to obtain additional radial velocities of the system. An analysis of the new velocities, obtained through 2002 September, resulted in a preliminary solution of the system that produced a long period of 2300 days (Fekel 2004). In this work we have analyzed the complete data set, including velocities from 2003, and find that the long period should be reduced to 2092 days. A reanalysis of the *Hipparcos* astrometric data enables us to determine an astrometric orbit

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TABLE 1
Radial Velocities of HD 166181

Heliocentric Julian Date (2,400,000+)	Light Time Correction (days)	ϕ_L	ϕ_S	V (km s^{-1})	$O - C$ (km s^{-1})	Weight	Observatory
32,760.665	0.015	0.481	0.587	−56.3	−1.6	0.01	DDO
33,136.587	0.013	0.660	0.299	−31.2	−3.5	0.01	DDO
33,507.653	0.006	0.838	0.330	−32.7	8.1	0.01	DDO
33,772.875	−0.001	0.964	0.879	30.8	8.1	0.01	DDO
34,303.521	0.012	0.218	0.074	29.4	−15.9	0.0	DDO
41,480.579	0.013	0.648	0.662	−23.9	15.7	0.0	OHP
41,488.539	0.013	0.652	0.060	38.6	−0.9	0.03	OHP
41,812.538	0.008	0.807	0.084	33.1	0.0	0.03	OHP
41,864.460	0.007	0.832	0.773	−4.3	2.2	0.03	OHP
41,865.454	0.007	0.832	0.323	−35.1	3.2	0.03	OHP
41,866.503	0.007	0.833	0.902	29.5	−0.4	0.03	OHP
41,867.455	0.007	0.833	0.428	−61.2	2.1	0.03	OHP
41,868.541	0.007	0.834	0.028	41.6	2.6	0.03	OHP
41,869.557	0.006	0.834	0.590	−61.9	−1.6	0.03	OHP
41,870.480	0.006	0.835	0.100	30.8	1.3	0.03	OHP
41,930.333	0.005	0.863	0.171	8.6	−2.0	0.03	OHP
41,930.488	0.005	0.863	0.257	−10.9	6.7	0.03	OHP
41,931.322	0.005	0.864	0.718	−26.3	−0.3	0.03	OHP
41,932.337	0.005	0.864	0.279	−21.5	3.4	0.03	OHP
41,933.334	0.005	0.865	0.830	11.3	0.4	0.03	OHP
41,934.328	0.005	0.865	0.379	−57.7	−3.2	0.03	OHP
41,935.424	0.005	0.866	0.984	38.0	−0.8	0.03	OHP
41,936.340	0.005	0.866	0.491	−70.7	−1.3	0.03	OHP
45,812.922	0.011	0.719	0.441	−62.6	0.2	1.00	KPNO
45,852.838	0.010	0.738	0.497	−65.9[a]	0.8	1.00	KPNO
48,678.994	0.006	0.089	0.054	51.7	−1.5	0.08	KPNO
48,679.975	0.006	0.089	0.596	−42.7	−0.1	0.08	KPNO
48,681.008	0.006	0.090	0.167	31.3	2.2	0.08	KPNO
48,681.917	0.006	0.090	0.669	−23.9	0.5	0.08	KPNO
48,887.606	0.011	0.189	0.317	−27.0	−2.3	0.08	KPNO
48,888.636	0.011	0.189	0.886	35.9	−2.7	0.08	KPNO
48,889.671	0.011	0.190	0.458	−56.2	−1.3	0.08	KPNO
48,889.707	0.011	0.190	0.478	−57.7	−1.5	0.08	KPNO
48,890.671	0.011	0.190	0.011	51.8	0.1	0.08	KPNO
48,890.707	0.011	0.190	0.031	54.2	3.4	0.08	KPNO
48,891.657	0.011	0.191	0.556	−54.3	−0.8	0.08	KPNO
48,892.670	0.011	0.191	0.115	35.9	−2.2	0.08	KPNO
48,893.677	0.011	0.192	0.672	−27.7	0.5	0.08	KPNO
49,618.630	0.015	0.538	0.233	−2.5	0.9	1.00	KPNO
49,619.668	0.015	0.539	0.806	9.4	−0.2	1.00	KPNO
49,621.737	0.015	0.540	0.950	42.4	0.1	1.00	KPNO
49,622.656	0.015	0.540	0.457	−61.6	0.0	1.00	KPNO
49,835.932	0.013	0.642	0.301	−28.4	−0.4	1.00	KPNO
49,900.802	0.012	0.673	0.145	21.3	−0.7	1.00	KPNO
49,968.656	0.011	0.705	0.637	−46.6	0.7	1.00	KPNO
49,969.704	0.011	0.706	0.216	−0.8	−0.4	1.00	KPNO
49,971.656	0.011	0.707	0.295	−28.1	−1.2	1.00	KPNO
49,972.653	0.011	0.707	0.845	18.7	0.0	1.00	KPNO
50,201.905	0.007	0.817	0.518	−68.1	−0.1	1.00	KPNO
50,203.867	0.007	0.818	0.602	−57.3	0.3	1.00	KPNO
50,262.851	0.006	0.846	0.193	4.2	0.0	1.00	KPNO
50,263.876	0.006	0.846	0.760	−12.3	−0.9	1.00	KPNO
50,266.802	0.006	0.848	0.377	−54.1	−0.6	1.00	KPNO
50,362.613	0.003	0.894	0.317	−38.4	−0.3	1.00	KPNO
50,364.592	0.003	0.895	0.411	−61.7	0.2	1.00	KPNO
50,365.630	0.003	0.895	0.984	37.9	−0.1	1.00	KPNO
50,366.582	0.003	0.896	0.510	−69.9	0.3	1.00	KPNO
50,401.593	0.002	0.912	0.856	17.1	0.2	1.00	KPNO
50,631.854	0.000	0.022	0.084	54.2	−0.4	1.00	KPNO
50,633.888	0.000	0.023	0.208	21.9	0.0	1.00	KPNO
50,719.601	0.004	0.064	0.566	−46.0	−0.3	1.00	KPNO
50,720.644	0.004	0.065	0.142	37.9	−0.2	1.00	KPNO
50,757.577	0.005	0.082	0.548	−49.4	−0.1	1.00	KPNO
50,926.958	0.010	0.163	0.135	34.5	0.1	1.00	KPNO

TABLE 1—*Continued*

Heliocentric Julian Date (2,400,000+)	Light Time Correction (days)	ϕ_L	ϕ_S	V (km s^{-1})	$O-C$ (km s^{-1})	Weight	Observatory
50,931.949	0.010	0.166	0.892	41.4	0.7	1.00	KPNO
51,003.758	0.011	0.200	0.569	−51.6	0.5	1.00	KPNO
51,088.626	0.013	0.241	0.461	−56.5	0.0	1.00	KPNO
51,092.615	0.013	0.243	0.665	−32.1	−0.5	1.00	KPNO
51,306.906	0.015	0.345	0.067	42.7	−0.7	1.00	KPNO
51,307.873	0.015	0.345	0.602	−50.6[a]	−0.9	1.00	KPNO
51,348.917	0.015	0.365	0.280	−16.1	0.5	1.00	KPNO
51,351.804	0.015	0.366	0.875	31.7	−0.2	1.00	KPNO
51,472.609	0.015	0.424	0.624	−46.1	0.0	1.00	KPNO
51,474.594	0.015	0.425	0.721	−17.7	−0.4	1.00	KPNO
51,656.967	0.015	0.512	0.489	−63.3	−0.3	1.00	KPNO
51,660.003	0.015	0.514	0.166	18.8	0.5	1.00	KPNO
51,731.831	0.014	0.548	0.854	24.2	0.6	1.00	KPNO
51,732.821	0.014	0.549	0.401	−54.0	−0.4	1.00	KPNO
51,803.670	0.014	0.582	0.548	−61.7	0.0	1.00	KPNO
51,806.665	0.014	0.584	0.203	6.0	0.2	1.00	KPNO
52,014.995	0.012	0.683	0.314	−32.2	0.6	1.00	KPNO
52,015.993	0.012	0.684	0.866	25.0	0.5	1.00	KPNO
52,180.653	0.009	0.763	0.848	18.0	−0.3	1.00	KPNO
52,181.628	0.009	0.763	0.386	−53.0	1.0	1.00	KPNO
52,392.993	0.005	0.864	0.176	7.6	−1.7	0.0	KPNO
52,536.648	0.001	0.933	0.553	−68.5	−0.2	1.00	KPNO
52,537.648	0.001	0.933	0.105	25.9	0.0	1.00	KPNO
52,706.030	−0.001	0.014	0.143	40.3	−0.4	1.00	KPNO
52,707.029	−0.001	0.014	0.695	−10.9	0.2	1.00	KPNO
52,710.012	−0.001	0.016	0.344	−22.3	0.4	1.00	KPNO
52,755.969	0.002	0.038	0.735	1.7	0.0	1.00	KPNO
52,759.002	0.002	0.039	0.411	−39.2	0.2	1.00	KPNO
52,768.976	0.002	0.044	0.922	51.6	−2.3	0.04	DAO
52,774.923	0.003	0.047	0.207	21.1	1.0	0.04	DAO
52,796.889	0.003	0.057	0.344	−27.3	−1.8	0.04	DAO
52,808.816	0.004	0.063	0.934	57.2	3.4	0.04	DAO
52,809.850	0.004	0.063	0.505	−47.9	2.2	0.04	DAO
52,817.830	0.004	0.067	0.914	50.0	−0.3	0.04	DAO
52,873.768	0.006	0.094	0.821	23.2	−2.0	0.04	DAO
52,880.752	0.006	0.097	0.680	−21.6	0.0	0.04	DAO
52,885.743	0.007	0.100	0.437	−48.0	0.7	0.04	DAO
52,902.665	0.007	0.108	0.787	13.7	0.2	1.00	KPNO
52,904.671	0.007	0.109	0.895	44.7	0.8	1.00	KPNO
52,907.768	0.007	0.110	0.607	−46.1	−4.4	0.04	DAO
52,935.646	0.008	0.123	0.010	49.4	−4.9	0.04	DAO
52,940.572	0.008	0.126	0.732	−6.5	−0.2	1.00	KPNO
52,941.564	0.008	0.126	0.280	−10.2	−0.1	1.00	KPNO
52,957.590	0.009	0.134	0.134	37.9	2.2	0.04	DAO

[a] Lithium region with central wavelength 6700 Å.

for the long-period system. With the results from these orbits and other information, we discuss the properties of this multiple star system and determine some fundamental parameters of its components.

2. OBSERVATIONS AND REDUCTIONS

In 1984 we obtained two spectrograms of HD 166181 at the KPNO with the coudé feed telescope, coudé spectrograph, and a TI CCD detector. A hiatus of 10 yr ensued before we resumed observations at KPNO in 1994 September because of the results later published in Dempsey et al. (1996). Through 2003 October we obtained an additional 58 spectrograms. All but two of the 60 KPNO 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. The remaining two are centered at 6700 Å. The spectra have typical signal-to-noise (S/N) ratios of 150–200.

Radial velocities (Table 1) were determined in the 6385–6444 Å region with the IRAF[5] cross-correlation program FXCOR (Fitzpatrick 1993). β Aql was used as the cross-correlation reference star, and a 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. All the KPNO velocities are listed in Table 1.

The preliminary long-period orbit of Fekel (2004) predicted a rapid velocity change during the spring of 2003, and so from 2003 May through October additional observations were acquired at the Dominion Astrophysical Observatory (DAO) in an attempt to cover more fully the anticipated rapid change from minimum to maximum velocity. Twelve radial velocities, listed

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[5] IRAF is distributed by NOAO.

TABLE 2

Orbital Elements of HD 166181

Parameter	Short-Period	Long-Period
P (days)	$1.80983433 \pm 0.00000056$	2092.2 ± 5.8
T_0 (HJD)	$2{,}450{,}204.5802 \pm 0.0006$	...
T (HJD)	...	$2{,}450{,}585.1 \pm 7.5$
γ (km s^{-1})	...	-7.73 ± 0.12
K (km s^{-1})	54.271 ± 0.095	12.48 ± 0.29
e	0.0 (adopted)	0.765 ± 0.013
ω (deg)	...	288.7 ± 1.4
i (deg)	...	78.4 ± 1.6
Ω (deg)	...	69.2 ± 2.3
$a_{\rm Aa} \sin i$ (km)	$1.3506 \pm 0.0024 \times 10^6$	...
a_A (km)	...	$236.6 \pm 8.4 \times 10^6$
a_A (mas)	...	48.8 ± 1.2
$f(m)$ ($M_\odot$)	0.03004 ± 0.00016	0.113 ± 0.011
Standard error of an observation of unit weight (km s^{-1})	0.5	

in Table 1, were obtained with the DAO 1.2 m telescope, coudé spectrograph, and radial velocity scanner (Scarfe 2001).

In addition to the above two data sets, three others are listed in Table 1. Included are the five DDO velocities of Heard (1956), the 18 OHP velocities of Nadal et al. (1974), and the 13 KPNO velocities of Dempsey et al. (1996).

3. SPECTROSCOPIC ORBITAL SOLUTIONS

Differential correction programs to determine the short- and long-period orbits of spectroscopic triple systems have been developed at the University of Victoria by one of us (D. J. B.) and used in studies of other single-lined systems such as V389 Cygni (Barlow 1989) and HR 5472 (Barlow & Scarfe 1991). These programs, modified to permit corrections for light travel time, have been used to determine several orbital solutions for HD 166181, which are described below.

Preliminary elements for the long-period orbit (Fekel 2004) were previously determined with the KPNO data in Table 1 up to JD 2,452,537, excluding the 13 with weight 0.08 from Dempsey et al. (1996). Our next solution incorporated all of the KPNO velocities plus the DAO data with a weight of 0.04, appropriate to their scatter. The addition of the more recent KPNO and DAO velocities was important because those data extended the coverage of the long-period orbit beyond the recent periastron passage. As a result, the new solution indicated that the long period is about 200 days *shorter* than that found in the preliminary solution. The DDO radial velocities (Heard 1956), with their small numbers and very low weights, and the OHP velocities (Nadal et al. 1974), with their poor phase distribution in the long-period orbit (all but two were taken within a period of 125 days) and low weights, do not significantly improve the uncertainties of the orbital elements. Nevertheless, our final solution incorporates the older DDO and OHP velocities, listed in Table 1 with weights 0.01 and 0.03 appropriate to their scatter, respectively. To determine whether a velocity offset should be added to the OHP velocities, separate orbital solutions for OHP and KPNO velocities were computed for two stars discussed by Stockton & Fekel (1992). A comparison of the OHP and KPNO orbital solutions showed no systematic center-of-mass velocity offset, and so no zero-point correction has been applied to the OHP velocities of HD 166181. Three velocities, one each from DDO, OHP, and KPNO, were assigned zero weight because their residuals were greater than 3 σ.

As a matter of interest we obtained two additional solutions. The first allowed the eccentricity of the short-period orbit to vary. The resulting eccentricity, $e = 0.0026 \pm 0.0017$, being less than twice its uncertainty, is not significant, and the application of Bassett's (1978) second test (Lucy 1989) concurred. The second solution included no light-time corrections. A standard variance-ratio test indicated that the use of light-time corrections led to a reduction of the sum of the weighted squares of the residuals that was significant at the 1% level, the reduction being approximately 50%.

The short- and long-period elements from the all-data solution with light-time corrections are presented in Table 2. Since a time of periastron passage is undefined in a circular orbit, as recommended by Batten et al. (1989), T_0, a time of maximum radial velocity, is listed instead for the short-period orbit. In addition to the Heliocentric Julian Dates and radial velocities, Table 1 lists the light-time corrections (to the center of mass of the long-period orbit), phases of the observations in the long- and short-period orbits, velocity residuals, the weight adopted for each radial velocity, and the observatory where the data were obtained. Figure 1 presents the short-period velocity curve for the primary, component Aa. Each plotted velocity consists of the observed velocity minus its calculated long-period velocity. Since the orbit is circular, zero phase is a time of maximum velocity. Figure 2 presents the velocity curve for the long-period orbit,

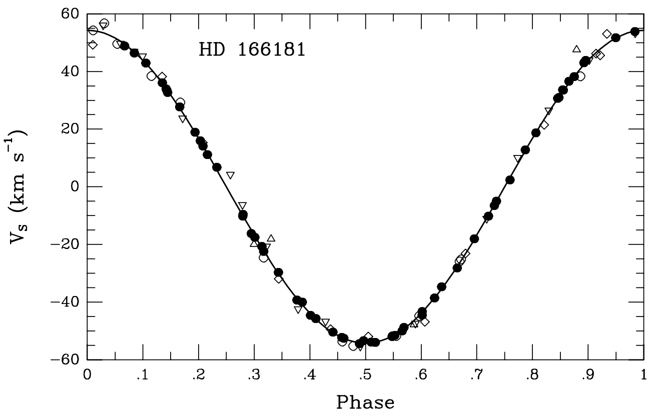

Fig. 1.—Radial velocity curve of HD 166181 in its short-period orbit. The points represent the observed velocities minus the velocities of the center of mass of Aa and Ab in the long period orbit, calculated from the elements in Table 2: *filled circles*, KPNO (this paper); *open circles*, KPNO (Dempsey et al. 1996); *diamonds*, DAO; *upward-pointing triangles*, DDO; and *downward-pointing triangles*, OHP. The curve represents the short-period elements from the same table. Zero phase is a time of maximum velocity.

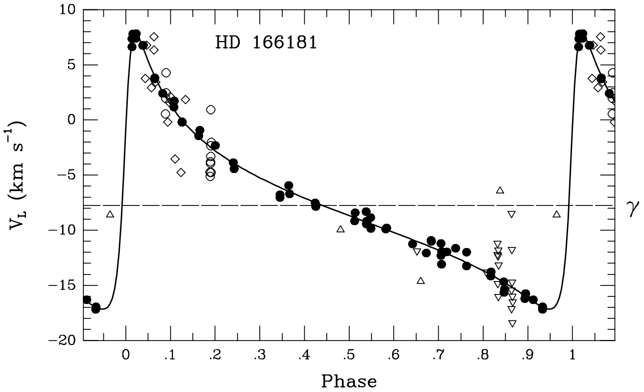

Fig. 2.—Radial velocity curve of HD 166181 in its long-period orbit. The points represent the observed velocities minus the velocities in the short-period orbit, calculated from the elements in Table 2. Their symbols are the same as in Fig. 1. The curve represents the long-period elements from the same table. Zero phase is a time of periastron passage. The horizontal dashed line is the center-of-mass, or γ, velocity of the system.

where zero phase is a time of periastron passage. Each plotted velocity consists of the observed velocity of Aa minus its short-period calculated velocity.

Because the actual long-period orbit was about 200 days shorter than that predicted by the preliminary orbit (Fekel 2004), much of the rapid velocity change associated with the periastron passage of 2002–2003 occurred when HD 166181 was behind the Sun. Therefore, as seen in Figure 2, almost no velocities were obtained on the rapidly rising branch of the long-period velocity curve except at maximum velocity. The Julian Dates for the next times of the descending and ascending nodes are 2,454,662.0 and 2,454,815.1, respectively. Thus, the rapid velocity change in the 5.73 yr orbit will occur in 2008 between mid-July and mid-December, a much more favorable time to observe this part of the orbit. New observations obtained during that time period would refine the long-period orbital elements.

4. ASTROMETRIC ORBIT

In the *Hipparcos* and Tycho Catalogues (ESA 1997), HD 166181, listed as HIP 88848, was placed in the DMSA/X category, meaning that no satisfactory solution for the position, parallax, and proper motion could be derived from the *Hipparcos* observations. As a result, additional uncertainty, termed "cosmic noise," was added to the observations, and a stochastic solution was published. Such an analysis explains the 2 mas uncertainty of the parallax, which is about twice as large as that for a typical 8th mag star. For more information about the *Hipparcos* analysis of such problematic systems, which in some cases might be overlooked astrometric binaries, see the explanation in § 2.3.6 of the Catalogue's Volume 1 (ESA 1997).

Clearly, in the original *Hipparcos* analysis there was no evidence of any astrometric wobble caused by the short-period system (Jancart et al. 2005). Can a long-period orbital solution (Pourbaix & Arenou 2001; Pourbaix & Boffin 2003) advantageously replace the stochastic one? We used two independent methods to fit the *Hipparcos* observations and determine the orbital parameters. When we adopted the spectroscopic values for the orbital elements P, T, e, K, and ω (Table 2) and reanalyzed the *Hipparcos* data,[6] the agreement between the two sets of parameters was assessed at the 99.9% confidence level. Parameters i, Ω, and a_A from our new astrometric solution are listed in Table 2.

To examine the robustness of the astrometric orbit, we computed an additional solution. When only the spectroscopic P, T, and e were imposed on the astrometric data, the derived values for K and ω are within 2 σ of their spectroscopic values, confirming the strong reliability of the astrometric fit. Furthermore, our adopted orbit, combined with the parallax, yields a radial velocity amplitude that is consistent with the spectroscopic value. Thus, the orbital inclination and the other parameters from the astrometric solution are very well constrained and should be confirmed once the system is resolved.

The new astrometric solution results in a parallax of 30.93 ± 0.77 mas. It is worth noting that the reduced uncertainty of the parallax is now consistent with that for an 8th mag star. In addition, the parallax remains identical, within its improved uncertainty, to the previously published *Hipparcos* value (ESA 1997).

The change from a stochastic solution of the astrometric data to an orbital model also produces a revised proper motion, $\mu_\alpha = 107$ mas yr^{-1} and $\mu_\delta = -31$ mas yr^{-1}. This result is consistent with the Tycho-2 value (Høg et al. 2000) at a 2 σ level rather than the 30 σ level of the earlier value. Of course, the uncertainty of the stochastic solution did not reflect the actual accuracy of the parameters.

5. SPECTRAL TYPE AND METAL ABUNDANCE

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. The spectrum of HD 166181 was compared with those of G and early K dwarfs from the lists of Keenan & McNeil (1989) and Fekel (1997). Spectra of the reference stars were obtained at KPNO with the same telescope, spectrograph, and detector as our spectra of HD 166181.

Examination of numerous spectra of HD 166181 in the 6430 Å region shows one set of relatively broad lines and no clear evidence of lines from additional components. Thus, spectra of the reference stars were rotationally broadened to facilitate a comparison with the spectrum of HD 166181. The overall spectrum of HD 166181 appears to be quite similar to that of κ Cet, G5 V (Keenan & McNeil 1989) and mean [Fe/H] = 0.08 (Taylor 2003), while the spectrum of 61 Vir, G6.5 V (Keenan & McNeil 1989) and mean [Fe/H] = 0.02 (Taylor 2003), provides a match that is nearly as good. Thus, we assign a spectral type of G6 V to HD 166181, in good agreement with the type of G5 V given by Heard (1956). Our comparison also indicates that HD 166181 has an iron abundance that is close to the solar value.

6. BASIC PROPERTIES OF HD 166181

Only component Aa is visible in the spectrum of HD 166181. Nevertheless, it is possible to determine basic properties of the system and its components with the help of our spectroscopic and astrometric orbits plus some assumptions.

Because HD 166181 is a chromospherically active variable star, we searched the literature to determine its brightest visual magnitude and corresponding $B - V$. Strassmeier et al. (1989) and Jetsu et al. (2000) have published extensive photometry between 1984 and 1998. G. W. Henry (2004, private communication) provided continued photometry from 1998 through

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[6] The *Hipparcos* data are available on the *Hipparcos* Catalogue CD-ROMs and also on the mission Web site at http://astro.estec.esa.nl/Hipparcos/InterMedData.html.

the summer of 2004. Over the 20 yr time span the maximum V magnitude of HD 166181 had a range of 0.2 mag. The star was brightest in 2003 with a peak differential V magnitude of 0.35. To convert this to an apparent V magnitude, we adopted $V = 7.21$ mag (Fernie 1983) for the comparison star, HD 166093. This results in a maximum V magnitude of 7.56 for HD 166181. In the same manner we obtained $B - V = 0.71$. The 13 observations of Mekkadan et al. (1980), acquired in 1980 March and April, have a similar maximum V magnitude and $B - V$ color index. 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. Nevertheless, we have adopted the historical maximum, noted above, as the unspotted V magnitude of the primary, since for HD 166181 we are unable to determine a specific correction.

Our revised *Hipparcos* parallax corresponds to a distance of 32.3 ± 0.8 pc, and so we assumed no interstellar reddening. Thus, the parallax and historical maximum V magnitude result in an absolute magnitude $M_V = 5.01 \pm 0.06$. With the $B - V$ color index a bolometric correction and an effective temperature were obtained from Table 3 of Flower (1996). Those two quantities in turn were used to compute the luminosity $L = 0.89 \pm 0.05\ L_\odot$ and the radius $R = 1.03 \pm 0.05\ R_\odot$ of the primary. The uncertainty of the effective temperature is estimated to be 100 K. If the unspotted V magnitude were 0.1 mag brighter than our adopted value, the luminosity would be increased by 10% and the radius by 5%. The various quantities are summarized in Table 3.

The radius determined from the Stefan-Boltzmann law can be compared with the *minimum* radius computed from the photometrically determined rotation period of 1.7924 ± 0.0003 days (Jetsu et al. 2000) and $v \sin i$ value of 31 ± 2 km s^{-1} (Fekel 1997). This produces $R \sin i = 1.10 \pm 0.07\ R_\odot$. Although the minimum radius is slightly larger than the radius from the Stefan-Boltzmann law, the uncertainties overlap. The similar values argue that the rotational inclination is close to 90°.

The mass of the companion in the short-period orbit, component Ab, can be computed from the short-period mass function (Table 2) if the primary mass and orbital inclination are known. Comparison with the solar abundance evolutionary tracks of Schaller et al. (1992) indicates that the primary, component Aa, has a mass of 0.9 $M_\odot$ with an estimated uncertainty of 0.05 $M_\odot$. Assuming the rotational and orbital inclinations are aligned, we estimate an orbital inclination of 80°. Thus, we obtain a mass of 0.37 $M_\odot$ for the secondary. From Figure 3*b* of Delfosse et al. (1999), such a mass corresponds to a spectral type of M2.5 V. Stockton & Fekel (1992) were able to detect the secondary components of binaries in red-wavelength spectra if the magnitude difference was $\lesssim 2.5$. Therefore, our derived spectral type of the secondary is consistent with its lack of detectable lines in the 6430 Å region.

In a similar manner the mass of the long-period companion, component B, can be determined from the total mass of Aa plus Ab, 1.27 $M_\odot$, the orbital inclination determined from astrometry, 78°, and the mass function of the long-period orbit. This combination results in a mass of 0.79 $M_\odot$ for component B, producing a mass ratio (Aa + Ab)/B = 1.6 and a mass of 2.06 $M_\odot$ for the entire system. From Kepler's third law, the long-period system has a semimajor axis of $0\farcs13$, or 4.1 AU.

The mass of component B, which has no lines visible in our spectra, is 88% of the mass estimated for the primary component, Aa. As noted earlier, if the magnitude difference is $\lesssim 2.5$ (Stockton & Fekel 1992), we should have detected lines of component B in our red-wavelength spectra, assuming that it is not a white dwarf. For component Aa, the G6 V star, we have determined $M_V = 5.0$ mag. According to Table B1 of Gray (1992), a K4 V star has $M_V = 7.3$ mag, which then results in $\Delta V = 2.3$. From Gray (1992) the mass listed for a K4 V star is 0.71 $M_\odot$, somewhat smaller than our derived value of 0.79 $M_\odot$ for component B. That mass corresponds instead to a K1 V star with $M_V = 6.2$ mag, and so components Aa and B have $\Delta V = 1.2$ mag. These comparisons suggest a violation of the mass-luminosity relation.

TABLE 3
Fundamental Parameters of HD 166181

Parameter	Value	Reference
V (mag)	7.56	This paper
$B-V$ (mag)	0.71	This paper
Parallax (mas)	30.93 ± 0.77	This paper
Spectral type of Aa	G6 V	This paper
$v \sin i$ (km s^{-1})	31 ± 2	Fekel (1997)
M_V (mag)	5.01 ± 0.06	This paper
$M_{\rm bol}$ (mag)	4.88 ± 0.06	This paper
L ($L_\odot$)	0.89 ± 0.05	This paper
R ($R_\odot$)	1.03 ± 0.05	This paper

The mass-luminosity problem for HD 166181 can be solved if component B is a white dwarf. However, this possibility appears to be excluded by the very young age of the system (see § 7) and the lack of detection of a hot white dwarf in ultraviolet spectra (Fekel et al. 1986). This argues that component B is indeed a main-sequence star. One answer to this enigma, suggested by the system's very young age, is that component B is rapidly rotating, making its lines more difficult to detect even in our spectra that have moderately high S/N ratios. The apparent violation of the mass-luminosity relation also disappears if early K dwarfs are somewhat more massive than canonical values, as has been argued by Griffin et al. (1985) and supported by additional results noted by Fekel et al. (2004). Finally, the mass-luminosity problem is eliminated if component B is also a binary, which would make HD 166181 a quadruple system.

The greatest impediment to the resolution of the system appears to be the magnitude differences of the stars. The components of the long-period system can be resolved by speckle interferometry on a moderate-sized telescope if the magnitude difference is $\lesssim 3$ mag (e.g., Horch et al. 2001). However, the resolution of the short-period system or systems would require long-baseline interferometers.

7. DISCUSSION

Fekel et al. (1986) noted that HD 166181 has a very strong 6708 Å lithium line, indicating that the star is very young. Fernández-Figueroa et al. (1993) determined an equivalent width of 178 mÅ for the line and computed a log lithium abundance of 3.3. Other equivalent width measurements, 201 mÅ by Barrado y Navascués et al. (1997), 186 mÅ by Wichmann et al. (2003), and 193 mÅ from our 1999 May spectrum, are slightly larger. Such equivalent widths are quite close to the upper envelope of equivalent widths for Pleiades members that have the same $B - V$ color as HD 166181 (Soderblom et al. 1993). Thus, Wichmann et al. (2003) noted that HD 166181 has an age similar to the Pleiades cluster and is quite near the zero-age main sequence.

Wichmann et al. (2003) searched for nearby young stars by cross-correlating the *ROSAT* All-Sky Survey with the *Hipparcos* and Tycho Catalogues (ESA 1997). They obtained spectroscopic follow-up observations of their sample of stars to examine the strength of the lithium line and determine radial velocities. They then computed in a right-handed coordinate system the *U*, *V*, *W* Galactic space velocities for the stars and compared them in the *U*-*V* velocity plane with various moving groups. Their observation of HD 166181 had a radial velocity of -57.1 km s^{-1}, far from its true center-of-mass velocity of -7.7 km s^{-1} (Table 2). As a result, they commented that HD 166181 was one of four stars in their Pleiades-like sample with a position that was somewhat apart from the rest of those stars. We have recomputed the space velocities of HD 166181 using proper motions from our new astrometric analysis in § 4. For *U*, *V*, and *W* we have obtained values of -2, 0, and -19 km s^{-1}, respectively. To compare our space velocities with the results of Wichmann et al. (2003), we added the solar motion determined by Dehnen & Binney (1998). Although our space velocities have significantly changed the position of HD 166181 in the *U*-*V* plane (see Fig. 5 of Wichmann et al. 2003), HD 166181 still is not associated with any particular moving group.

In triple systems the third star may cause some of the orbital elements of the close pair to vary with time. Changes in the eccentricity have been examined numerically by Mazeh & Shaham (1979) and both analytically and numerically by Söderhjelm (1984). Their results showed that even if the short-period system attained a circular orbit, its eccentricity would be modulated. From Mazeh & Shaham (1979) we computed a modulation period of about 17,000 yr.

Fekel (1981) compared the short- and long-period orbital inclinations for 20 multiple star systems and found that at least 33% of the orbital pairs are not coplanar. For HD 166181 the long-period orbit has an inclination of 78°. The orbital inclination of the short-period binary containing component Aa is unknown. However, if, as we have assumed earlier, the orbital and rotational axes are parallel, then the orbital inclination is high, and it is possible that the short-period orbit of Aa and the long-period orbit are coplanar.

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