

An astronomer's dozen: spectroscopy of six double-lined binaries and constraints on detection limits[★]

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SUMMARY

Out of a group of 11 previously known binaries with $f(m) \lesssim 0.1 M_{\odot}$ observed at red wavelengths centred near 6430 Å, seven have been found to be double-lined. Orbital elements and the mass ratio for six double-lined systems have been determined from the current and previously published radial-velocity observations. Spectrum addition was used to estimate the spectral types of the secondaries for the four solar-type systems but, because of the weakness of the secondary lines, only a limiting range of spectral types could be determined. HR 7038 appears to be metal rich relative to the spectral-type reference stars.

On the basis of the detection or non-detection of the secondaries in these 11 main-sequence systems, it is estimated that secondaries with mass ratios as small as 0.6 can be detected at red wavelengths with solid-state detectors. Components with a red-magnitude difference slightly greater than 2.5 mag can be detected at wavelengths near 6430 Å.

It appears that the secondary may be detected in a roughly solar-type main-sequence system if its mass function is greater than $0.05 M_{\odot}$, provided that the inclination is not close to 90°.

Eleven of the 12 components were determined to be synchronously or pseudo-synchronously rotating. The primary of HR 7038 appears to be rotating more slowly than its computed pseudo-synchronous velocity, unless it is a significantly evolved main-sequence star.

Key words: binaries: spectroscopic – stars: individual: HR 7038.

1 INTRODUCTION

From a study of the mass ratios and mass functions found in the *Sixth Catalogue of the Orbital Elements of Spectroscopic Binaries* (Batten 1967), Trimble (1974) concluded that the mass ratios for that sample of stars display a bimodal distribution with a significant peak near $q = 0.3$ and a smaller peak around $q = 1.0$. If this bimodality were true, then it holds important implications for binary formation. She suggested that the peak at $q = 1.0$ was the result of fissioning of the protostar before it reached hydrogen ignition. The protostar sheds its excess angular momentum by splitting into two separate components. Theoretical work at the time suggested

that this process has a tendency to create two stars of roughly equal mass. The peak at $q = 0.3$ was attributed to the fragmentation of the original progenitor gas cloud into two separately condensing stars. Currently, this latter theory is the most likely hypothesis of binary formation (Boss 1988).

Scarfe (1986) suggested that the sample selected by Trimble is strongly biased by as much as a factor of 10 towards double-lined spectroscopic binaries. He noted that the peak at $q = 0.3$ is composed primarily of SB1s while the peak at $q = 1.0$ is made up mostly of SB2s. From an analysis of magnitude-limited data from Andersen & Nordström (1983), Andersen *et al.* (1985), and Nordström & Andersen (1985), Scarfe obtained a mass-ratio distribution that fits an approximate Gaussian distribution with a maximum at $q = 0.25$. This is consistent with the dominant binary forming process being the separate condensation of stars from a common gas cloud. A peak mass ratio of 0.3 has also been found by Halbwachs (1986, 1987) from catalogues similar to the one used by Trimble.

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In a new study, Trimble (1990) used a sample of 132 SB1s and 32 SB2s, whose orbits were determined in numerous papers by Griffin and collaborators (see Trimble 1990 for references). The SB2s were given a lower weighting than the SB1s in the computation. As a result, the number of systems with a mass ratio near 1.0 was reduced but was still significant. She concluded that the mass-ratio distribution fits roughly a q^{-1} power law and that selection effects are the most important factor in choosing an unbiased sample of stars.

More recently, Duquennoy & Mayor (1991) studied a sample of 164 solar-type stars in the solar neighbourhood. They found no maximum at $q=1.0$ but, instead, that the number of systems increased towards smaller secondary masses with a peak at $q \approx 0.3$.

Originally, our research was begun to see if a significant number of SB2 systems could be found in the gap between Trimble's (1974) mass-ratio peaks of 0.3 and 1.0. The primary objective was to find SB1s, with relatively narrow lines and known orbits, whose secondaries might be detected at red wavelengths from spectrograms that have high signal-to-noise (S/N) ratios. Single-lined binaries of spectral type A or later and with mass functions of about $0.1 M_{\odot}$ or less were chosen from the seventh orbital-elements catalogue (Batten, Fletcher & Mann 1978) and from the literature. A list of the programme stars whose secondaries were detected can be found in Table 1. In addition to these programme stars, several other systems were observed but no secondary-star absorption lines were detected. These will be mentioned briefly in Section 4.

2 OBSERVATIONS, REDUCTIONS AND ORBITAL ANALYSIS

2.1 Observations

Two observations for HR 8170 were made in the autumn of 1979 at McDonald Observatory with the 2.7-m reflector, the coude spectrograph, and a Reticon detector. All other observations of the six SB2 stars in this study were obtained between 1984 January and 1991 April at the Kitt Peak National Observatory (KPNO) with the 0.9-m reflecting telescope, the coude-feed spectrograph (employing camera 5, the long-focus collimator, and either grating A or grating D), and an 800×800 Texas Instruments charge-coupled device (TI CCD) as the solid-state detector (Willmarth 1990). The resolution of these spectrograph-detector combinations at KPNO is about $0.2 \text{ \AA}$.

Ten of the total 98 observations were made with grating A in the blue portion of the spectrum centred at a wavelength of $4500 \text{ \AA}$. Two observations were centred in the red region at a wavelength of $6700 \text{ \AA}$. The rest of the observations also

were obtained in the red region but were centred at a wavelength of $6430 \text{ \AA}$. The reciprocal dispersion was 7.0 or $7.6 \text{ \AA mm}^{-1}$ in the red with grating A or grating D, respectively, and $7.0 \text{ \AA mm}^{-1}$ in the blue.

2.2 Data reduction

The radial velocities of the programme stars were determined relative to the velocities of standard or reference stars. The assumed velocities of the International Astronomical Union (IAU) radial-velocity standard stars (Pearce 1957) were taken from Scarfe, Batten & Fletcher (1990). Two stars not on the IAU list were also used and are called reference stars. The velocity for the reference star 68 Tau comes from Cole *et al.* (1992), while the velocity of μ Her A has been determined in the present study. Table 2 lists the standard and reference stars that were used in this analysis. The radial velocities of the programme stars were determined with the procedure of Fekel, Bopp & Lacy (1978).

2.3 Orbital analysis

All six systems have their orbital elements listed in the most recent catalogue of Batten, Fletcher & McCarthy (1989). The known orbital periods were used to determine preliminary orbital elements for each data set with a program that uses the value of a preliminary period and a series of sines and cosines to fit the data with the Wilsing-Russell method (Wolfe, Horak & Storer 1967). Each set of elements was improved with a differential-corrections program (Barker, Evans & Laing 1967). Orbital solutions were obtained separately for old observations from various observatories, as well as for our data of the primary and secondary. Those solutions were used to determine appropriate weights for each data set, and to determine velocity shifts so that all sets of velocities have the same zero-point. From the results of Lucy & Sweeney (1971), a zero-eccentricity solution was assumed, if the formal value of the eccentricity was less than 2.45 times larger than its associated error. The final analysis was done with a computer program, a modified version of the SB1 program, that allows the secondary component to be used simultaneously in the solution. The results of the final analysis for each system will be discussed in the next section.

Tables 3 to 8 list the radial velocities for each of our six programme systems, respectively, and include both our

Table 1. Programme stars.

HD	HR	R. A. (1950)	Dec. (1950)	V (mag)	B-V (mag)	Spec. Ty.	Obsv. No.
22403		3:34:10.2	+ 25° 49' 50.7"	8.10	+ 0.70	G2 V	19
30453	1528	4:46:04.7	+ 32° 30' 8.4"	5.84	+ 0.25	A8 m	19
40536	2108	5:56:41.8	- 9° 33' 37.0"	5.04	+ 0.19	A6 m	17
173282	7038	18:42:19.6	- 21° 03' 14.4"	6.35	+ 0.47	F5/6 V	15
203454	8170	21:19:04.1	+ 40° 08' 6.6"	6.40	+ 0.53	F8 V	14
222317		23:36:59.4	+ 27° 57' 59.1"	7.00	+ 0.67	G5 V	17

Table 2. Radial-velocity standard and reference stars.

Name	HD	HR	V (mag)	Spec. Ty.	V (km s ⁻¹)	Source
α Ari	12929	617	2.00	K2 III	- 14.5	Scarfe <i>et al.</i> (1990)
10 Tau	22484	1101	4.29	F8 V	+ 27.9	Scarfe <i>et al.</i> (1990)
68 Tau*	27962	1389	4.30	A2 IV	+ 39.0	Cole <i>et al.</i> (1992)
β Gem	62509	2990	1.15	K0 III	+ 3.2	Scarfe <i>et al.</i> (1990)
β Vir	102870	4540	3.61	F8 V	+ 4.4	Scarfe <i>et al.</i> (1990)
5 Ser	136202	5694	5.06	F8 IV-V	+ 54.4	Scarfe <i>et al.</i> (1990)
β Oph	161096	6603	2.77	K2 III	- 12.2	Scarfe <i>et al.</i> (1990)
μ Her A*	161797	6623	3.35	G5 IV	- 16.4	This work
α Aql	187691	7560	5.10	F8 V	- 0.0	Scarfe <i>et al.</i> (1990)
ζ Psc	222368	8969	4.13	F7 V	+ 5.6	Scarfe <i>et al.</i> (1990)

*Reference star.

Table 3. Radial velocities of HD 22403 = V837 Tau.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard	Source
32112.805	0.685	-49.6	-0.8	0.01	—	—	—	—	1
32453.891	0.420	-93.1	-7.4	0.01	—	—	—	—	1
32467.858	0.657	-58.0	+2.7	0.01	—	—	—	—	1
32591.510	0.728	-10.0	+18.6	0.01	—	—	—	—	1
33554.897	0.911	+55.7	+7.6	0.01	—	—	—	—	1
33587.785	0.952	+53.1	-3.4	0.01	—	—	—	—	1
41572.535	0.283	-29.4	+4.4	0.08	—	—	—	—	2
41572.645	0.340	-53.2	+6.2	0.08	—	—	—	—	2
41675.372	0.569	-89.9	-1.6	0.08	—	—	—	—	2
41931.633	0.351	-65.2	-1.3	0.08	—	—	—	—	2
41932.511	0.806	+10.1	+0.9	0.08	—	—	—	—	2
41932.642	0.874	+35.2	-1.8	0.08	—	—	—	—	2
41933.532	0.335	-57.5	-0.1	0.08	—	—	—	—	2
41933.662	0.403	-79.4	+2.0	0.08	—	—	—	—	2
41935.552	0.382	-74.9	+0.1	0.08	—	—	—	—	2
41936.581	0.915	+49.2	0.0	0.08	—	—	—	—	2
42024.324	0.380	-72.0	+2.2	0.08	—	—	—	—	2
42284.617	0.252	-17.3	+1.1	0.08	—	—	—	—	2
42286.615	0.287	-39.3	-3.8	0.08	—	—	—	—	2
42289.632	0.850	+31.7	+3.7	0.08	—	—	—	—	2
42737.446	0.887	+40.5	-0.6	0.08	—	—	—	—	2
42738.447	0.405	-83.3	-1.2	0.08	—	—	—	—	2
42739.513	0.958	+54.5	-2.8	0.08	—	—	—	—	2
43028.640	0.770	-7.8	+0.1	0.08	—	—	—	—	2
43029.634	0.285	-35.2	-0.5	0.08	—	—	—	—	2
43409.538	0.134	+31.0	-3.1	0.08	—	—	—	—	2
43409.648	0.191	+12.0	+1.6	0.08	—	—	—	—	2
45716.696	0.598	-81.4	-0.1	1.00	+78.7	+2.0	0.07	α Ari	3
45717.758	0.148	+28.2	-0.5	1.00	-88.2	-1.5	0.07	10 Tau	3
45718.729	0.651	-63.2	-0.2	1.00	+49.1	-0.4	0.07	B Gem	3
45719.734	0.172	+18.9	-0.1	1.00	-70.5	+1.8	0.07	10 Tau	3
45720.670	0.657	-61.0	-0.3	1.00	+43.1	-3.0	0.07	10 Tau	3
45721.684	0.182	+15.3	+0.8	1.00	-64.8	+0.7	0.07	10 Tau	3
45973.839	0.837	+22.7	-0.2	1.00	-80.5	-2.5	0.07	ϵ Psc	3
46076.709	0.140	+31.7	-0.3	1.00	-88.9	+2.6	0.07	ϵ Psc	3
46720.930	0.954	+56.4	+0.9	1.00	-126.8	-0.4	0.07	10 Tau	3
46721.980	0.490	-95.6	-0.3	1.00	+96.9	-0.6	0.07	10 Tau	3
46814.702	0.534	-94.3	-0.6	1.00	+94.3	-0.8	0.07	10 Tau	3
46867.613	0.950	+56.4	+0.2	1.00	-127.3	+0.2	0.07	10 Tau	3
46869.622	0.991	+59.9	0.0	1.00	-130.8	+2.1	0.07	10 Tau	3
47247.617	0.851	+28.2	+0.1	1.00	-84.8	+1.0	0.07	10 Tau	3
47556.623	0.963	+58.8	+0.9	1.00	-131.7	-1.7	0.07	10 Tau	3
47556.786	0.048	+57.2	+0.7	1.00	-128.5	-0.6	0.07	10 Tau	3
47915.782	0.063	+52.1	-1.9	1.00	-126.5	-2.3	0.07	10 Tau	3
47917.661	0.037	+57.5	-0.4	1.00	-129.4	+0.7	0.07	10 Tau	3
48162.867	0.091	+45.9	-1.7	1.00	-115.2	-0.5	0.07	10 Tau	3

1 = Heard (1956). 2 = Carquillat *et al.* (1979). 3 = This work.

observations and previous observations obtained by others. The first column lists the heliocentric Julian date. The second column gives the corresponding phase as calculated in the final analysis. The third column shows the radial velocity for the primary. The radial-velocity residual, or the observed-minus-computed value (O-C), is in the fourth column. The weights given to the various observations are listed in column five. The secondary velocities from our observations are listed in column six along with their residuals in column seven. Column eight lists the weights given to the secondary observations in the final solution. The standard or reference star used for each of our observations is given in column nine. The source for each observation is

Table 4. Radial velocities of HR 1528 = HD 30453.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard	Source
24863.851	0.202	+32.3	-3.1	0.00	—	—	—	—	1
26326.919	0.701	-1.3	-1.4	0.00	—	—	—	—	1
26337.799	0.245	+17.9	-1.9	0.00	—	—	—	—	1
26347.788	0.661	-23.2	-9.8	0.00	—	—	—	—	1
26361.874	0.659	-7.1	+7.0	0.00	—	—	—	—	1
26375.732	0.624	-26.5	-2.5	0.00	—	—	—	—	1
26382.720	0.615	-23.8	+2.5	0.00	—	—	—	—	1
26386.795	0.193	+32.9	-5.4	0.00	—	—	—	—	1
26405.667	0.870	+58.2	+0.2	0.00	—	—	—	—	1
26417.635	0.567	-35.6	+0.3	0.00	—	—	—	—	1
26434.651	0.981	+75.7	-0.5	0.00	—	—	—	—	1
26449.687	0.113	+59.6	-2.8	0.00	—	—	—	—	1
26452.679	0.537	-39.7	-0.3	0.00	—	—	—	—	1
26609.004	0.708	+4.5	+2.0	0.00	—	—	—	—	1
26620.918	0.398	-31.1	-1.7	0.00	—	—	—	—	1
26624.983	0.974	+78.2	+2.3	0.00	—	—	—	—	1
26648.842	0.358	-14.1	+4.8	0.00	—	—	—	—	1
26665.822	0.766	+24.1	+0.2	0.00	—	—	—	—	1
26669.769	0.326	-5.9	+3.4	0.00	—	—	—	—	1
26728.704	0.685	-5.3	+0.4	0.00	—	—	—	—	1
26730.661	0.962	+77.2	+2.2	0.00	—	—	—	—	1
45716.720	0.664	-12.3	+0.3	1.00	+66.0	+1.9	0.68	10 Tau	2
45720.766	0.238	+23.0	+0.6	1.00	—	—	—	—	2
45974.004	0.153	+52.2	+0.8	1.00	-34.3	-0.8	0.68	10 Tau	2
46388.917	0.998	+76.6	0.0	1.00	-73.5	-1.6	0.68	68 Tau	2
46390.732	0.256	+16.3	+0.6	1.00	—	—	—	68 Tau	2
46392.986	0.575	-35.2	-0.6	1.00	+98.8	+1.1	0.68	68 Tau	2
47457.852*	0.600	-31.2	-1.4	1.00	+92.4	+2.1	0.68	68 Tau	2
47458.862*	0.744	+15.1	-0.3	1.00	—	—	—	68 Tau	2
47627.615	0.677	-8.9	-0.6	1.00	+58.7	+1.1	0.68	68 Tau	2
47810.860*	0.666	-13.5	-1.5	1.00	+64.9	+1.7	0.68	68 Tau	2
47812.921*	0.958	+74.5	-0.1	1.00	—	—	—	68 Tau	2
47813.880*	0.094	+66.5	-0.2	1.00	-54.3	+2.4	0.68	68 Tau	2
48005.627	0.289	+4.3	+0.6	1.00	+38.3	-1.0	0.68	B Vir	2
48162.957	0.602	-29.6	-0.2	1.00	+89.4	-0.4	0.68	68 Tau	2
48167.981	0.314	-5.8	-0.4	1.00	+52.5	-0.6	0.68	10 Tau	2
48345.653	0.513	-40.4	+0.5	1.00	+106.4	-0.8	0.68	10 Tau	2
48346.646	0.654	-16.2	-0.5	1.00	+69.8	+0.9	0.68	10 Tau	2
48347.618	0.791	+32.6	-0.3	1.00	-6.2	-0.9	0.68	10 Tau	2
48348.637	0.936	+73.2	+1.3	1.00	-66.1	-1.3	0.68	10 Tau	2

*Observations taken in the blue portion of the spectrum.
1 = Harper (1932). 2 = This work.

listed in column ten. Table 9 lists the radial-velocity values calculated for μ Her A.

The radial-velocity curves and individual velocities for each of the six systems are shown in Figs 1 to 6.

2.4 Spectral type of the secondary

A determination of the spectral types of the secondaries was attempted for the solar-type dwarf stars, via the method of spectrum addition (Strassmeier & Fekel 1990). Analysis of the two A-star systems was not attempted because no appropriate spectral-type reference stars are available for the Am stars in these systems. Various combinations of spectral types were tried for the other four systems. Several different spectral-type reference stars from F4 to G8 were used for the primaries' spectral types. Spectral-type reference stars from G2 to K7 were used to represent the various secondary spectra. The spectra of two stars from the list of Strassmeier

Table 5. Radial velocities of HR 2108 = HD 40536 = 2 Mon.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
43112.007	0.171	-4.6	-0.4	0.00	—	—	—	1
43186.851	0.171	-3.7	+0.4	0.00	—	—	—	1
43188.842	0.383	-27.3	+0.5	0.00	—	—	—	1
43221.744	0.900	+82.9	-3.6	0.00	—	—	—	1
43460.904	0.463	-25.1	-4.1	0.00	—	—	—	1
43461.885	0.568	-1.4	+2.6	0.00	—	—	—	1
43571.763	0.312	-28.8	-0.5	0.00	—	—	—	1
43632.012	0.129	+14.0	+1.7	0.00	—	—	—	1
44187.951	0.173	-6.9	-2.0	0.00	—	—	—	1
44188.952	0.280	-27.4	-1.1	0.00	—	—	—	1
44189.985	0.391	-29.2	-1.7	0.00	—	—	—	1
44235.946	0.303	-27.2	+0.7	0.00	—	—	—	1
44236.779	0.392	-28.7	-1.3	0.00	—	—	—	1
44237.878	0.510	-9.8	+4.6	0.00	—	—	—	1
44270.884	0.037	+57.5	-1.5	0.00	—	—	—	1
44307.711	0.974	+80.7	-3.2	0.00	—	—	—	1
45718.840	0.802	+62.6	+1.6	1.00	-31.3	+0.6	0.79	B Vir 2
45720.794	0.011	+71.1	-0.3	1.00	-44.6	+0.3	0.79	B Gem 2
45721.757	0.114	+19.5	+0.4	1.00	—	—	—	B Gem 2
45973.986	0.074	+38.8	-1.1	1.00	-4.0	+1.5	0.79	10 Tau 2
46393.005	0.860	+78.3	0.0	1.00	-54.5	-1.0	0.79	68 Tau 2
47456.873*	0.572	-2.6	+0.5	1.00	+48.8	+0.6	0.79	68 Tau 2
47458.869*	0.785	+55.5	0.0	1.00	-27.0	-2.0	0.79	68 Tau 2
47556.694*	0.241	-22.1	-0.7	1.00	+71.6	+0.6	0.79	68 Tau 2
47810.873*	0.409	-26.6	-0.4	1.00	+75.8	-1.3	0.79	68 Tau 2
47813.886*	0.731	+38.7	+0.5	1.00	-4.8	-1.3	0.79	68 Tau 2
47915.866	0.631	+11.5	+1.2	1.00	—	—	—	10 Tau 2
48163.029	0.049	+52.2	-0.6	1.00	-19.6	+2.1	0.79	B Gem 2
48167.989	0.580	-1.0	+0.6	1.00	+45.4	-0.8	0.79	10 Tau 2
48345.612	0.565	-3.7	+0.9	1.00	+49.7	-0.3	0.79	10 Tau 2
48346.647	0.675	+21.6	-0.2	1.00	—	—	—	10 Tau 2
48347.630	0.780	+54.0	0.0	1.00	-24.4	-1.3	0.79	10 Tau 2
48348.651	0.890	+85.1	+0.3	1.00	-61.8	-0.2	0.79	10 Tau 2

*Observations taken in the blue portion of the spectrum. 1 = Abt & Levy (1985). 2 = This work.

Table 6. Radial velocities of HR 7038 = HD 173282.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
43672.827	0.570	-11.8	+0.4	0.06	—	—	—	1
43727.658	0.223	+20.0	+4.2	0.06	—	—	—	1
44008.884	0.704	-20.8	+0.6	0.06	—	—	—	1
44023.864	0.155	+25.3	-0.2	0.06	—	—	—	1
44054.766	0.087	+38.2	-2.6	0.06	—	—	—	1
44080.731	0.870	-35.8	-0.6	0.06	—	—	—	1
44358.919	0.259	+11.5	-0.3	0.06	—	—	—	1
44385.856	0.072	+45.9	+0.2	0.03	—	—	—	1
44434.738	0.546	-6.2	+4.4	0.03	—	—	—	1
44439.731	0.696	-18.6	+2.2	0.06	—	—	—	1
44448.680	0.966	-31.7	+1.2	0.03	—	—	—	1
44469.650	0.599	-13.5	+0.6	0.06	—	—	—	1
44744.813	0.897	-37.0	+0.6	0.06	—	—	—	1
44755.798	0.228	+12.4	-2.8	0.03	—	—	—	1
44862.523	0.446	-3.8	0.0	1.00	—	—	—	2
45128.732	0.474	-5.6	+0.2	1.00	—	—	—	2
45128.830	0.477	-6.2	-0.3	0.03	—	—	—	1
45130.755	0.535	-9.6	+0.3	0.03	—	—	—	1
45143.804	0.929	-41.3	-1.7	0.03	—	—	—	1
45158.798	0.381	-1.7	-2.7	0.06	—	—	—	1
45163.739	0.530	-7.9	+1.6	0.03	—	—	—	1
45176.712	0.921	-35.4	+3.9	0.03	—	—	—	1
45181.721	0.072	+48.3	+2.7	0.06	—	—	—	1
45189.678	0.312	+6.7	0.0	0.03	—	—	—	1
45190.661	0.342	+2.3	-1.8	0.03	—	—	—	1

Table 6 – continued

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
45193.644	0.432	-4.3	-1.5	0.06	—	—	—	1
45250.536	0.147	+26.3	-0.7	0.06	—	—	—	1
45250.547	0.148	+30.8	+3.9	0.06	—	—	—	1
45478.862	0.033	+58.4	-0.9	0.06	—	—	—	1
45480.830	0.092	+42.7	+3.2	0.03	—	—	—	1
45489.814	0.363	+2.2	-0.2	0.06	—	—	—	1
45491.836	0.423	-1.2	+1.0	0.06	—	—	—	1
45492.829	0.454	-3.2	+1.1	0.03	—	—	—	1
45493.848	0.485	-9.7	-3.2	0.06	—	—	—	1
45500.817	0.695	-22.8	-2.1	0.06	—	—	—	1
45507.791	0.905	-39.5	-1.2	0.03	—	—	—	1
45523.723	0.385	-1.3	-2.0	0.06	—	—	—	1
45526.747	0.477	-7.4	-1.5	0.06	—	—	—	1
45528.722	0.536	-11.0	-1.1	0.03	—	—	—	1
45531.722	0.627	-18.7	-2.7	0.03	—	—	—	1
45533.727	0.687	-19.8	+0.4	0.06	—	—	—	1
45534.710	0.717	-25.0	-2.7	0.03	—	—	—	1
45537.690	0.807	-32.8	-3.4	0.03	—	—	—	1
45541.708	0.928	-39.8	-0.2	0.06	—	—	—	1
45571.588	0.829	-33.5	-2.1	0.03	—	—	—	1
45571.600	0.829	-32.9	-1.5	0.06	—	—	—	1
45576.614	0.980	-22.9	-4.4	0.03	—	—	—	1
45577.602	0.010	+49.2	+0.6	0.03	—	—	—	1
45577.614	0.011	+49.9	-0.5	0.03	—	—	—	1
45586.615	0.282	+7.5	-2.0	0.06	—	—	—	1
46972.893	0.087	+41.1	+0.2	1.00	-62.9	+0.4	0.66	μ Her A 3
46973.884	0.117	+32.8	-0.4	1.00	-52.9	-0.4	0.66	μ Her A 3
48056.859	0.775	-26.5	+0.3	1.00	+32.1	+1.2	0.66	μ Her A 3
48059.841	0.865	-34.7	0.0	1.00	+42.3	+0.5	0.66	μ Her A 3
48060.883	0.896	-37.2	+0.4	1.00	+44.7	-1.1	0.66	μ Her A 3
48162.603	0.964	-33.9	+0.3	1.00	+41.2	0.0	0.66	μ Her A 3
48163.639	0.995	+14.7	+0.2	1.00	-27.2	-0.6	0.66	μ Her A 3
48167.608	0.115	+32.6	-1.0	1.00	-53.5	-0.4	0.66	μ Her A 3
48347.028	0.526	-8.5	+0.7	1.00	—	—	—	μ Her A 3
48356.935	0.824	-31.8	-0.9	1.00	+36.3	-0.3	0.66	μ Her A 3
48425.840	0.902	-38.4	-0.4	1.00	+46.9	+0.4	0.66	μ Her A 3
48426.848	0.933	-39.7	0.0	1.00	+48.7	-0.1	0.66	μ Her A 3
48427.881	0.963	-34.4	-0.1	1.00	+41.5	+0.1	0.66	μ Her A 3
48428.879	0.994	+10.9	+0.2	1.00	-20.2	+1.1	0.66	μ Her A 3
49429.880	0.024	+60.1	+0.3	1.00	-89.3	+0.3	0.66	μ Her A 3

1 = Salzer & Beavers (1985). 2 = Andersen *et al.* (1985). 3 = This work.

& Fekel (1990) were rotationally broadened, shifted in radial velocity, and added together to determine the best fit to the double-lined spectrum.

Because of the small depths of the secondaries' absorption lines, it was found that a range of spectral types resulted in similar fits to the spectra. At best the secondary could be classified only as early- to mid-KV or mid- to late-GV, depending on the system. In addition, HR 7038 appeared to be metal rich relative to the reference stars, since the line depths of the primary were greater than those of the spectral-type reference stars.

2.5 Measurement of rotational velocities

To measure the projected rotational velocity, $v \sin i$, of each star, several unblended absorption lines were chosen from a high-S/N plot of each star's spectrum at red wavelengths. The full-width half-maximum of each line was measured for

Table 7. Radial velocities of HR 8170 = HD 203454.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
21829.826	0.712	-16.5	-2.4	0.34	—	—	—	1
21875.713	0.861	+40.1	+0.4	0.34	—	—	—	1
21880.677	0.391	-46.9	+0.5	0.34	—	—	—	1
21886.677	0.241	+2.2	-1.6	0.34	—	—	—	1
21921.562	0.997	+64.0	+2.1	0.34	—	—	—	1
21922.568	0.307	-22.6	-1.3	0.34	—	—	—	1
21924.553	0.919	+54.3	+0.2	0.34	—	—	—	1
21928.561	0.155	+36.4	+1.4	0.34	—	—	—	1
21939.569	0.549	-56.4	+2.1	0.34	—	—	—	1
21943.587	0.788	+15.1	+0.4	0.34	—	—	—	1
21948.544	0.316	-23.4	+1.1	0.34	—	—	—	1
21948.628	0.342	-34.0	-0.7	0.34	—	—	—	1
21949.560	0.629	-43.0	-0.9	0.34	—	—	—	1
21949.662	0.661	-35.8	-3.3	0.34	—	—	—	1
21951.552	0.243	+3.3	+0.5	0.34	—	—	—	1
44176.570	0.738	-4.2	+0.1	0.50	—	—	—	1 Psc 4
44179.650	0.688	-26.2	-3.0	0.50	—	—	—	1 Psc 4
44441.557	0.440	-56.5	+0.5	1.00	—	—	—	2
44457.527	0.364	-40.4	-0.3	1.00	—	—	—	2
44458.491	0.661	-34.5	-2.1	1.00	—	—	—	2
44459.514	0.976	+62.3	+1.0	1.00	—	—	—	2
44460.480	0.274	-8.8	+0.2	1.00	—	—	—	2
44461.489	0.585	-51.1	+1.6	1.00	—	—	—	2
44462.453	0.883	+45.8	-0.1	1.00	—	—	—	2
44464.537	0.525	-60.0	+0.6	1.00	—	—	—	2
44465.441	0.804	+20.2	-0.5	1.00	—	—	—	2
44466.436	0.111	+48.4	+0.7	1.00	—	—	—	2
44797.814	0.282	-43.6	-31.5	0.00	—	—	—	3
44893.605	0.817	+27.1	+1.7	0.29	—	—	—	3
44896.620	0.746	-0.1	+1.0	0.29	—	—	—	3
44897.630	0.058	+57.8	-0.1	0.12	—	—	—	3
44903.587	0.895	+52.9	+4.0	0.29	—	—	—	3
44904.581	0.201	+17.8	-1.2	0.29	—	—	—	3
44905.559	0.503	-60.8	+0.5	0.29	—	—	—	3
44914.555	0.276	-7.5	+2.3	0.12	—	—	—	3
44918.529	0.502	-61.5	-0.2	0.12	—	—	—	3
44918.539	0.505	-60.3	+1.0	0.29	—	—	—	3
44919.521	0.807	+23.0	+1.0	0.12	—	—	—	3
44919.532	0.811	+21.4	-1.9	0.29	—	—	—	3
45127.603	0.964	+61.5	+1.1	1.00	—	—	—	2
45128.571	0.262	-5.5	-1.0	1.00	—	—	—	2
45161.584	0.441	-56.7	+0.5	1.00	—	—	—	2
45175.565	0.752	+1.3	+0.4	1.00	—	—	—	2
45231.652	0.045	+61.4	+1.9	1.00	—	—	—	2
45232.651	0.353	-36.3	+0.5	0.12	—	—	—	3
45232.664	0.357	-37.2	+0.8	0.29	—	—	—	3
45233.653	0.662	-30.0	+2.2	0.12	—	—	—	3
45233.668	0.666	-29.1	+1.6	0.12	—	—	—	3
45233.682	0.671	-33.4	-4.2	0.12	—	—	—	3
45233.698	0.676	-29.9	-2.4	0.29	—	—	—	3
45238.653	0.203	+13.8	-4.4	0.29	—	—	—	3
45238.668	0.208	+15.6	-0.9	0.29	—	—	—	3
45246.626	0.662	-31.6	+0.7	0.29	—	—	—	3
45246.640	0.666	-31.0	-0.2	0.12	—	—	—	3
45247.654	0.978	+55.4	-6.0	0.12	—	—	—	3
45267.585	0.124	+43.2	-1.1	0.12	—	—	—	3
45267.594	0.126	+42.6	-0.9	0.12	—	—	—	3
45853.960	0.917	+52.8	-0.9	1.00	-97.7	-3.3	0.10	1 Psc 4
45939.819	0.389	-47.5	-0.5	1.00	+81.2	-2.9	0.10	1 Psc 4
45941.865	0.020	+60.7	-0.8	1.00	-108.7	-0.6	0.10	1 Psc 4
45972.817	0.563	-57.2	-0.7	1.00	+96.1	-5.0	0.10	1 Psc 4
46259.872	0.069	+55.9	-0.4	1.00	-101.4	-2.5	0.10	5 Ser 4
46389.620	0.073	+55.4	-0.1	1.00	-95.9	+1.7	0.10	1 Psc 4

Table 7 – continued

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
46721.714	0.466	-58.3	+1.6	1.00	+108.4	+1.4	0.10	1 Psc 4
47457.704	0.389	-45.3	+1.6	1.00	+81.8	-2.2	0.10	1 Psc 4
47812.792	0.871	+43.3	+0.6	1.00	-72.3	+2.5	0.10	1 Psc 4
48347.010	0.583	-52.9	+0.3	1.00	+99.8	+4.6	0.10	0 Aql 4
48348.016	0.893	+48.7	+0.3	1.00	-86.4	-1.4	0.10	0 Aql 4
48349.014	0.200	+19.3	+0.1	1.00	-31.8	+1.4	0.10	0 Aql 4

1 = Plaskett (1922). 2 = Mayor & Mazeh (1987). 3 = Beavers & Eitter (1986). 4 = This work.

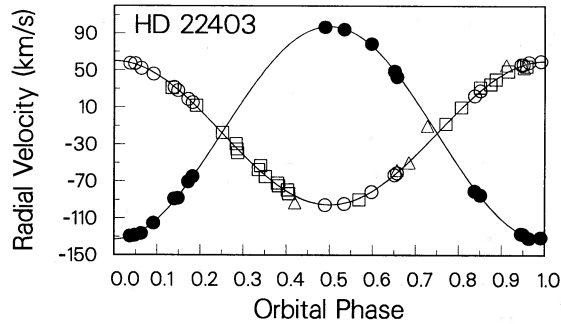
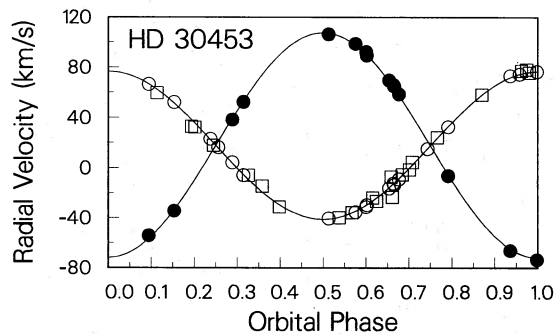
Table 8. Radial velocities of HD 222317 = KT Peg.

HJD (2400000+)	Phase	V_A (km s ⁻¹)	O-C (km s ⁻¹)	Wt. A	V_B (km s ⁻¹)	O-C (km s ⁻¹)	Wt. B	Standard Source
32101.692	0.316	-19.9	-0.6	0.03	—	—	—	1
32109.711	0.609	-36.6	-2.2	0.03	—	—	—	1
33129.650	0.093	+31.6	+1.1	0.03	—	—	—	1
33190.702	0.906	+30.1	-0.3	0.03	—	—	—	1
33514.819	0.167	+19.2	+2.2	0.03	—	—	—	1
34659.578	0.746	-1.9	+2.3	0.03	—	—	—	1
39832.307	0.790	+3.8	-3.1	0.03	—	—	—	2
39837.284	0.592	-36.4	+0.4	0.03	—	—	—	2
39838.272	0.752	-2.0	+0.7	0.03	—	—	—	2
39838.377	0.769	+6.2	+4.6	0.03	—	—	—	2
39840.264	0.073	+30.9	-2.1	0.03	—	—	—	2
39842.305	0.402	-36.9	-0.9	0.03	—	—	—	2
39989.628	0.156	+22.5	+3.2	0.03	—	—	—	2
40018.617	0.830	+19.0	+2.6	0.03	—	—	—	2
40050.543	0.978	+36.5	-0.3	0.03	—	—	—	2
40051.604	0.149	+19.3	-1.4	0.03	—	—	—	2
40052.555	0.303	-16.3	-0.1	0.03	—	—	—	2
40073.623	0.699	-15.6	+0.1	0.03	—	—	—	2
40075.560	0.012	+40.0	+2.9	0.03	—	—	—	2
40369.601	0.423	-39.4	-0.7	0.03	—	—	—	2
40372.596	0.905	+30.6	+0.3	0.03	—	—	—	2
40373.585	0.065	+32.5	-1.4	0.03	—	—	—	2
40374.594	0.228	+4.6	+2.1	0.03	—	—	—	2
43731.836	0.545	-43.5	-1.7	0.29	—	—	—	3
43756.778	0.567	-40.6	-0.6	0.29	—	—	—	3
44488.793	0.596	-36.9	-0.5	0.29	—	—	—	3
45231.751	0.389	-34.5	-0.5	0.29	—	—	—	3
45245.757	0.648	-26.2	+1.1	0.29	—	—	—	3
45246.732	0.805	+9.8	-0.6	0.29	—	—	—	3
45719.654	0.058	+34.6	+0.1	1.00	-60.3	-1.0	0.08	1 Psc 4
45852.970	0.554	-41.0	+0.2	1.00	—	—	—	1 Psc 4
45939.907	0.571	-38.9	+0.6	1.00	+50.9	-0.1	0.08	1 Psc 4
45972.877	0.887	+27.6	+0.1	1.00	-49.5	-0.7	0.08	1 Psc 4
46389.717	0.098	+29.7	-0.1	1.00	-51.7	+0.5	0.08	1 Psc 4
47096.727	0.095	+30.3	+0.2	1.00	-49.5	+3.3	0.08	1 Psc 4
47098.773	0.425	-39.2	-0.1	1.00	+52.7	+2.2	0.08	1 Psc 4
47151.669	0.954	+35.6	+0.1	1.00	-62.5	-1.7	0.08	1 Psc 4
47152.651	0.113	+27.7	+0.2	1.00	-49.4	-0.6	0.08	1 Psc 4
47453.780	0.666	-23.0	+0.4	1.00	+25.8	-1.3	0.08	1 Psc 4
47809.751	0.062	+33.7	-0.4	1.00	-58.4	+0.3	0.08	1 Psc 4
47811.826	0.397	-35.2	+0.1	1.00	+46.5	+1.7	0.08	1 Psc 4
47812.729	0.543	-42.5	-0.5	1.00	+51.5	-3.3	0.08	1 Psc 4
47814.745	0.868	+23.9	-0.1	1.00	-42.7	+0.9	0.08	1 Psc 4
47815.751	0.030	+36.2	-0.3	1.00	-62.3	-0.1	0.08	1 Psc 4
48057.982	0.869	+30.7	-0.6	1.00	-53.4	+1.1	0.08	1 Psc 4
48162.764	0.982	+36.5	-0.4	1.00	-63.5	-0.7	0.08	1 Psc 4

1 = Heard (1956). 2 = Imbert (1969). 3 = Beavers & Eitter (1986). 4 = This work.

Table 9. Radial velocities of μ Her A.

HJD (2440000+)	V_r (km s^{-1})	HJD (2440000+)	V_r (km s^{-1})
5448.962	-16.2	7456.598	-16.6
5451.923	-16.3	7458.588	-16.3
5815.022	-16.3	7623.951	-16.2
5855.886	-16.1	7625.033	-16.4
5941.656	-15.9	7625.981	-16.4
5942.656	-15.9	7809.601	-16.4
5972.707	-16.0	7811.562	-16.8
6258.658	-16.7	7812.560	-16.9
6259.810	-16.1	7813.553	-16.9
6530.952	-16.1	7814.555	-16.7
6531.979	-16.2	7815.557	-16.1
6720.623	-16.1	8056.843	-16.8
6721.556	-16.2	8057.911	-16.5
6973.909	-17.4	8162.587	-16.4
6974.884	-17.0	8163.592	-16.6
7244.917	-16.6	8167.617	-16.3
7245.968	-16.1	8345.945	-16.8
7247.940	-16.9	8347.040	-16.5
7248.986	-16.5	8425.868	-16.6
7453.630	-16.4	8429.885	-16.4

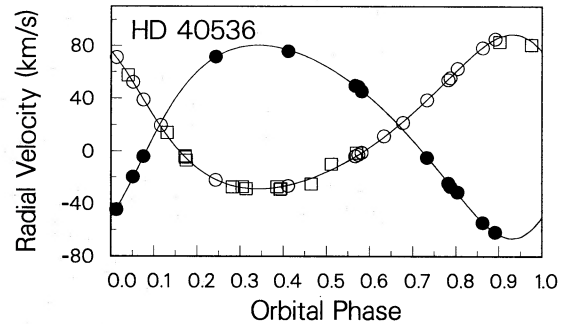
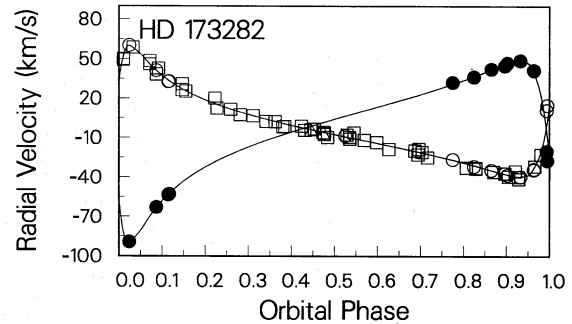
**Figure 1.** Radial-velocity curves and observations of HD 22403 = V837: solid circles, our secondary observations; open circles, our primary observations; open squares, Carquillat *et al.*'s (1979) primary observations; open triangles, Heard's (1956) primary observations. Phase is computed from T_0 .**Figure 2.** Radial-velocity curves and observations of HR 1528 = HD 30453: solid circles, our secondary observations; open circles, our primary observations; open squares, Harper's (1932) primary observations. Phase is computed from T_0 .

both the primary and secondary components after macro-turbulence was taken into account where needed. The measurements were converted to $v \sin i$'s with an empirical formula. The estimated uncertainty for each primary's rotational velocity is 2 km s^{-1} . The greater estimated uncertainty of 3 km s^{-1} or more for the secondaries is due to increased blending problems in the much weaker secondary lines. The inclination of each system was determined with the mass assumed from the spectral type of the primary and $M_1 \sin^3 i$ for that star. This inclination was then used to determine the equatorial rotational velocity v_{eq} from $v \sin i$. In our survey, only the rotational velocities of HD 222317 and HR 2108 were changed significantly as a result of the low inclination of the systems. For the rest of the systems the observed $v \sin i$ was compared with the calculated equatorial velocity.

The calculated equatorial velocity for synchronous (circular orbits) and pseudo-synchronous (eccentric orbits) rotation (Hut 1981), v_{eq} , is computed from the equation

$$v_{\text{eq}} = 50.6 R/nP,$$

where R is the star's radius in solar radii, P is the orbital period in days, and n is the ratio of the rotational period to the orbital period ($P_{\text{rot}}/P_{\text{orb}}$) in systems known to be pseudo-synchronous. The ratio n was determined from the work of Hut (1981). In cases where the eccentricity is zero (a circular orbit), the ratio n is equal to 1. The radius was estimated on

**Figure 3.** Radial-velocity curves and observations of HR 2108 = HD 40536 = 2 Mon: solid circles, our secondary observations; open circles, our primary observations; open squares, Abt & Levy's (1985) primary observations. Phase is computed from T .**Figure 4.** Radial-velocity curves and observations of HR 7038 = HD 173282: solid circles, our secondary observations; open circles, our primary observations; open squares, Salzer & Beavers' (1985) primary observations; open triangles, Andersen *et al.*'s (1985) primary observations. Phase is computed from T .

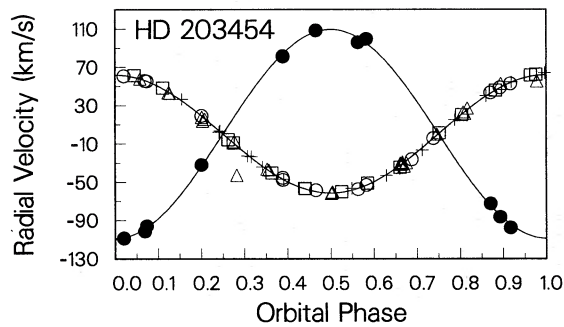


Figure 5. Radial-velocity curves and observations of HR 8170 = HD 203454: solid circles, our secondary observations; open circles, our primary observations; open squares, Mayor & Mazeh's (1987) primary observations; open triangles, Beavers & Eitter's (1986) primary observations; pluses, Plaskett's (1922) primary observations. Phase is computed from T_0 .

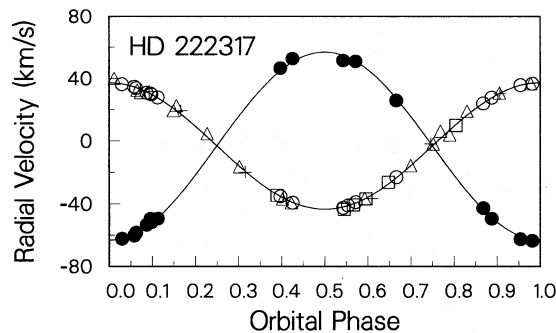


Figure 6. Radial-velocity curves and observations of HD 222317 = KT Peg: solid circles, our secondary observations; open circles, our primary observations; open squares, Beavers & Eitter's (1986) primary observations; open triangles, Imbert's (1969) primary observations; pluses, Heard's (1956) primary observations. Phase is computed from T_0 .

the basis of the spectral type (or estimated spectral type in the cases of the secondaries) for each star. The calculated v_{eq} was then compared to the measured v_{eq} or $v \sin i$, to judge whether the system was rotating synchronously (or pseudo-synchronously).

3 DISCUSSION OF INDIVIDUAL STARS

3.1 General remarks

This paper examines the properties of six double stars whose primaries are in the middle of the main sequence. HR 1528 and 2108 are both of spectral type Am. HR 7038 and 8170 are both F dwarfs. HD 22403 and 222317 are chromospherically active G-type dwarfs. A red-wavelength spectrum of each star, showing the linewidths and differences in line depths, is presented in Figs 7 to 12. Table 10 lists the orbital elements determined in this work as well as elements previously determined by other authors. In this table, T_0 is the time of maximum positive velocity of the primary and Gm is 10^6 km. 'Sigma' is the standard error of an observation of unit weight for that particular system.

It should be noted that main-sequence stars occupy a band or region in the Hertzsprung–Russell (H–R) diagram and not a narrow line. Consequently, the canonical values of a star's

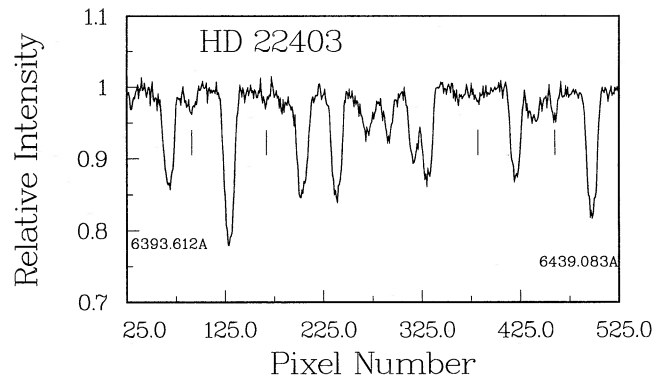


Figure 7. A portion of a spectrum near 6430 Å of HD 22403 = V837 Tau. Tick marks denote lines of the secondary component.

mass, radius and luminosity, estimated from a spectral-type–mass relation or a spectral-type–radius relation such as those listed in Allen (1973), may differ significantly from the true values. This point is expounded more extensively by Nordström (1989), who estimates for B- to F-type stars an uncertainty of ± 15 per cent for a mean spectrum–mass relation due to the effects of evolution within the main-sequence band. Relations such as those in Allen (1973) are useful as long as their limitations are understood.

3.2 HD 22403 = V837 Tau

HD 22403 is a chromospherically active star with strong Ca II H and K emission. Heard (1956) found HD 22403 to be an SB1 with radial velocity variations of 150 km s^{-1} , and listed it as a G2V star. Carquillat *et al.* (1979) determined a period of 1.9299 d from their measurements of the primary's radial velocity and confirmed the G2V classification. Raveendran, Mohin & Mekkadon (1985) found light variations in V of 0.09 mag. More recently, Strassmeier *et al.* (1989) determined a photometric period, presumably due to starspots, of about 1.9 d, so the star is rotating synchronously.

Between 1984 January and 1990 September, 19 double-lined observations of HD 22403 were obtained in the red portion (see Fig. 7) of the visible spectrum. The eccentricity derived from these data was 0.004 ± 0.009 . According to the precepts of Lucy & Sweeney (1971), this is consistent with the orbit being circular, and so such an orbit was adopted. The data of Heard (1956) and Carquillat *et al.* (1979) were added to the present data to improve the accuracy of the period. In the combined solution, 1.0 km s^{-1} was added to the data of Heard and Carquillat *et al.* to equalize the centre-to-mass velocities. The final orbital elements can be found in Table 10.

If the primary is a $1-M_{\odot}$ G2V star, then from $M_1 \sin^3 i = 0.86 M_{\odot}$ the orbital inclination is 73° . The mass ratio was determined to be 0.67, consistent with the secondary being a mid-KV (Allen 1973) star if the primary is a G2V star. From the broadening of the spectral lines, we determined $v \sin i$ to be $31 \pm 2 \text{ km s}^{-1}$ for the primary and $23 \pm 4 \text{ km s}^{-1}$ for the secondary. These are consistent with Fekel, Moffett & Henry's (1986) values of 30 km s^{-1} for the primary and 19 km s^{-1} for the secondary. If the primary is a G2V star with a radius of $1.0 R_{\odot}$, an equatorial velocity of 26 km s^{-1} is found. If, from the mass ratio, the secondary

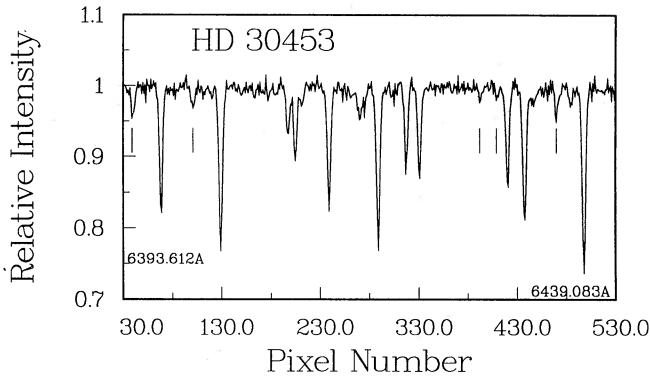


Figure 8. A portion of a spectrum near 6430 Å of HR 1528 = HD 30453. Tick marks denote lines of the secondary component.

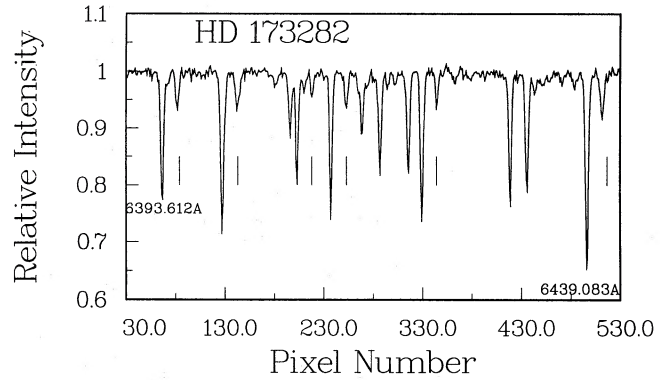


Figure 10. A portion of a spectrum near 6430 Å of HR 7038 = HD 173282. Tick marks denote lines of the secondary component.

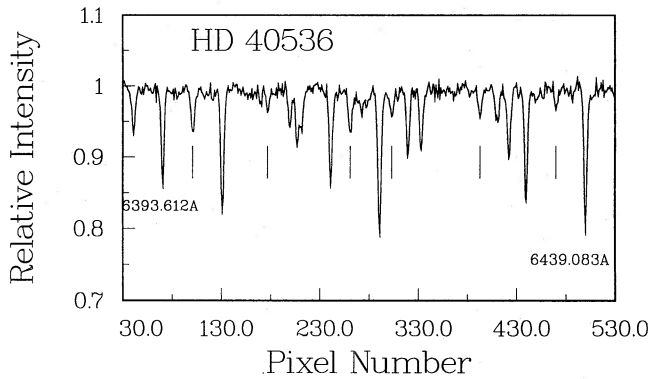


Figure 9. A portion of a spectrum near 6430 Å of HR 2108 = HD 40536 = 2 Mon. Tick marks denote lines of the secondary component.

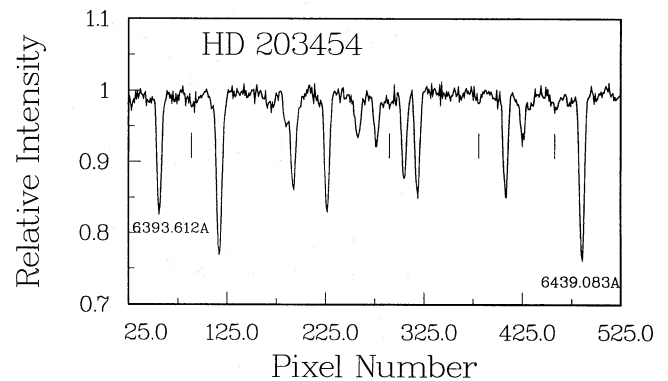


Figure 11. A portion of a spectrum near 6430 Å of HR 8170 = HD 203454. Tick marks denote lines of the secondary component.

star is of mass $0.67 M_{\odot}$, then the secondary has a spectral type of about K5V with $R_2 = 0.72 R_{\odot}$ (Allen 1973). This results in a v_{eq} of 19 km s^{-1} . From the photometric data it is known that the primary exhibits synchronous rotation. Since the system is synchronously rotating, the measured value of $v \sin i = 31 \text{ km s}^{-1}$ suggests that the radius of the primary is about $1.2 R_{\odot}$.

The analysis of the secondary via the method of spectrum addition (Strassmeier & Fekel 1990) was difficult due to the extreme width and weakness of the secondary's lines. The best fits resulted if the secondary spectrum was early- to mid-KV, but no unique spectral type could be assigned. This is in agreement with the predicted spectral type for the secondary, based on the mass ratio.

3.3 HR 1528 = HD 30453

HR 1528 has been classified as spectral type A8m by Cowley *et al.* (1969). HR 1528 was first discovered to be a spectroscopic binary by Harper in 1930 (Harper 1932). Luyten (1936) later used Harper's data to recalculate the elements with the methods of Wilsing-Russell and least-squares instead of the Lehmann-Filhés method. Lucy & Sweeney (1971) assumed a circular orbit for the system and derived new elements.

19 observations of HR 1528 were made between 1984 January and 1991 April with the secondary lines visible in all but four. Only five of the observations were obtained in the

blue because it became apparent that the secondary was more easily detected at red wavelengths (see Fig. 8).

The new observations were combined with Harper's data after an appropriate weighting was established. Separate solutions of Harper's data and the present data were made. They resulted in a velocity correction of -2.7 km s^{-1} to shift Harper's velocities onto our velocity system. Harper's data were only used to improve the orbital period and then were given zero weight in the final computation of the elements. Since the orbital eccentricity was determined to be 0.010 ± 0.009 , the orbit was recomputed with $e = 0$. The final elements can be found in Table 10.

The inclination determined from $M_1 \sin^3 i = 1.45 M_{\odot}$ and an assumed mass for the A8m primary of $1.85 M_{\odot}$ (Allen 1973) is 67° . A $v \sin i$ of $10 \pm 2 \text{ km s}^{-1}$ was found for the primary and a value of $9 \pm 3 \text{ km s}^{-1}$ for the secondary. The value for the primary is in reasonable agreement with Abt & Moyn's (1973) value of 15 km s^{-1} . Since $M_2/M_1 = 0.66$, the secondary has a mass $\sim 1.25 M_{\odot}$ which corresponds to spectral type F6V. This is consistent with our observations, because the secondary was not readily detected at blue wavelengths. If typical radii for an A8m and F6V star are assumed to be 1.49 and $1.14 R_{\odot}$, respectively (Allen 1973), then values for v_{eq} of 11 and 8 km s^{-1} are computed for the primary and secondary. Thus, our measured values are consistent with the assumption of synchronous rotation for both components.

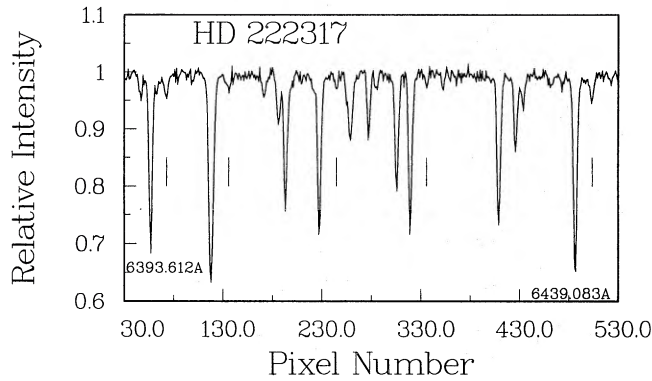


Figure 12. A portion of a spectrum near 6430 Å of HD 222317 = K1 Peg. Tick marks denote lines of the secondary component.

3.4 HR 2108 = HD 40536 = 2 Mon

HR 2108 was classified by Cowley *et al.* (1969) as A6m. Abt & Levy (1985) classified it as A3, A8, and F2 from the Ca II *K* line, the H I Balmer lines, and the metallic lines, respectively. Barrett (1914) discovered HR 2108's velocity variation in 1914 while observing it at the Yerkes Observatory. Because of his other duties he was unable to continue work on this system himself and passed it to Elvey (1924), who continued the observations and determined the orbital elements. Elvey detected lines of the secondary on several plates and calculated a mass ratio of $M_2/M_1 = 0.86$. Abt & Levy (1985) obtained additional observations of this star as part of their survey of bright Am stars, and determined a more accurate set of orbital elements. They were able to measure only one velocity of the secondary, so they adopted Elvey's mass ratio.

A total of 17 observations were made between 1984 January and 1990 October, with lines of the secondary visible in 15 of these observations. Five observations were obtained in the blue part of the spectrum, while the rest were obtained at red wavelengths (see Fig. 9).

The velocity scatter of Elvey's individual observations is so great that they were not used. Only Abt & Levy's observations were combined with the current observations to obtain a new orbital solution. A value of -0.9 km s^{-1} was added to each of their observations to adjust their velocity system to that of the current observations. Their data were used only to improve the orbital period and then were given zero weight in the final analysis. Our orbital elements are given in Table 10.

From our mass ratio of 0.80, the assumed mass of the primary star, and the tables of Allen (1973), the secondary was estimated to be about spectral type F1V. The relatively small spectral-type difference is consistent with our observations because lines of the secondary, although much weaker than those of the primary, were seen easily in the blue. From an assumed mass for the primary of $2.00 M_\odot$ and a computed value of $M_1 \sin^3 i$ of $1.16 M_\odot$, an inclination of 57° was deduced. The $v \sin i$ was determined to be $9 \pm 2 \text{ km s}^{-1}$ for the primary and $10 \pm 3 \text{ km s}^{-1}$ for the secondary. Our value of 9 km s^{-1} is reasonably consistent with Abt's (1975) value of 15 km s^{-1} for the primary. Because of the moderate eccentricity of 0.224, the binary will probably not exhibit synchronous rotation but it may display pseudo-synchronous

rotation (Hut 1981). For an eccentricity of 0.224, the ratio n reduces to 0.76. The v_{eq} of the two stars, with assumed radii of $1.65 R_\odot$ for the primary and $1.32 R_\odot$ for the secondary, would be 12 and 9 km s^{-1} , respectively, if they were pseudo-synchronous. Thus, both components may be pseudo-synchronously rotating.

3.5 HR 7038 = HD 173282

HR 7038 is an F5/6V star as classified by Houk (Houk & Smith-Moore 1988). Beavers & Eitter (1980) discovered the duplicity of this highly eccentric ($e = 0.726$) system in a survey of 211 stars without previous radial-velocity measurements. Salzer & Beavers (1985) determined an orbit for the system from 48 observations. They were unable to detect lines of the secondary in their observations, but concluded that the large mass function suggested a minimum mass of $0.88 M_\odot$ for the secondary and an upper limit of 0.68 for the mass ratio. Andersen *et al.* (1985) obtained two observations of HR 7038 as part of the survey to determine the radial velocities of 790 late-type bright stars.

During the period from 1987 June to 1991 June, 15 observations, of which 14 were double-lined, were obtained at red wavelengths (see Fig. 10). The reference star μ Her A, a G5IV star, was used to determine the radial velocities of HR 7038. Since μ Her A is not an IAU standard, its average radial velocity was determined in the same manner as that of a programme star, with β Oph used as the standard star. Over a period of eight years, from 1983 to 1991, 40 observations of μ Her A were obtained in conjunction with β Oph. On the basis of these observations (see Table 9) we have assumed that μ Her A has a constant velocity of $-16.4 \pm 0.05 \text{ km s}^{-1}$. However, it should be noted that Heintz (1987) has found that μ Her A is an astrometric binary with a period of 63 yr. Since its radial velocity appears to have remained constant over the time-span of our observations, no velocity correction was made for any orbital motion. In the future, observations of a different reference star should be used.

The data of Salzer & Beavers and the two observations of Andersen *et al.* (1985) were weighted appropriately and then combined with the current observations to yield a final set of elements, which can be found in Table 10. No velocity-shift correction was needed for the older data. A mass of $1.29 M_\odot$ for a typical F5 dwarf, combined with our $M_1 \sin^3 i = 1.11 M_\odot$, results in an orbital inclination of 72° . The value of $v \sin i$ was determined to be $8 \pm 2 \text{ km s}^{-1}$ for the primary and $6 \pm 3 \text{ km s}^{-1}$ for the secondary. From our mass ratio of 0.72 and an assumed primary mass of $1.29 M_\odot$, the secondary has a mass of $0.93 M_\odot$, implying a spectral type of about G5V. If the rotational velocity is pseudo-synchronous, the ratio of $P_{\text{rot}}/P_{\text{orb}} = 0.14$. The value of v_{eq} for a pseudo-synchronous orbit would be 13 km s^{-1} for the primary and 10 km s^{-1} for the secondary, if radii of 1.20 and $0.93 R_\odot$ (Allen 1973), respectively, are assumed. The primary does not appear to be pseudo-synchronously rotating unless its radius is as large as $1.8 R_\odot$. Nordström (1989) has shown that, because of main-sequence evolution, there is a considerable range in the radii for early F stars that have been classified as dwarfs. Thus, the primary might have a significantly larger radius than that assumed for its spectral type in the tables of Allen (1973). If this is the case it could be pseudo-synchronously rotating.

Table 10. Orbital elements for the six programme stars.

HD	Author	P (days)	T or T ₀ (HJD)	V (km s ⁻¹)	K _A (km s ⁻¹)	K _B (km s ⁻¹)	e	w (°)
22403	Stockton & Fekel	1.9299275 ± 0.0000062	2448160.761	- 17.7 ± 0.9	77.7 ± 1.2	115.4 ± 4.4	0	---
	Carquillat et al. (1979)	1.9299395 ± 0.0000028	2441926.590* ± 0.160	- 19.4 ± 1.3	77.8 ± 1.5	-----	0.035 ± 0.020	266.0 ± 29.6
30453	Stockton & Fekel	7.050933 ± 0.000024	2448158.713	+ 17.8 ± 0.1	58.9 ± 0.3	89.7 ± 0.7	0	---
	Harper (1932)	7.0507 -----	2426327.626* ± 0.296	+ 20.3 ± 0.6	57.8 ± 0.9	-----	0.033 ± 0.016	289.7 ± 16.9
40536	Stockton & Fekel	9.355849 ± 0.000033	2447030.493* ± 0.019	+ 19.7 ± 0.1	58.9 ± 0.3	73.5 ± 0.7	0.224 ± 0.004	38.8 ± 0.8
	Abt & Levy (1985)	9.35749 ± 0.00012	2443110.051* ± 0.049	+ 21.6 ± 1.0	58.1 ± 1.3	67.6 -----	0.16 ± 0.18	33.9 ± 1.8
	Elvey (1924)	9.3553 -----	2419673.815* ± 0.059	+ 22.2 -----	57.1 ± 2.5	-----	0.208 ± 0.007	35.4 ± 2.4
173282	Stockton & Fekel	33.1607 ± 0.0011	2445079.853* ± 0.107	- 2.7 ± 0.3	49.8 ± 0.7	69.5 ± 1.6	0.726 ± 0.006	290.8 ± 0.9
	Salzer & Beavers (1985)	33.161 ± 0.003	2445079.89* ± 0.06	- 3.0 ± 0.3	50.3 ± 0.8	-----	0.724 ± 0.007	291.4 ± 1.2
203454	Stockton & Fekel	3.243347 ± 0.000001	2448345.120	+ 0.3 ± 0.3	61.6 ± 0.4	109.3 ± 2.3	0	---
	Mayor & Mazeh (1987)	3.243346 ± 0.000001	2444800.143 ± 0.003	- 1.4 ± 0.3	61.8 ± 0.3	-----	0	---
	Plaskett (1922)	3.24343 ± 0.00040	2421801.549* -----	+ 0.2 ± 0.4	62.2 ± 0.7	-----	0.022 ± 0.013	357.6 ± 1.5
222317	Stockton & Fekel	6.201986 ± 0.000038	2446996.904	- 3.1 ± 0.4	40.3 ± 0.4	60.1 ± 1.9	0	---
	Imbert (1969)	6.20197 ± 0.00003	2439842.7* ± 0.9	- 2.1 ± 0.6	41.3 ± 0.9	-----	0.019 ± 0.022	168 ± 53

Spectrum addition was applied to HR 7038 to determine the spectral type of the secondary. Spectra with types from late GV to early KV yielded the best matches to the secondary spectrum, consistent with the spectral type assumed from its mass, but no definitive type could be determined. Although the line-strength ratios indicate a spectral class of F5 for HR 7038, an F7 or F8 spectrum was needed to match the line strength of the primary. Thus, the primary appears to be metal rich relative to the reference stars.

3.6 HR 8170 = HD 203454

HR 8170 was classified as an F8V star by Harlan (1974) and later classified as F9V by Cowley (1976), who noted the presence of many weak metallic lines. Wilson (1966) detected weak but definitely present Ca II *H* and *K* emission lines on 10 Å mm⁻¹ plates. HR 8170 was the *first* spectroscopic binary to be discovered and have its orbital elements determined at the Dominion Astrophysical Observatory

(Plaskett 1922). Plaskett determined the star's elements from his 15 observations, by holding the time of periastron passage fixed and then solving for the other elements with the method of Lehmann-Filhés. Luyten (1936) later revised Plaskett's elements with the method of Wilsing-Russell, which gives a more exact determination for the orbital elements, especially those with small eccentricity. Lucy & Sweeney (1971) re-examined Plaskett's data and determined that the data were fitted just as well by a circular-orbit solution. Beavers & Eitter (1986) obtained 26 radial-velocity measurements during the first eight years of the Fick Observatory, but did not determine orbital elements based on those data. Mayor & Mazeh (1987), in a search for possible triple systems, obtained 15 observations of HR 8170 with CORAVEL and determined a new set of elements from their own data.

Fourteen observations of HR 8170 were obtained between 1979 October and 1991 April, 12 of these double-lined. The first two observations were made at the

Table 10 – continued

HD	Author	$a_A \sin i$ (Gm)	$a_B \sin i$ (Gm)	$M_A \sin^3 i$ $M_\odot$	$M_B \sin^3 i$ $M_\odot$	M_B/M_A	T (conjunction) (HJD)	Sigma (km s ⁻¹)
22403	Stockton & Fekel	2.06 ± 0.03	3.06 ± 0.12	0.86 ± 0.05	0.58 ± 0.03	0.673 ± 0.052	2448161.244	0.57
	Carquillat et al. (1979)	2.06 -----	-----	-----	-----	-----	-----	-----
30453	Stockton & Fekel	5.71 ± 0.03	8.70 ± 0.07	1.45 ± 0.02	0.95 ± 0.01	0.656 ± 0.009	2448160.476	0.69
	Harper (1932)	5.60 -----	-----	-----	-----	-----	-----	-----
40536	Stockton & Fekel	7.38 ± 0.04	9.22 ± 0.08	1.16 ± 0.02	0.93 ± 0.01	0.801 ± 0.009	2443111.491	0.75
	Abt & Levy (1985)	7.38 -----	8.586 -----	-----	-----	-----	-----	-----
	Elvey (1924)	7.20 -----	-----	-----	-----	0.86 -----	-----	-----
173282	Stockton & Fekel	15.60 ± 0.30	21.7 ± 0.5	1.10 ± 0.05	0.79 ± 0.03	0.719 ± 0.024	2445091.831	0.47
	Salzer & Beavers (1985)	15.80 ± 0.30	-----	-----	-----	-----	-----	-----
203454	Stockton & Fekel	2.75 ± 0.02	4.87 ± 0.10	1.08 ± 0.04	0.61 ± 0.02	0.564 ± 0.035	2448345.931	0.95
	Mayor & Mazeh (1987)	2.76 ± 0.02	-----	-----	-----	-----	-----	-----
	Plaskett (1922)	2.77 -----	-----	-----	-----	-----	-----	-----
222317	Stockton & Fekel	3.44 ± 0.04	5.13 ± 0.16	0.39 ± 0.02	0.26 ± 0.10	0.671 ± 0.043	2446998.455	0.39
	Imbert (1969)	3.52 ± 0.78	-----	-----	-----	-----	-----	-----

*Time of periastron passage (T).

McDonald Observatory while the rest were obtained at the KPNO. Due to the lower S/N ratio of the McDonald observations, they were given half weight in the orbital solution. Absorption lines of the secondary are not easily detected, even with high-S/N observations at red wavelengths (see Fig. 11).

The proper weights for the three previous sets of data were determined. To adjust these other data sets to our system, 0.4, 1.0, and 1.9 km s⁻¹ were added to the radial velocities of Plaskett, Beavers & Eitter, and Mayor & Mazeh, respectively. The velocities were then combined with the present set and a solution for the orbital elements was determined (see Table 10). The eccentricity of 0.013 ± 0.007 was deemed not to be statistically significant and the final analysis was made for a circular orbit.

A mass ratio of 0.56, the lowest for the six systems sur-

veyed, was found. If the F8V star is thought to have a mass of $1.17 M_\odot$, the secondary has a mass of $0.66 M_\odot$ and a spectral type of about K6V (Allen 1973). An orbital inclination of 77° results from the assumed mass of the primary and $M_1 \sin^3 i = 1.08 M_\odot$. The measured $v \sin i$ of the primary is 15 ± 2 km s⁻¹. This agrees with the three previous determinations of 10–15 km s⁻¹ by Wilson (1966), 18 km s⁻¹ by Soderblom (1982), and 16 km s⁻¹ by Benz & Mayor (1984). The secondary's $v \sin i$ is 12 ± 3 km s⁻¹. The value of v_{eq} for the primary with a radius of $1.11 R_\odot$ would be 17 km s⁻¹, and v_{eq} for the secondary with a radius of $0.72 R_\odot$ would be 11 km s⁻¹. The binary appears to be synchronously rotating. A determination of the secondary's spectral type was attempted with the method of spectrum addition, but the extreme weakness of the secondary lines in the spectrum prevented any firm conclusion.

3.7 HD 222317 = KT Peg

HD 222317 is a chromospherically active G5V star. Heard (1956) first recognized this star's binary nature and listed the above spectral type. Imbert (1969) discovered its Ca II *H* and *K* emission and determined an orbital period of 6.20197 d. Strassmeier *et al.* (1989) detected a very small light variation of 0.013 mag in *V* and a photometric period, presumably due to starspots, of 6.092 d. The close agreement of the photometric and spectroscopic periods is indicative of synchronous rotation.

From 1984 January to 1990 September, 17 observations of HD 222317 were obtained in the red portion of the spectrum (see Fig. 12). In all but one of the spectra, lines of both the primary and secondary were visible.

To determine new elements, the present radial velocities were combined with the older data of Heard (1956), Imbert (1969), and Beavers & Eitter (1986). In addition, -1.0 km s^{-1} was added to each observation obtained by Heard and Imbert to adjust their centre-of-mass velocities to our system. The orbital solution results in an orbit with an eccentricity of 0.006 ± 0.016 , so the orbit was considered to be circular. Orbital elements for the double-lined solution are presented in Table 10.

For HD 222317, the combination of $M_1 \sin^3 i = 0.39 M_\odot$ and an assumed mass of $0.93 M_\odot$ for a G5V star results in an orbital inclination of 49° . The $v \sin i$ of the primary was determined from several lines in the spectrum and found to be $8 \pm 2 \text{ km s}^{-1}$ or a measured v_{eq} of $11 \pm 2 \text{ km s}^{-1}$. The $v \sin i$ agrees with the previous determination of 7 km s^{-1} by Fekel (Strassmeier *et al.* 1988). If the radius of the primary is assumed to be $0.93 R_\odot$ from its spectral type, then a v_{eq} of 8 km s^{-1} is computed for synchronous rotation. From the assumed mass of the primary and the mass ratio of 0.67, the secondary's mass is determined to be $0.62 M_\odot$. This would make it approximately a K6V star, and results in an assumed radius of $0.72 R_\odot$. A v_{eq} of 6 km s^{-1} is computed for the secondary, which compares to the measured v_{eq} of $7 \pm 3 \text{ km s}^{-1}$.

The method of spectrum addition was used to try and determine the spectral type of the secondary. Spectral standards of G7.5, K0, K2, K3, K5 and K7 dwarfs were used to model the secondary. Because of the weakness of the secondary lines, a specific determination could not be made for the spectral type, but it was confined within the range of early- to mid-KV.

4 CONCLUSIONS

This project was started as a result of Trimble's (1974) work, which brought forth the idea that the mass-ratio distribution of spectroscopic binaries is bimodal. The original thrust of the present research was to find a significant number of double-lined systems that fell between these two peaks. During the period this project has spanned, other astronomers (Scarfe 1986; Duquennoy & Mayor 1991) have argued that Trimble's original results were strongly biased by selection effects. The most widely accepted notion today is that the mass-ratio distribution roughly fits a Gaussian distribution and is singly peaked at $q \approx 0.3$. This is consistent with the prevalent theory of fragmentation for the formation of binary and multiple stars (Boss 1988). Although the

results of the present work now have only a slight bearing on the overall distribution of mass ratios, useful conclusions can be made about the detection limits of secondaries with current high-S/N detectors (mostly CCDs), the approximate magnitude difference of such components, the significance of the mass function of roughly solar-type SB1s, and which stars are synchronously rotating.

This paper confirms that it is possible, with high-S/N detectors at red wavelengths, to detect the secondaries of mid- and late-type main-sequence stars whose mass ratios are as small as 0.6. These detectors enable searches to be made for the weak secondary lines of cooler stars. The system HR 8170 has the smallest mass ratio (0.56) and the highest inclination ($\sim 77^\circ$) of the six double-lined systems surveyed. Table 11 lists a summary of the orbital elements for the six programme stars while Table 12 summarizes the stars' properties.

Eleven main-sequence systems with $f(m) \leq 0.1 M_\odot$ were initially observed to determine if the secondaries could be discovered or confirmed in their spectra. Secondary lines were only detected in seven of these systems, the six described in this paper and another system (HD 210027 = ι Peg, F5V+G8V, $q=0.62$), already presented by Fekel & Tomkin (1983). Of the four systems that remained SB1s (see Table 13), HD 178450 [previously studied by Fekel (1988)] was later determined by Hall *et al.* (1990) to be an eclipsing binary with an inclination of 83° . Since lines of the secondary were detected in spectra of HR 8170, lines of the secondary were expected to be seen in another system, HD 131511, because its mass function of $0.061 M_\odot$ was slightly larger. However, no secondary lines were seen. A minimum mass for the secondary was computed, taking $i=90^\circ$ and the mass of the K1V primary to be $0.76 M_\odot$ (Allen 1973). The estimated mass for the secondary was determined as $\geq 0.45 M_\odot$, which is about spectral type M0V. From this, the mass ratio was estimated to be ≥ 0.59 , implying that the secondary should have been detected if the inclination of the system were significantly less than 90° . Therefore, there is a chance that eclipses may be detected in this long-period, high-eccentricity system.

From the mass-luminosity relation (Smith 1983), values for the magnitude differences of ΔB , ΔV and ΔR were computed on the basis of the assumed individual masses of the six SB2 systems of this work, as well as for ι Peg and the four SB1 systems for which no secondary lines were seen. Table 14 lists all 11 systems and for each, the mass function $f(m)$, the mass ratio q , ΔB , ΔV , ΔR and i in order of increasing ΔR , which is also the order of decreasing ease of detectability for the six SB2s presented in this work. Based on the 11 ΔR s, the maximum magnitude difference that can be detected at red wavelengths near 6430 Å, with signal-to-noise ratios of about 150–200, is estimated to be slightly greater than 2.5 mag.

The value of the mass function is dependent on the mass of the secondary, the mass of the primary, and the orbital inclination. The mass of the primary can be estimated from its spectral type, leaving only the secondary's mass and the inclination as the unknowns. If a mass function is small, then either the secondary's mass is small or the orbital inclination is far from 90° , or a combination of the two. From the mass functions of the 11 stars used in this survey, and the subsequent detection or non-detection of their secondaries, it

Table 11. Summary of the orbital elements for the six systems.

HD	Spec. Ty.	V (mag)	P (days)	T or T ₀ (2400000+)	w (°)	e	V (km s ⁻¹)	K _A (km s ⁻¹)	K _B (km s ⁻¹)	q = M _B /M _A
22403	G2 V	8.10	1.9299275	48160.761	-	0	- 17.7	77.7	115.4	0.67
30453	A8m	5.84	7.050933	48158.713	-	0	+ 17.8	58.9	89.7	0.67
40536	A6m	5.04	9.355849	47030.493	38.8	0.224	+ 19.7	58.9	73.5	0.80
173282	F5/6 V	6.35	33.16071	45079.853	290.8	0.726	- 2.7	49.8	69.3	0.72
203454	F8 V	6.40	3.243347	48345.120	-	0	+ 0.3	61.6	109.3	0.56
222317	G5 V	7.00	6.201986	46996.904	-	0	- 3.1	40.3	60.1	0.67

Table 12. Summary of the properties of the programme stars.

HD	Spectral Type	Mass	Radius	v(calc)	v sin i	Synch.	i
	Pri. Sec.	Pri. Sec. (M _⊙)	Pri. Sec. (R _⊙)	Pri. Sec. (km s ⁻¹)	Pri. Sec. (km s ⁻¹)	Rot? (°)	
22403	G2 V ~K5 V	1.00 0.67	1.00 0.74	26 19	31±2 23±4	yes	72
30453	A8 m ~F6 V	1.85 1.25	1.49 1.14	11 8	10±2 9±3	yes	67
40536	A6 m ~F1 V	2.00 1.60	1.65 1.32	12 9	9±2 10±3	pseudo	57
173282	F5 V ~G5 V	1.29 0.93	1.20 0.93	13 10	8±2 6±3	no	72
203454	F8 V ~K5 V	1.17 0.66	1.11 0.74	17 12	15±2 12±3	yes	77
222317	G5 V ~K6 V	0.93 0.62	0.93 0.72	8 6	8±2 5±3	yes	49

Table 13. Null detections.

HD	Pri. Spec. Ty.	M _A (M _⊙)	R _A (R _⊙)	v sin i (km s ⁻¹)	i (°)	M _B (M _⊙)	q = M _B /M _A	Sec. Spec. Ty.
131511	K1 V	0.76	0.8	4	90*	≥0.45*	≥0.59*	≥M0 V*
166181	G5 V	0.93	1.0	27	75	0.39	0.42	M2 V
175742	K0 V	0.78	0.9	15	73	0.38	0.50	M2 V
178450	G8 V	0.84	0.9	21	83	0.24	0.29	M4 V

*Limiting case.

Table 14. Detection limits.

HD	r(m) M _⊙	q	B (mag)	V (mag)	R (mag)	i (°)
30453	0.14	0.80	1.13	0.97	0.81	57
173282	0.15	0.72	1.75	1.52	1.38	72
40536	0.18	0.66	1.96	1.73	1.53	66
222317	0.05	0.67	2.99	2.40	1.88	49
210027	0.13	0.62	2.54	2.23	2.05	90
22403	0.09	0.67	3.04	2.52	2.06	73
203454	0.08	0.56	3.67	3.06	2.54	77
131511	0.06	0.59	3.73	3.19	2.60	90*
175742	0.04	0.50	4.92	4.14	3.33	73
166181	0.03	0.42	6.07	5.21	4.25	75
178450	0.01	0.29	7.27	6.45	5.33	83

*Limiting case.

appears that the secondaries of roughly solar-type systems usually can be detected for mass functions greater than 0.05 M_⊙. HD 222317 has a small mass function owing to its relatively low inclination, but the secondary is visible in the spectrum. HD 131511, on the other hand, has a slightly larger mass function than HD 222317 and roughly the same

ΔR, but the secondary component was not detected. If both components of HD 131511 are on the main sequence, then it is probable that the inclination of the system is high. Another possibility is that the secondary is itself a double star. The combined luminosity of the two stars would be less than that of a single star with the same mass. If the secondary is not on the main sequence, then it is possible that the secondary is a white dwarf.

The question of synchronous rotation was explored for the six systems. The results are that HR 1528, HR 8170 and HD 222317 appear to have synchronous rotation. Another system, HR 2108, probably has pseudo-synchronous rotation. The primary of HD 22403 is known from photometry to be synchronously rotating, but the measured $v \sin i$ is larger than that expected. Thus either the $v \sin i$ is too large or the radius is larger than the assumed value. If the radius is larger, then HD 22403 would be slightly evolved, though still on the main sequence. The primary of HR 7038 may be in pseudo-synchronous rotation if it is a somewhat evolved main-sequence star, otherwise it is rotating too slowly.

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