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Contribution to the study of F-G-K-M binaries.

XII. Orbital elements of seven new spectroscopic binaries

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Key words Binaries: spectroscopic — Stars: individual (HD 31855, HD 59643, HD 60092, HD 133189, HD 162262, HD 203522, BD +43° 1331)

The orbital elements of seven single-lined spectroscopic binaries, HD 31855, 59643, 60092, 133189, 162262, 203522, BD +43° 1331 are presented. They are obtained from observations made with two photoelectric spectrometers of CORAVEL type, the first located at the *Observatoire de Haute-Provence* and the second at the Cambridge Observatories. From those orbital elements and other data available in the literature, we deduce some information about the unseen companions and their separations with respect to the primaries. We then discuss the rotation-revolution synchronism and conclude that some of those stars have probably reached the state of (pseudo-)synchronism. Finally we give a synopsis of the results obtained in this series of papers. Our radial velocity monitoring of more than three decades has allowed us to derive accurate orbital elements of 35 spectroscopic binaries, with a cool primary star of type F-G-K-M. The corresponding range of periods varies from a few days to more than 10 years.

1 Introduction

This paper is the twelfth and last of a series devoted to the study of late-type stars suspected to be spectroscopic binaries (SB), in order to determine their orbital elements (see Table 1). The aim of this study was to contribute to fill the deficit of cool stars in the distribution of the number of SBs of known orbit vs spectral type, stated in the 1970's (Carquillat, Ginestet & Pédoussaut 1971). The observing programme of radial velocities (RV) was mainly carried out at the *Observatoire de Haute-Provence* (OHP): it started in 1972 with the 1.52-m telescope with conventional photographic spectroscopy and continued after 1982 with the CORAVEL instrument at the 1-m Swiss telescope.

In this paper we present the study of seven new SBs, namely HD 31855, 59643, 60092, 133189, 162262, 203522 and BD +43° 1331. Some of those systems have long orbital periods (7.3, 10.2 and 5.5 yr for HR 31855, 133189 and BD +43° 1331, respectively) and required a monitoring over a long period of time. The observations reported here were made from 1982 to 2006, with the CORAVEL spectrometer of OHP and also from 2000 onwards with a similar instrument at the Cambridge Observatories. In Sect. 2, we present those observations and the orbital elements we have obtained. In Sect. 3, we discuss the case of each star. We make a synthesis of the relevant data available in the literature and attempt to precise the nature of the stellar components with our new results. We then derive some estimates of the minimum masses and separations of the companions and discuss the occurrence of spin-orbit synchronism among those systems. Finally, in Sect. 4, we give a synopsis of the orbital elements we have obtained for the 35 binaries

Table 1 Presentations of the papers of this series.

Name	Reference
Paper I	Nadal et al. (1983)
Paper II	Carquillat et al. (1983)
Paper III	Ginestet et al. (1985)
Paper IV	Pédoussaut, Carquillat & Ginestet (1987)
Paper V	Pédoussaut, Carquillat & Ginestet (1989)
Paper VI	Ginestet & Carquillat (1995)
Paper VII	Carquillat & Ginestet (1996)
Paper VIII	Carquillat & Ginestet (2000)
Paper IX	Griffin, Ginestet & Carquillat (2003)
Paper X	Carquillat, Prieur & Udry (2005)
Paper XI	Prieur, Carquillat & Griffin (2006)

studied in this series of papers and for some other objects related to this programme. We present the distributions in spectral types and luminosity classes for the primary components of those SBs and draw the general conclusions of this study.

2 Observations and derivation of the orbital elements

Most of the observations used for the present study were made at the 1-m Swiss telescope at OHP with CORAVEL, a spectrophotometer that allows measurements of heliocentric RVs by performing a cross-correlation of the stellar spectrum with a mask (made from the spectrum of Arcturus) placed in the focal plane of the spectrograph (Baranne, Mayor & Poncet 1979). Complementary observations were

made at Cambridge Observatory with a similar instrument, associated with a 36-inch reflector, thanks to the collaboration of R.F. Griffin.

For HD 60092, S. Udry kindly provided two additional RVs obtained with the CORALIE spectrograph mounted at the 1.2-m Swiss telescope of the European Southern Observatory (ESO, La Silla). For HD 203522, we used three old observations made by Albitzky (1948) at the Crimean Astrophysical Observatory (CAO) with a reduced weight since they were less precise (see below).

The observed RVs for the seven studied stars are given in Tables 2 to 8. The observations from Cambridge are labelled with ^{Camb}, those from ESO with ^{ESO} and those from the Crimean Astrophysical Observatory with ^{CAO}. The other measurements were obtained by us with the OHP CORAVEL. All the RVs were reduced to the RV data base system of the Geneva Observatory (Udry, Mayor & Queloz 1999).

The orbital elements (Table 8) were determined with our programme BS1 based on an iterative scheme of Gauss-Newton type that performs a least-square minimization of the residuals ($O - C$), starting from an initial guess of the orbital parameters. The whole procedure is fully automatic, from the search of an initial value for the period to the determination of the final elements. The measures obtained with CORAVEL, CORALIE and Crimean Astrophysical Observatory were weighted 1, 2 and 1/20, respectively.

The orbital elements are given in Table 9, and the corresponding computed RV curves are displayed in Fig 1. The $\sigma_{(O-C)}$ of the residuals are comparable to the measurements errors, which are close to 0.5 km.s^{-1} for all those observations. Note that the small values of K_1 (less than 6 km.s^{-1}) for HD 31855, 59643 and 133189 lead to larger relative errors, as can be seen in Figs 1a, 1b and 1d.

3 Discussion

3.1 Individual cases

We report here some information we have collected in the literature for the seven new SBs, concerning mainly their classification, from which we estimate the masses \mathfrak{M}_1 of the primaries that will be used in the next section. In the following the indices 1 and 2 will be used for the primary and secondary components, respectively.

3.1.1 HD 31855 (HIP 23355)

This star initially belonged to our other programme devoted to the study of composite-spectrum stars, because it was listed by Hynek (1938) as a “suspected spectrum binary”. Nevertheless our spectroscopic observations made at OHP in the near infrared spectral region (Ginestet et al. 1997) did not reveal any signature of a cool spectrum like what was expected for *bona fide* composite-spectrum objects. We

Table 2 Radial velocities and ($O - C$) residuals for HD 31855.

Date (JD) 2400000+	Cycle	RV km s ⁻¹	($O - C$) km s ⁻¹
45600.64	-0.36	13.7	-0.1
46015.66	-0.21	12.2	-0.4
46334.64	-0.09	11.4	-0.5
46487.34	-0.03	13.4	0.1
46722.48	0.06	18.5	-0.1
46861.32	0.11	18.4	-0.1
47098.70	0.20	18.2	0.7
47459.62	0.33	16.5	0.3
47464.59	0.33	16.6	0.4
47605.30	0.39	15.0	-0.7
47867.62	0.48	15.0	0.0
47872.50	0.49	15.0	0.1
47966.28	0.52	15.1	0.4
48132.67	0.58	13.9	-0.3
48262.31	0.63	13.4	-0.5
48672.35	0.79	13.2	0.6
48937.58	0.88	11.7	-0.2
48967.48	0.90	12.3	0.4
49319.43	1.03	17.2	-0.5
49325.48	1.03	18.4	0.6
49642.57	1.15	18.3	0.2
49785.36	1.20	16.6	-0.9
50123.40	1.33	16.0	-0.2
50416.50	1.44	16.2	0.9
50739.64	1.56	13.4	-1.0
50838.42	1.59	13.7	-0.4
51107.59	1.69	13.8	0.4
51186.39	1.72	13.8	0.7
53628.59	2.64	13.8	0.0

simply obtained the classification F2-3 V, which is consistent with both the spectral type F2 quoted in the Henry Draper Catalogue and the parallax measured by Hipparcos, $\pi = 11.95 \pm 0.95 \text{ mas}$ (ESA 1997). Indeed, this parallax and the apparent visual magnitude $m_V = 7.41$ leads to $M_V = 2.8 \pm 0.2$, that well agrees with a dwarf star. Thus we can assume $\mathfrak{M}_1 \approx 1.5 \mathfrak{M}_\odot$, which is a typical value for this spectral type (Schmidt-Kaler 1982).

3.1.2 HD 59643 (HIP 36623, NQ Gem)

This object is a well known symbiotic carbon star classified R9 C6₂ by Keenan & Morgan (1941). Our study corroborates the model proposed by Johnson et al. (1988) based on the binary hypothesis (red giant primary plus small hot companion) to account for the properties of the IUE UV spectrum. Like for the three red giants studied in the previous paper of this series (Prieur, Carquillat & Griffin 2006), we will assume $\mathfrak{M}_1 \approx 2.5 \mathfrak{M}_\odot$ which can be considered as a typical value for a red giant.

3.1.3 HD 60092 (HIP 36652)

This new SB is the primary component of the close visual binary CCDM 07323-1831AB (Hipparcos observations: $\rho = 0.44''$, $\Delta m = 2.5$). Listed by Hynek (1938) as a star with composite spectrum, HD 60092 initially belonged

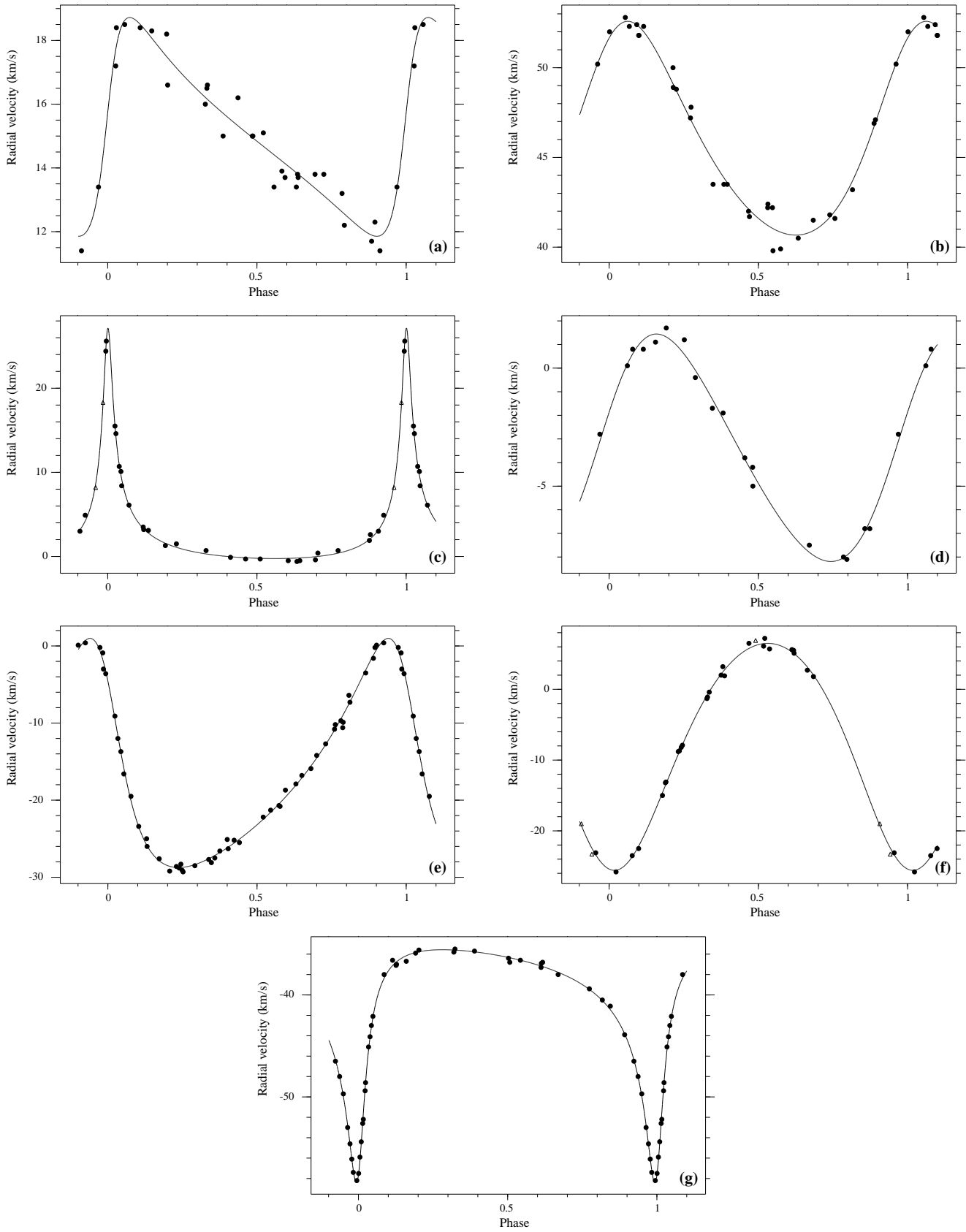


Fig. 1 RV curves (solid lines) computed with the orbital elements of Tables 9 of HD 31855 (a), HD 59643 (b), HD 60092 (c), HD 133189 (d), HD 162262 (e), HD 203522 (f) and BD +43° 1331 (g). The CORAVEL and complementary measurements (see text) are plotted as black dots and small triangles, respectively. The origin of the phases corresponds to the periastron passage.

Table 9 Orbital elements of the seven new SBs. In Col. 3, T is the epoch of periastron passage.

Name (HD/BD)	P days	T (JD) 2400000+	ω deg.	e	K_1 km s ⁻¹	V_0 km s ⁻¹	$a_1 \sin i$ Gm	$f(m)$ \mathfrak{M}_\odot	$\sigma_{(O-C)}$ km s ⁻¹
31855	2678. ±35.	46570. ±34.	277.5 ±6.4	0.547 ±0.047	3.43 ±0.22	15.04 ±0.11	106. ±12.	0.0066 ±0.0021	0.48
59643	1304.8 ±4.3	46207 ±35.	327.5 ±10.5	0.182 ±0.029	5.96 ±0.18	45.71 ±0.13	105.1 ±4.0	0.0272 ±0.0030	0.61
60092	606.61 ±0.22	48897.5 ±1.3	355.9 ±0.8	0.795 ±0.004	13.70 ±0.39	2.60 ±0.09	69.4 ±2.7	0.0363 ±0.0041	0.34
133189	3722 ±51.	49899. ±117.	288.3 ±11.3	0.141 ±0.030	4.82 ±0.15	-3.59 ±0.10	244. ±12.	0.0419 ±0.0050	0.32
162262	200.407 ±0.026	46249.47 ±0.96	51.1 ±1.3	0.404 ±0.007	14.86 ±0.14	-17.64 ±0.10	37.47 ±0.50	0.0523 ±0.0021	0.54
203522	514.109 ±0.099	45281.7 ±5.8	171.4 ±3.8	0.144 ±0.013	16.04 ±0.16	-7.26 ±0.15	112.2 ±1.3	0.2134 ±0.0076	0.43
+43° 1331	2008.23 ±0.45	48088.7 ±1.5	200.8 ±0.6	0.711 ±0.003	11.41 ±0.07	-39.39 ±0.05	221.6 ±2.4	0.1078 ±0.0035	0.25

Table 3 Radial velocities and $(O - C)$ residuals for HD 59643.

Date (JD) 2400000+	Cycle	RV km s ⁻¹	$(O - C)$ km s ⁻¹
45595.66	-0.47	42.2	1.0
45596.66	-0.47	42.4	1.2
46336.67	0.10	51.8	-0.5
46337.65	0.10	51.8	-0.5
46486.47	0.21	50.0	0.9
46723.62	0.40	43.5	-0.1
47099.67	0.68	41.5	0.6
47461.67	0.96	50.2	0.0
47600.37	1.07	52.3	-0.3
47867.69	1.27	47.2	0.1
47966.42	1.35	43.5	-1.3
48261.62	1.57	39.9	-0.9
48670.46	1.89	46.9	0.2
48676.44	1.89	47.1	0.2
48937.66	2.09	52.4	0.0
48967.66	2.12	52.3	0.3
49318.62	2.38	43.5	-0.4
49426.43	2.47	42.0	-0.1
49643.58	2.63	40.5	-0.2
49781.45	2.74	41.8	0.1
50123.54	3.00	52.0	0.3
50192.40	3.05	52.8	0.2
50415.58	3.23	48.8	0.1
50835.60	3.55	42.2	1.1
51108.66	3.76	41.6	-0.4
51185.60	3.82	43.2	-0.5
53011.52	5.21	48.9	-0.2
53089.37	5.27	47.8	0.7
53344.54	5.47	41.7	-0.4
53447.46	5.55	39.8	-1.2

Table 4 Radial velocities and $(O - C)$ residuals for HD 60092.

Date (JD) 2400000+	Cycle	RV km s ⁻¹	$(O - C)$ km s ⁻¹
48675.43	-0.37	-0.6	-0.4
48940.68	0.07	6.1	0.0
48969.59	0.12	3.5	0.2
48970.58	0.12	3.2	-0.1
49319.60	0.70	-0.4	-0.4
49324.61	0.70	0.4	0.4
49429.32	0.88	1.9	-0.1
49431.33	0.88	2.6	0.5
49643.70	1.23	1.5	0.4
49784.35	1.46	-0.3	-0.1
50125.44	2.02	15.5	0.0
50127.41	2.03	14.6	0.4
50193.31	2.14	3.1	0.3
50420.60	2.51	-0.3	-0.1
50477.54	2.60	-0.5	-0.3
50740.71	3.04	10.7	-0.2
50745.68	3.05	8.4	-0.8
50834.47	3.19	1.3	-0.3
51107.70	3.64	-0.5	-0.3
51185.51	3.77	0.7	0.3
51573.44	4.41	-0.1	-0.1
51957.40	5.04	10.1	0.4
53087.31	6.91	3.0	-0.2
53343.62	7.33	0.7	0.4
53704.63	7.92	4.9	0.7
53725.78	7.96	8.2 ^{ESO}	-0.4
53740.75	7.98	18.3 ^{ESO}	0.2
53746.48	7.99	24.4	-0.2
53747.51	8.00	25.6	0.0

to our other programme devoted to the study of such objects. But Houk & Smith-Moore (1988) and Ginestet, Carquillat & Jaschek (1999) classified this star as a peculiar, metallic-lined object. Houk & Smith-Moore's classification, Fm- δ Del, seems realistic because it is in agreement with both the colour index $B - V = 0.41$ (ESA 1997) and the ab-

solute magnitude $M_V = 1.7 \pm 0.3$ deduced from $V = 7.34$ and $\pi = 7.50 \pm 0.99$ (ESA 1997). Indeed, according to Schmidt-Kaler (1982), a visual absolute magnitude of 1.7 is consistent with an evolved (class III) early F-type star, a feature that characterizes the members of the δ Del family. Strömgren H_β photometry is available with $\beta = 2.72$ (Hauck & Mermilliod 1998), which indicates a temperature

Table 5 Radial velocities and ($O - C$) residuals for HD 133189.

Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O - C)$ km s^{-1}
47966.70	-0.52	-4.2	0.3
47969.57	-0.52	-5.0	-0.5
48673.69	-0.33	-7.5	0.3
49141.46	-0.20	-8.1	-0.2
49427.60	-0.13	-6.8	-0.3
49783.68	-0.03	-2.8	0.3
50126.71	0.06	0.1	-0.1
50192.59	0.08	0.8	0.2
50325.32	0.11	0.8	-0.4
50477.70	0.16	1.1	-0.3
50611.46	0.19	1.7	0.4
50836.75	0.25	1.2	0.6
50974.49	0.29	-0.4	-0.3
51186.74	0.35	-1.7	-0.4
51320.52	0.38	-1.9	0.3
51590.70	0.45	-3.8	0.1
52821.38	0.79	-8.0	0.0
53087.60	0.86	-6.8	0.1

Table 6 Radial velocities and ($O - C$) residuals for HD 162262.

Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O - C)$ km s^{-1}
46227.46	-0.11	-1.6	-0.4
46228.49	-0.10	-0.2	0.6
46229.55	-0.10	0.1	0.6
46297.37	0.24	-28.8	-0.1
46299.40	0.25	-29.1	-0.4
46334.29	0.42	-25.2	0.4
47604.70	6.76	-10.2	0.5
47609.68	6.79	-10.6	-1.6
47967.69	8.57	-20.7	-0.2
48128.35	9.38	-26.6	0.2
48133.31	9.40	-25.1	1.1
49143.54	14.44	-25.5	-0.4
49641.28	16.92	0.4	-0.3
49782.71	17.63	-17.9	0.2
49786.70	17.65	-16.8	0.3
49808.64	17.76	-10.8	0.1
50126.73	19.35	-28.1	-0.7
50193.61	19.68	-15.9	-0.3
50325.35	20.34	-27.7	-0.1
50329.44	20.36	-27.5	-0.3
50420.23	20.81	-7.3	0.0
50478.72	21.10	-23.4	0.0
50614.55	21.78	-9.7	-0.2
50739.25	22.40	-26.3	-0.2
50974.50	23.58	-20.8	-0.5
51105.28	24.23	-28.6	0.1
51108.27	24.24	-28.3	0.4
51256.66	24.99	-3.0	-0.9
51686.49	27.13	-25.0	0.8
52820.55	32.79	-9.9	-1.0
52824.41	32.81	-6.4	1.1
53089.64	34.13	-26.0	-0.1
53258.37	34.97	-0.2	0.4
53260.29	34.98	-0.9	0.9
53262.28	34.99	-3.6	-0.3
53305.23	35.21	-29.2 <i>Camb</i>	-0.6
53314.23	35.25	-29.3 <i>Camb</i>	-0.6
53479.64	36.08	-19.5 <i>Camb</i>	0.6
53498.59	36.17	-27.6 <i>Camb</i>	0.3
53522.55	36.29	-28.5 <i>Camb</i>	-0.1
53568.47	36.52	-22.2 <i>Camb</i>	0.3
53573.47	36.55	-21.3 <i>Camb</i>	0.3
53583.39	36.60	-18.7 <i>Camb</i>	0.9
53604.39	36.70	-14.2 <i>Camb</i>	0.3
53610.41	36.73	-12.7 <i>Camb</i>	0.1
53637.31	36.86	-3.5 <i>Camb</i>	-0.4
53669.26	37.02	-9.1 <i>Camb</i>	0.4
53671.25	37.03	-12.0 <i>Camb</i>	-0.3
53673.25	37.04	-13.7 <i>Camb</i>	0.1
53675.24	37.05	-16.6 <i>Camb</i>	-0.8

$T_{\text{eff}} \approx 7000$ K (from the grids of Moon & Dworetzky 1985). Using those values of T_{eff} and M_V , we plotted this star on the theoretical HR diagram of Schaller et al. (1992) and derived an estimate of its mass: $\mathfrak{M}_1 \approx 1.8 \mathfrak{M}_{\odot}$.

3.1.4 HD 133189 (BD +15° 2810)

Like HD 31855 and HD 60092, this object initially belonged to our observing programme of composite-spectrum stars, because its was reported in Hynek (1938)’s list with the spectral type F2 (from the HD Catalogue) and the mention “suspected spectrum binary”. We tentatively classified this star as F4 V (Ginestet et al. 1997) from a near infrared spectrum taken at OHP that did not reveal any composite spectrum. Nassau & MacRae (1955) give the spectral type of F2 III from low-resolution objective-prism spectra. This star was unfortunately not observed by Hipparcos and so we cannot test its luminosity class. The value of the colour index $B - V = 0.42$ favours our classification as F4. Thus, we will assume $\mathfrak{M}_1 \approx 1.5 \mathfrak{M}_{\odot}$, corresponding to a main-sequence star of this spectral type (Schmidt-Kaler 1982).

3.1.5 HD 162262 (HIP 87284)

This star was mentioned as SB in the Wilson Catalogue (Wilson 1953, hereafter GCRV) on the basis of 5 spectrographic observations from the Lick Observatory (Moore & Paddock 1950). It belongs to the close ($\rho \approx 0.5''$, $\Delta m_V = 0.75$) visual binary ADS 10822 AB (CCDM 17501+0214AB) which is now found to be a triple system. The spectral type quoted in the SIMBAD data base, F5 V, comes from Moore & Paddock (1950), which implies that $\mathfrak{M}_1 \approx 1.4 \mathfrak{M}_{\odot}$ according to Schmidt-Kaler (1982).

3.1.6 HD 203522 (HIP 105548)

The SB nature of this star, mentioned in the GCRV, was first discovered at the Crimean Astrophysical Observatory (Albitzky 1948). Two different classifications are proposed in the literature: Fm (Abt, Brodzik & Schaefer 1979) and composite A+G (Harlan 1974). To decide between those two possibilities, we obtained a photographic spectrum (dispersion of 40 Å/mm) with our BS Cass spectrograph mounted at the Cassegrain focus of the 80-cm telescope at OHP. Using our

Table 7 Radial velocities and ($O - C$) residuals for HD 203522.

Date (JD) 2400000+	Cycle	RV km s ⁻¹	($O - C$) km s ⁻¹
28782.38	-32.09	-19.0	0.3
28800.36	-32.06	-23.3	-0.9
29082.51	-31.51	6.9	0.7
44859.41	-0.82	-15.0	-0.4
44864.46	-0.81	-13.2	0.4
44865.45	-0.81	-13.1	0.3
45596.49	0.61	5.6	0.3
45599.43	0.62	5.5	0.4
47100.31	3.54	5.7	-0.8
47462.29	4.24	-8.2	0.0
47464.37	4.25	-7.9	-0.1
50615.63	10.38	2.0	-0.1
50741.34	10.62	5.1	0.1
50976.63	11.08	-23.5	0.2
51105.34	11.33	-1.3	-0.4
51106.32	11.33	-1.1	-0.3
51109.32	11.34	-0.4	-0.1
52820.58	14.66	2.7	-0.5
53259.36	15.52	6.1	-0.4
53261.40	15.52	7.2	0.7
53345.20	15.68	1.8	-0.2
53626.50	16.23	-8.8	0.4
53628.40	16.24	-8.7	0.1
53703.27	16.38	3.2	0.8
53706.22	16.39	1.9	-0.8
53748.23	16.47	6.5	0.7
53998.42	16.96	-23.1 <i>Camb</i>	0.3
54033.40	17.02	-25.8 <i>Camb</i>	-0.2
54072.30	17.10	-22.5 <i>Camb</i>	-0.3

Atlas of Stellar Spectra produced with the same instrument (Ginestet et al. 1992), we were able to solve this question: a composite classification of about G8 III + A3 V was retained. Like HD 59643, we can take $\mathfrak{M}_1 \approx 2.5 \mathfrak{M}_\odot$ for the red giant primary.

3.1.7 BD +43° 1331

The discovery of this new SB results of a misidentification (error of target) of BD +43° 1332 that was mentioned as SB in the GCRV. BD +43° 1331 is the primary component of the wide ($\rho \approx 4''$, $\Delta m_V \approx 1$) visual binary ADS 4283 AB (CCDM 05432+4322AB). The spectral type K0 III, quoted in SIMBAD comes from Chuadze (1973). Like HD 59643, we will assume $\mathfrak{M}_1 \approx 2.5 \mathfrak{M}_\odot$ for this red giant.

Note that we have obtained 9 RVs of BD +43° 1332 between 1994 and 1999 but failed in detecting any significant variation. Its RV remained practically constant and equal to 9.6 ± 0.6 km.s⁻¹.

3.2 Minimum masses and separations of companions

Like in the previous papers of the series we now estimate for each binary the minimum mass, $\mathfrak{M}_{2,min}$, of the companion and its mean distance, a , to the primary component. For this purpose, we use the following expressions of the

Table 8 Radial velocities and ($O - C$) residuals for BD +43° 1331.

Date (JD) 2400000+	Cycle	RV km s ⁻¹	($O - C$) km s ⁻¹
46333.65	-0.87	-37.1	-0.3
46336.57	-0.87	-37.0	-0.2
46487.32	-0.80	-35.6	0.2
46722.62	-0.68	-35.8	-0.2
46861.34	-0.61	-35.7	0.1
47098.67	-0.49	-36.8	-0.4
47871.53	-0.11	-43.9	-0.1
48136.65	0.02	-48.6	0.0
48261.58	0.09	-38.0	0.4
49317.62	0.61	-37.3	-0.1
49319.57	0.61	-36.9	0.3
49432.42	0.67	-38.0	-0.2
49642.68	0.77	-39.4	0.1
49783.47	0.84	-41.1	0.3
50125.41	1.01	-52.6	-0.1
50194.36	1.05	-42.1	0.1
50326.67	1.11	-36.6	0.5
50418.67	1.16	-36.7	-0.5
50481.50	1.19	-35.9	-0.1
50746.56	1.32	-35.5	0.1
51106.61	1.50	-36.4	-0.1
51186.43	1.54	-36.6	0.0
53344.49	2.62	-36.8	0.4
53746.45	2.82	-40.5	0.1
53958.62	2.92	-46.5 <i>Camb</i>	-0.1
53986.67	2.94	-48.0 <i>Camb</i>	0.0
54011.71	2.95	-49.7 <i>Camb</i>	0.2
54040.65	2.96	-53.0 <i>Camb</i>	-0.2
54056.64	2.97	-54.6 <i>Camb</i>	0.0
54068.66	2.98	-56.1 <i>Camb</i>	0.0
54078.62	2.98	-57.4 <i>Camb</i>	-0.2
54102.56	2.99	-58.2 <i>Camb</i>	0.2
54114.58	3.00	-57.5 <i>Camb</i>	0.0
54123.42	3.01	-55.9 <i>Camb</i>	0.3
54132.35	3.01	-54.4 <i>Camb</i>	0.1
54146.46	3.02	-52.2 <i>Camb</i>	-0.6
54158.30	3.02	-49.4 <i>Camb</i>	-0.2
54181.36	3.03	-45.1 <i>Camb</i>	0.3
54191.38	3.04	-44.1 <i>Camb</i>	0.0
54200.41	3.04	-43.0 <i>Camb</i>	0.2

mass function and the semi-major axis of the relative orbit:

$$f(m) = \frac{\mathfrak{M}_1 \sin^3 i \mu^3}{(1 + \mu)^2} \quad (1)$$

$$a = a_1 + a_2 = a_1 \sin i (1 + 1/\mu) / \sin i \quad (2)$$

where $\mu = \mathfrak{M}_2/\mathfrak{M}_1$ is the mass-ratio of the two components.

In those equations, we can use the values of \mathfrak{M}_1 estimated in the previous section (Table 10, col. 8) and those of $f(m)$ and $a_1 \sin i$ from Table 9. The minimum values of the masses of the companions ($\mathfrak{M}_{2,min}$ in col. 9 of Table 10) were derived from Eq. (1) when assuming that $i = 90^\circ$. They correspond to stars of type K-M V for the first five systems (HD 31855 to 162262). For HD 203522, $\mathfrak{M}_{2,min} = 1.5 \mathfrak{M}_\odot$ is consistent with the composite nature of the system. A possible combination would be $\mathfrak{M}_2 \approx 2.3 \mathfrak{M}_\odot$, corresponding to the type A3 V (Schmidt-Kaler 1982), $\mu \approx 0.9$

Table 10 Physical parameters derived from observational and theoretical data.

Name HD/BD	V	$B - V$	Spectral type	$v \sin i$ (km.s ⁻¹)	π (mas)	M_V	\mathfrak{M}_1 (\mathfrak{M}_\odot)	$\mathfrak{M}_{2 \min}$ (\mathfrak{M}_\odot)	a (au)	a ($''$)
31855	7.41	0.37	F2-3 V	17.2 ± 1.0	11.95 ± 0.95	2.80 ± 0.17	1.5	0.3	4.8 ± 0.3	0.057 ± 0.008
59643	7.80	2.24	R8-9 - C6,2	5.4 ± 0.5	0.11 ± 1.37	—	2.5	0.6	3.7 ± 0.3	—
60092	7.34	0.41	Fm - δ Del	13.7 ± 1.0	7.50 ± 0.99	1.72 ± 0.29	1.8	0.6	2.0 ± 0.1	0.015 ± 0.003
133189	9.51	0.42	F4 V	13.8 ± 1.5	—	—	1.5	0.6	6.4 ± 0.4	—
162262	8.46	0.81	F5 V	6.8 ± 0.6	2.61 ± 2.46	0.54 ± 2.05	1.4	0.6	0.9 ± 0.1	—
203522	6.53	0.65	G8 III + A3 V	1.4 ± 0.8	3.75 ± 1.00	-0.60 ± 0.58	2.5	1.5	2.1 ± 0.1	0.008 ± 0.003
+43° 1331	9.06	0.93	K0 III	1.7 ± 0.8	—	—	2.5	1.1	5.0 ± 0.3	—

and finally, via equation (1), $i \approx 48^\circ$. For BD +43° 1331, the minimum mass of the secondary is consistent with a G0 V star.

As for the value of a , we have shown (Carquillat et al. 1982) that the absence of knowledge of i was not a real handicap because the value of a obtained in this way is not very sensitive to the (arbitrary) value assigned to i . The values of a given in col. 10 of Table 10) are the average of the two extreme values corresponding to the range $20^\circ < i < 90^\circ$, of 94 % likelihood. Note that this range was sometimes reduced by the constraint $\mu \leq 1$.

The expected angular separations a'' (col. 11 of Table 10) could be estimated only for the three systems that have significant parallaxes, namely HD 31855, 60092 and 203522. The system HD 31855 has the largest angular expected separation ($a = 0.057''$), but it is likely that the secondary is too faint to be detected by speckle interferometry.

3.3 Rotation-revolution synchronism

In this section we test the occurrence of rotation-revolution synchronism, or pseudo-synchronism, among the studied systems. This phenomenon caused by tidal effects was first thought to affect only close systems with circular orbits. But Hut (1981) demonstrated that it is also efficient near the periastron passage for binaries having an eccentric orbit, and generally precedes the state of circularization of the orbit. In the case of a circular orbit, the basic equation of synchronism is: $R = vP$, where R is the radius of the star, v its equatorial velocity and P the orbital period. With the usual unities: R in solar radii, v in km.s⁻¹ and P in days, this relation becomes:

$$R = vP/50.6 \tag{3}$$

In fact we do not know v but only the quantity $v \sin i$ (Table 9, col 5), an observable which may be deduced from the profile of the correlation dips given by CORAVEL (Benz &

Mayor 1981). Thus we can write the equation (3) under the form: $R = Pv \sin i / (50.6 \sin i)$, or, because i is generally unknown:

$$R \geq Pv \sin i / 50.6 \tag{4}$$

This inequality constitutes the so-called Kitamura & Kondo (1978) test. Indeed, if the expected radius of the component of a binary system verifies (4), it may be synchronized. If it does not, the star rotates too fast for synchronism. In the case of an eccentric orbit, we can also use the test (4), by replacing P by the period of pseudo-synchronism, P_{ps} , corresponding to a state of pseudo-equilibrium reached before the orbit is circularized. The value of P_{ps} is a function of P and e (see Hut (1981) or Paper X, Eq. (2) therein). Note that P_{ps} is always smaller than P . Indeed for HD 31855, 59643, 60092, 133189, 162262, 203522 and BD +43° 1331, the periods of pseudo-synchronism are 808, 1087, 51, 3324, 97, 457 and 291 days, respectively. Those values associated with the $v \sin i$ values quoted in col. 5 of Table 10 and the theoretical values of R tabulated by Drilling & Landolt (1999) for dwarf and red giant stars led to only two positive tests for HD 203522 and BD +43° 1331. For those stars we obtained $R \geq 12.6R_\odot$ and $R \geq 9.8R_\odot$ respectively, which is verified for those two G8-K0 red giants, for which the expected radius is about $15 R_\odot$. Therefore, it is likely that those stars have reached the pseudo-synchronism state. Notice that those two stars have the largest mass functions of the seven studied SBs (see Table 9) which may indicate that they have the most massive companions, which could account for a higher efficiency of the tidal effects.

4 Synopsis of our study of F-G-K-M SBs

In Table 11 we list all the F-G-K-M SBs we have studied for this programme, with their spectral type in col. 2, their orbital elements in cols. 3 to 10 and the bibliographical references of the orbits in col. 11. Most of the orbits were published in this series of papers (see Table 1),

Table 12 Distribution in spectral types and luminosity classes of the primary stars of our whole sample.

Luminosity class	Spectral type				
	F	G	K	M	C
V	11	4	—	—	—
IV	4	—	—	—	—
III	1	4	4	4	1
II-III	—	—	1	—	—
Total	16	8	5	4	1

but we also included five stars that were studied by our team before we started this series (HD 4676, 22403, 92168, 160861 and 166181) and three others whose study was published in collaboration in another context (HD 7351, 191226 and 206058). This leads to a total of 34 F-G-K-M stars, from which 7 were detected as SB2s and 27 as SB1s by CORAVEL. HD 191588 was found to be a triple spectroscopic system (see Paper IX).

The distribution of the spectral types and luminosity classes of the primary components is given in Table 12. The number of the SBs with cool primaries that we have found decreases with the spectral type for the dwarf stars: this is an instrumental effect caused by the corresponding decrease in luminosity of those stars. For the giants, the distribution is rather uniform according to the spectral type, which may suggest that the formation of binaries is not influenced by the temperature of the stars.

The diagram e versus P plotted in Fig. 2 is similar to the diagrams derived for other samples of binaries, for instance the solar-type binaries in the solar neighbourhood studied by Duquennoy & Mayor (1991). The general distribution is explained by the influence of gravitational tidal effects that tend to circularize the orbits. The cut-off between the domains of circular (or quasi-circular) and eccentric orbits seems to be located at about $P \approx 10$ days, which is similar to the value obtained by Duquennoy & Mayor.

Fig. 3 shows that the of the logarithm of the periods of the systems of our sample is rather uniform, over a very large range, from a few days to about 13 years.

5 Conclusion

This paper concludes our study of late-type SBs. We have monitored and studied in detail 34 objects with types F-G-K-M and luminosity classes between II and V. Our work has reached its initial goal and contributed to fill the deficit of cool stars in the distribution of the number of SBs of known orbit vs spectral type, stated in the 1970's. Our RV monitoring of more than three decades has allowed us to derive accurate orbital elements, even for binaries with long periods. Those elements associated to other observational data have allowed us to precise the nature of the primaries and of some of their companions. We also studied the occurrence

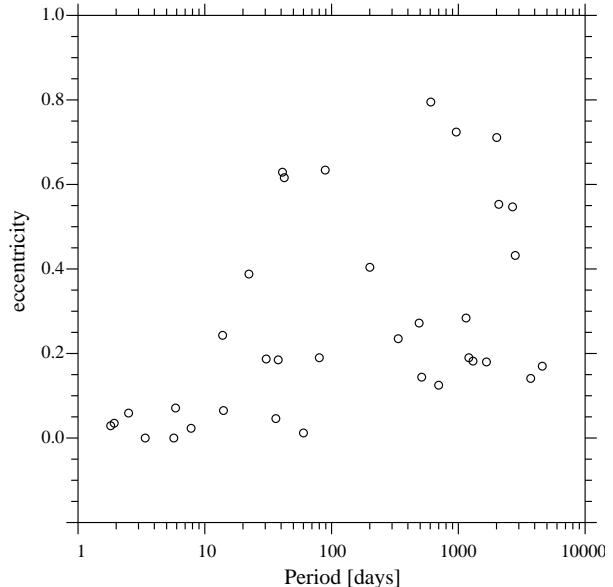


Fig. 2 Diagram e vs $\log P$ of the F-G-K-M stars of our sample.

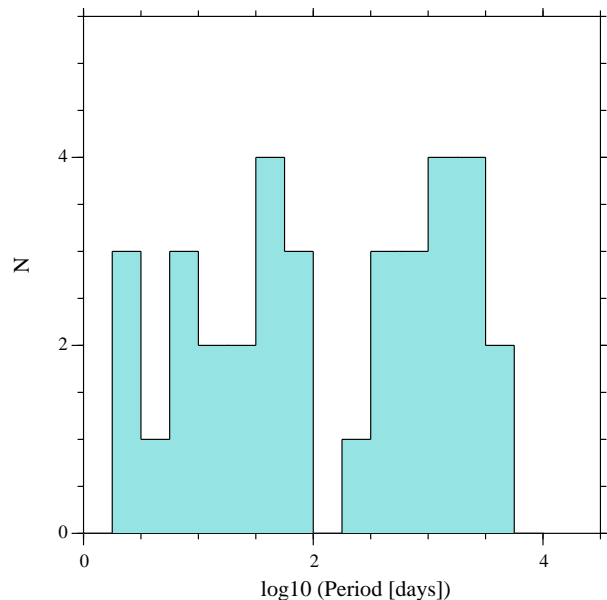


Fig. 3 Distribution of the periods of the F-G-K-M stars of our sample.

of spin-orbit synchronization for most of the primary stars of this sample.

Although this sample is rather small, which makes difficult to derive statistical conclusions, it seems that our observations do not support the initial idea of a real deficit of cool stars among SBs.

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We are indebted to M. Mayor (Geneva Observatory) for giving us observing time with CORAVEL at OHP, and to S. Udry for the reduction of our observations until 1999. We thank R. Griffin for his kind help for observing for us some stars of this programme with

Table 11 Synopsis of the orbital elements published for all binaries of the programme. In col. 1, for HD 191588, s=short-period system, l=long-period system. In col. 4, T_0 is the periastron passage for the eccentric orbits or the ascending node for circular orbits.

Name HD/BD	Spectral type	P (days)	T_0 2400000+ (JD)	ω (deg.)	e	K_1 K_2 (km s ⁻¹)	V_0 (km s ⁻¹)	$a_1 \sin i$ $a_2 \sin i$ (Gm)	$f(m)$ or $\mathfrak{M}_{1/2} \sin^3 i$ (\mathfrak{M}_\odot)	References Notes
4676	F8 V	13.824581	41934.202	199.6	0.243	57.53 58.77	4.06	10.61 10.84	1.041 1.019	Nadal et al. 1979 64 Psc. SB2
7351	M3 III S	4593.	44696.	104.3	0.17	5.43	1.55	337.5	0.073	Carquillat et al. 1998
22403	G2 V	1.9299395	41926.590	266.0	0.035	77.8	-19.4	2.064	0.0943	Carquillat et al. 1979
23838	G7 III	962.8	42288.1	108.8	0.724	20.2	18.4	184.4	0.270	Paper IV
26659	G8 IIIb	699.30	45469.4	134.5	0.125	4.45	-26.81	42.5	0.0063	Paper XI
31855	F2-3 V	2678.	46570.	277.5	0.547	3.43	15.04	105.8	0.0066	This paper
37171	K5 II-III	1150.69	46337.1	236.8	0.284	7.61	-115.27	115.4	0.0464	Paper XI
47415	F8 IV	5.698292	42494.271	—	0.0	43.9 52.3	30.2	3.44 4.10	0.287 0.240	Paper I SB2
54901	F2-3 IV	41.00285	47709.105	349.0	0.629	44.62 58.47	-9.82	19.56 25.64	1.245 0.950	Paper X SB2
59643	C (R8)	1304.8	46207.	327.5	0.182	5.96	45.71	105.1	0.0272	This paper
60092	Fm	606.61	48897.5	355.9	0.795	13.70	2.60	69.4	0.0363	This paper
69148	G8 III	80.06533	42573.79	185.1	0.19	22.7	-3.3	27.3	0.103	Paper II
79968	G4 V	30.50253	48008.696	65.8	0.187	40.27 45.34	25.34	16.6 18.7	0.998 0.886	Paper VI SB2
85091	G0 V	3.3901472	44685.227	—	0.0	33.6	41.5	1.57	0.013	Paper II
92168	F8 V	7.7991499	20165.164	285.6	0.023	24.10	6.05	2.585	0.01134	Ginestet et al. 1974
102928	K0 III	490.765	51667.7	126.4	0.272	13.60	14.12	88.35	0.114	Imbert & Carquillat 2005
120544	F6 IV	89.1477	45025.31	175.3	0.634	17.57	-30.35	16.65	0.0232	Paper X
123280	F6 V	36.35588	45015.91	88.5	0.046	17.68	3.15	8.831	0.0208	Paper X
126947	M3 III	2812.3	47781.2	181.6	0.432	5.96	19.85	207.8	0.0453	Paper XI
133189	F4 V	3722.	49899.	288.3	0.141	4.82	-3.59	244.1	0.0419	This paper
145206	K4 III	2084.8	42980.9	2.1	0.553	11.54	-47.69	275.7	0.193	Paper III
147395	M2 III	335.537	48335.0	336.9	0.235	16.87	-20.12	75.67	0.154	Paper VII
160861	F5 V	2.50574	42280.70	33.6	0.059	44.99	-15.83	1.548	0.0236	Carquillat et al. 1976
162262	F5 V	200.407	46249.47	51.1	0.404	14.86	-17.64	37.47	0.0523	This paper
166181	G5 V	1.8098368	41931.127	218.5	0.029	54.6	-13.4	1.359	0.0306	Nadal et al. 1974
189578	F5 V	14.0420	45596.4	6.6	0.065	41.6	4.3	8.01	0.104	Paper V
191226	M2 III S	1210.4	48481.	207.4	0.19	4.76	-25.05	77.76	0.0128	Carquillat et al. 1998
191588 s	K2.5 III	60.0269	50482.6	233.	0.012	24.03	var.	19.83	0.0865	Paper IX
191588 l		1667.	50901.	228.	0.18	2.51	2.09	56.7	0.0026	Sp. triple system
195850	F5 V	37.94106	44872.24	111.5	0.185	34.15 44.72	0.75	17.51 22.93	1.04 0.79	Paper VIII SB2
201193	F6 V	22.299540	48137.004	144.7	0.388	54.15 54.77	-13.01	15.31 15.48	1.179 1.165	Paper VIII SB2
203522	G8 III	514.109	45281.7	171.4	0.144	16.04	-7.26	112.2	0.2134	This paper
206058	F7 V	5.883933	46989.08	286.	0.071	14.60	-15.86	1.178	0.00188	Griffin et al. 1996
210763	F5 IV	42.38113	42452.09	294.7	0.616	49.5 62.1	13.7	22.7 28.5	1.66 1.32	Paper I SB2
+43°1331	K0 III	2008.23	48088.7	200.8	0.711	11.41	-39.39	221.6	0.1078	This paper

its own CORAVEL instrument at Cambridge Observatories. We thank also M. Imbert, B. Pernier and S. Udry for some occasional RV measures made at OHP and ESO, to our request, and again M. Imbert for reducing at *Observatoire de Marseille* our observations made after 2000. For bibliographical references, this work made use of the SIMBAD data base operated by the *Centre de Données Astronomiques de Strasbourg* (France).

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