Contribution to the study of binaries with spectral types F, G, K, and M – XI. Orbital elements of three red-giant spectroscopic binaries: HR 1304, HR 1908, and HD 126947

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Contribution to the study of F-G-K-M binaries. XI. Orbital elements of three red-giant spectroscopic binaries: HR 1304, HR 1908 and HD 126947.

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The orbital elements of three red-giant single-lined spectroscopic binaries, HR 1304, HR 1908 and HD 126947, 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. HR 1304 and HR 1908 are known to be chromospherically active stars and to have high spatial velocities; HD 126947 is an intrinsic variable newly detected by Hipparcos. The three systems have long orbital periods: 1.9, 3.2 and 7.7 yr for HR 1304, HR 1908 and HD 126947, respectively. From the orbital elements that we determined and other data available in the literature, we deduce some information about the unseen companions and their separations with respect to the primaries. Finally we discuss the rotation–revolution synchronism and conclude that one star, HR 1908, may have reached the state of pseudo-synchronism, despite its long orbital period.

1 Introduction

This paper is the eleventh of a series (Nadal et al., Paper I) devoted to the study of late-type stars suspected to be spectroscopic binaries (SB), in order to determine their orbital elements. Indeed, when the Toulouse team started this observing program, the statistics showed a relative lack of SBs with known orbits among the cooler stars (Carquillat, Ginestet & Pédoussaut 1971). Through this series of papers, we have contributed to filling that gap and published the orbits of 16 systems whose primary stars have spectral types in the range F–G–K–M. In our last paper (Carquillat et al. 2005, Paper X), we presented a study of three nearby F-type stars. We now report the results of a new investigation about three red giant stars: HR 1304 = HD 26659 (G8 IIIb), HR 1908 = HD 37171 (K5 II–III) and HD 126947 (M3 III). Those systems appeared to us as single-lined only: the companions were not detected spectroscopically.

HR 1908 and HD 126947 were previously reported as spectroscopic binaries in the *General Catalogue of Stellar Radial Velocities* (Wilson 1953). In fact each of those two stars was recognized as a SB at the Mount Wilson Observatory from 4 plates which showed their radial velocities to be variable (Wilson & Joy 1950). As for HR 1304, that star was listed by Glebocki, Musielak & Stawikowski (1980) in their *Catalogue of Stars with CaII H and K Emissions*; such objects are frequently involved in binary systems.

The determination of spectroscopic orbits with long orbital periods such as those presented here (1.9, 3.2 and 7.7 yr for HR 1304, HR 1908 and HD 126947, respectively) requires a monitoring over a long period of time. Indeed the observations concerned in this study were made from 1982 to 2005, with the CORAVEL spectrometer of the Observatoire de Haute-Provence (OHP) and with a similar instrument at the Cambridge Observatories. In Sect. 2, we present those observations and the orbital elements of the spectroscopic orbits that we computed for the first time (to our knowledge) for those three single-lined binaries. In Sect. 3, we attempt to characterize the intrinsic parameters of the stellar components. Finally, in Sect. 4, we discuss the possibility of (pseudo-)synchronism of the axial rotations of the primary stars with the orbital motions in those binary systems.

2 Observations and derivation of the orbital elements

The observations used for this work were started in the 1980s with the CORAVEL spectrometer mounted at the Cassegrain focus of the 1-m Swiss telescope at OHP. Since 1999, complementary observations were also made with a similar instrument, *'the Cambridge CORAVEL'* operating at the coudé focus of the 36-inch reflector of the Cambridge Observatories. Let us recall that those CORAVEL instruments are spectrophotometers that allow measurements of heliocentric radial velocities (hereafter RVs) by performing a cross-correlation of the stellar spectrum with a physical mask placed in the focal plane of the spectrograph (Baranne, Mayor & Poncet 1979).

For the present study, we used additional RV measurements from Beavers & Eitter (1986), obtained at the Fick Observatory with another photoelectric radial-velocity spectrometer. Those measurements appeared to be less pre-

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cise than the CORAVEL observations, and have consequently been attributed appropriately reduced weights in the orbit computations (see below).

Finally we also made use of unpublished observations of HR 1304 and HR 1908 by de Medeiros & Mayor (1999) obtained with the CORAVEL at OHP.

All the RVs were reduced to the RV data base system of the Geneva Observatory (Udry, Mayor & Queloz 1999). For that purpose, an offset of -0.8 km s^{-1} was applied to the RVs from the Cambridge CORAVEL. Likewise, an offset of $+0.8$ km s^{-1} was made to the RVs of Fick Observatory.

The mean internal standard errors of the CORAVEL RVs are similar for the three stars we studied here, about 0.3 km s^{-1}. The orbital elements were determined with our program BS1 based on an iterative scheme of Gauss–Newton type that performs a least-square minimization of the residuals, starting from an initial guess of the orbital parameters. The whole procedure is fully automatic, from the search of the initial value of the period to the determination of the final elements.

For HR 1304 we used 37 RVs from the CORAVEL instruments (weight 1) and one from Beavers & Eitter (weight 0.1), listed in Table 1. For HR 1908 (Table 2), 52 RVs were obtained with the CORAVEL instruments (weight 1) and we added 12 RVs from Beavers & Eitter that we weighted as follows: 0.1 for measures of quality "A", 0.05 for quality "B", and 0.02 for quality "C". The orbital elements of HD 126947 were computed from 70 RVs from the CORAVEL instruments only (Table 3). In Tables 1, 2 and 3, the RVs from Cambridge are labeled with ^{Camb}, those from Fick Observatory with ^{Fick}, and those from de Medeiros & Mayor with ^{dMM}. The other measurements were obtained by us with the OHP CORAVEL.

The orbital elements are given in Table 4, and the corresponding computed radial-velocity curves are displayed in Fig 1. For red giants, especially among the later types, it is not unusual for envelope pulsation or atmospheric motions to induce 'jitter' in the RVs (Carquillat et al. 1998, Jorissen et al. 1998). Such phenomena are probably responsible for the big scatter of the measurements around the computed RV curve of HD 126947 and also, with a minor intensity (for CORAVEL observations), around the curve of HR 1908. Indeed, for HR 1908 and HD 126947, the $\sigma_{(O-C)}$ of the residuals are 0.56 and 0.76 km s^{-1}, which is larger than would be expected from the internally estimated standard errors of the RVs (i.e., ~ 0.3 km s^{-1} for CORAVEL measurements).

3 Discussion

3.1 HR 1304 (HIP 20982)

3.1.1 Intrinsic parameters of the primary

The *Hipparcos–Tycho Catalogue* (ESA 1997) gives for the system: $V = 5.47$, $B - V = 0.855$, and the parallax $\pi = 10.74 \pm 0.54$ mas. Thus HR 1304 is a relatively nearby star with a distance less than 100 pc from the Sun, i.e. $d = 93(-4, +5)$ pc, and an absolute magnitude $M_V = 0.63 \pm 0.12$.

The spectral type given in Simbad is G8 III. It seems that that classification originates from the *Catalogue of High Velocity Stars* of Roman (1955), from slit spectra taken with a prismatic dispersion of 125 Å/mm at H_γ.

HR 1304 was recognized as a star with an active chromosphere by Wilson (1976). Using the correlation that he found between the absolute magnitude and the width of the K emission line, he gave an absolute magnitude $M_V(K) = 1.4 \pm 0.3$ for HR 1304.

That value appears to be somewhat discordant with $M_V = 0.63 \pm 0.12$ deduced from the Hipparcos parallax, but the Hipparcos magnitude is a global one which includes the companion, whereas Wilson's estimation refers to the primary only: $M_V(K) = M_{V1}(K)$. Let us now estimate the possible contribution of the companion. To do so, we can use the fact that the companion was not detected with CORAVEL. The absence of the secondary correlation dip with CORAVEL implies that $\Delta m_V \gtrsim 2$. In that case, the absolute magnitude of the primary as deduced from the Hipparcos catalogue would then be such that: $0.6 \lesssim M_{V1} \lesssim 0.8$, which is still in disagreement with Wilson's determination. It should be noted that the graph $(m_V - M_V(K))$ versus π, provided by Wilson (Fig 1 of his paper), shows a rather large scatter of the observations with respect to the mean relationship, so the discrepancy that we find between $M_{V1}(K)$ and $M_{V1}(\pi)$ for HR 1304 is not very surprising.

The absolute magnitude of HR 1304 obtained from the Hipparcos parallax, $M_V \sim 0.6$–0.7, is consistent with a luminosity class IIIb (Keenan & Barnbaum 1999). Its colour-index, $B - V = 0.855$, or $B - V = 0.87$ (Roman 1955) is consistent with a G8 type, although unusually small for a star of that type.

3.1.2 Minimum mass and separation of the companion

Writing the mass-function: $f(m) = M_1 \times \sin^3 i \times \mu^3/(1+\mu)^2$, where $\mu = M_2/M_1$ is the mass-ratio in the system, we can calculate the minimum mass of the secondary from the value of M_1 as deduced from the evolutionary status of the primary. We shall first assume that the contribution of the secondary to the global photometry of the system is negligible. Using the tables of Flower (1996) giving $\log T$ and BC versus $(B - V)$, and the theoretical H–R diagram of Schaller et al. (1992) for solar metallicity, we obtain an estimate of the mass of the primary: $M_1 = 2.5 \pm 0.5$ M$_\odot$. From the mass function given by our orbit, that value of M_1 leads to $M_{2\,\min} = 0.37 \pm 0.05$ M$_\odot$, which corresponds to the mass of a dwarf M star (Schmidt-Kaler 1982). Thus it is likely that the companion is a very faint star, several magnitudes fainter than the giant primary. That largely justifies our initial assumption that the contribution of the secondary to the global photometry of the system is negligible.

Table 1 Radial velocities and $(O-C)$ residuals for HR 1304.

Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}	Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}
43800.86	−2.39	-23.7^{Fick}	−0.8	51136.51	8.10	−31.8	−0.2
44982.41	−0.70	−28.3	−0.1	51185.42	8.17	−31.0	0.0
45032.27	−0.62	-26.3^{dMM}	0.2	51573.29	8.73	−23.2	−0.1
45339.41	−0.19	−25.1	−0.5	52647.38	10.27	-29.0^{Camb}	0.2
45344.35	−0.18	−24.2	0.5	52684.39	10.32	-28.0^{Camb}	−0.1
45377.27	−0.13	-25.7^{dMM}	0.4	52713.38	10.36	-26.9^{Camb}	0.0
45600.61	0.19	−30.8	0.0	52745.34	10.41	-25.7^{Camb}	0.2
46008.66	0.77	−23.8	−0.1	52882.56	10.60	-22.7^{Camb}	0.2
46127.31	0.94	-28.7^{dMM}	−0.2	52906.65	10.64	-22.5^{Camb}	0.3
46337.61	1.24	−30.1	−0.4	52946.64	10.69	-22.6^{Camb}	0.2
46755.54	1.84	-25.3^{dMM}	−0.1	53010.36	10.78	−24.1	−0.2
47069.60	2.29	-28.5^{dMM}	0.1	53021.51	10.80	-24.0^{Camb}	0.2
47464.57	2.85	−25.9	−0.3	53044.40	10.83	-25.0^{Camb}	0.0
47871.48	3.44	−25.5	−0.3	53078.36	10.88	-26.4^{Camb}	0.1
48266.41	4.00	−30.4	−0.1	53088.31	10.90	−26.8	0.1
48675.32	4.58	−22.9	0.2	53109.33	10.93	-27.9^{Camb}	0.1
49321.49	5.51	−24.2	−0.2	53258.65	11.14	−31.4	0.1
50834.34	7.67	−23.2	−0.4	53258.57	11.14	-31.1^{Camb}	0.4
51106.53	8.06	−31.5	−0.1	53339.41	11.25	−29.5	−0.1

Table 2 Radial velocities and $(O-C)$ residuals for HR 1908.

Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}	Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}
43510.76	−2.46	-114.1^{Fick}	−0.7	50480.44	3.60	−115.3	−0.4
43531.64	−2.44	-116.4^{Fick}	−2.6	50739.62	3.83	−122.6	−0.2
43563.57	−2.41	-114.6^{Fick}	0.0	50803.54	3.88	−123.8	0.0
43826.85	−2.18	-125.8^{Fick}	−3.6	50834.42	3.91	−123.9	0.2
43947.58	−2.08	-125.0^{Fick}	−1.0	51106.60	4.14	−110.8	−0.2
44967.72	−1.19	-121.5^{Fick}	0.4	51186.42	4.21	−108.9	0.2
45006.63	−1.16	-121.5^{Fick}	1.4	52547.69	5.40	-109.7^{Camb}	0.5
45021.65	−1.14	-124.6^{Fick}	−1.3	52619.63	5.46	-111.2^{Camb}	0.2
45312.79	−0.89	-111.0^{Fick}	1.2	52649.55	5.49	-112.4^{Camb}	−0.4
45346.67	−0.86	-110.1^{Fick}	0.7	52690.41	5.52	-113.6^{Camb}	−0.8
45737.64	−0.52	-109.3^{Fick}	2.5	52715.38	5.54	-114.3^{Camb}	−1.0
45751.60	−0.51	-109.3^{Fick}	2.8	52900.70	5.70	-117.7^{Camb}	0.5
46336.64	0.00	−120.6	0.0	52924.68	5.72	-118.4^{Camb}	0.5
46337.65	0.00	−120.2	0.4	52956.63	5.75	-119.4^{Camb}	0.5
46486.33	0.13	−111.7	−0.5	52979.52	5.77	-120.3^{Camb}	0.3
46753.63	0.36	-108.3^{dMM}	1.4	53010.53	5.80	−121.1	0.4
46865.29	0.46	−112.3	−0.9	53013.53	5.80	-121.3^{Camb}	0.3
47098.67	0.66	−116.4	0.4	53044.45	5.83	-123.0^{Camb}	−0.5
47101.56	0.66	−116.1	0.7	53078.37	5.86	-124.2^{Camb}	−0.9
47120.55	0.68	-116.5^{dMM}	0.9	53101.34	5.88	-123.9^{Camb}	−0.1
47459.64	0.98	−121.8	0.4	53258.67	6.02	−119.6	−0.2
47608.28	1.10	−112.5	0.0	53264.70	6.02	-119.8^{Camb}	−0.8
47868.50	1.33	−108.5	0.8	53300.70	6.05	-116.1^{Camb}	0.3
47969.29	1.42	−110.0	0.6	53322.68	6.07	-114.3^{Camb}	0.5
48135.67	1.56	−114.7	−0.8	53339.48	6.09	−113.6	0.2
48261.46	1.67	−117.4	−0.3	53357.60	6.10	-112.5^{Camb}	0.3
48265.45	1.68	−117.8	−0.6	53375.50	6.12	-111.5^{Camb}	0.4
48673.30	2.03	−118.5	−0.3	53445.30	6.18	−110.1	−0.4
48938.57	2.26	−109.0	−0.2	53392.53	6.13	-111.0^{Camb}	0.2
48970.53	2.29	−108.9	0.0	53410.42	6.15	-111.0^{Camb}	−0.5
50327.68	3.47	−111.3	0.3	53447.38	6.18	-110.3^{Camb}	−0.7
50415.48	3.54	−114.1	−0.7	53464.34	6.19	-109.4^{Camb}	−0.1

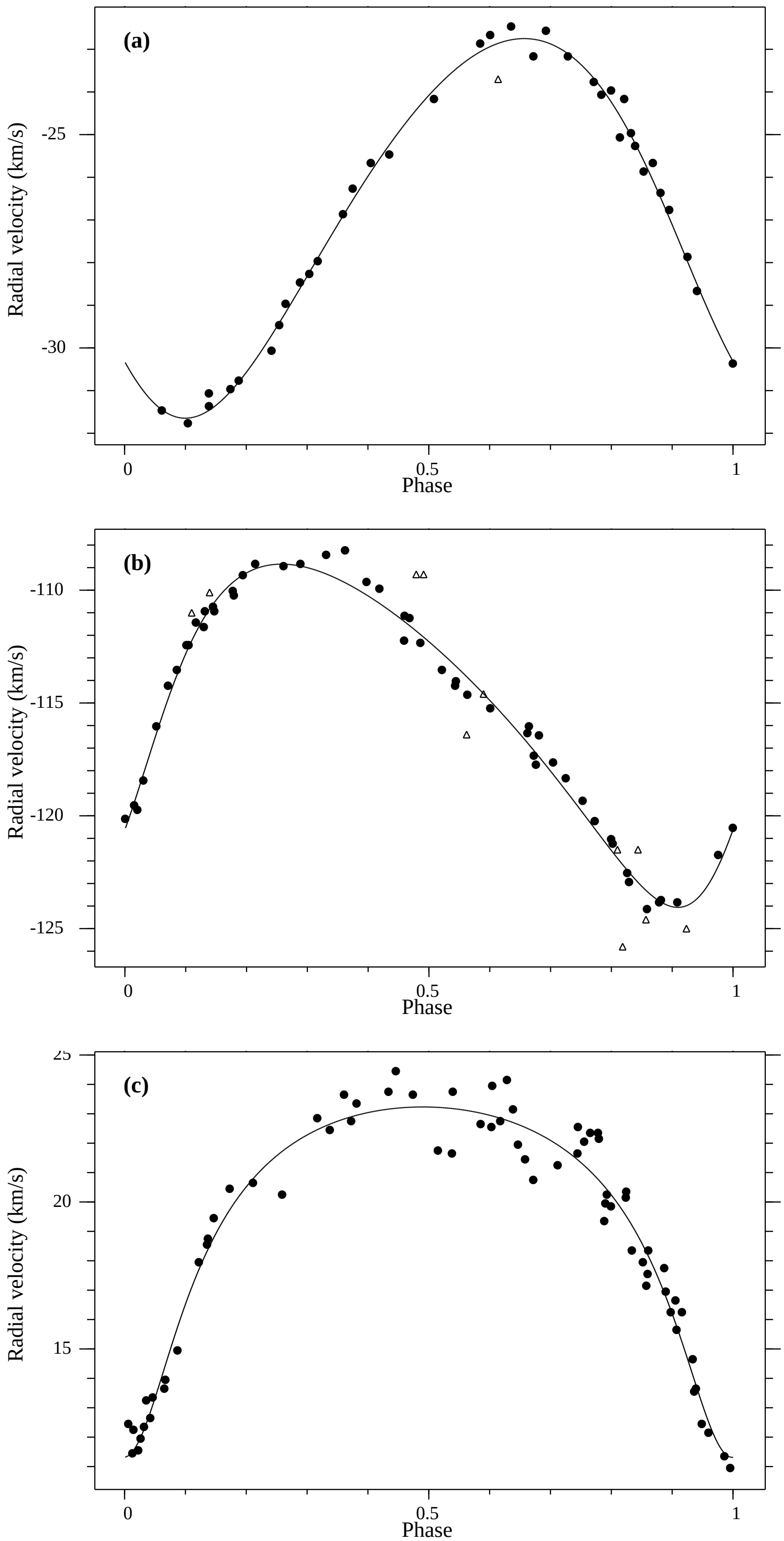

Fig. 1 RV curves computed with the orbital elements of Tables 4: (a) HD 1304, (b) HR 1908, and (c) HD 126947. The origin of the phases corresponds to the periastron passage. The black dots and white triangles correspond to CORAVEL and Fick Observatory measurements, respectively.

Table 3 Radial velocities and $(O-C)$ residuals for HD 126947.

Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}	Date (JD) 2400000+	Cycle	RV km s^{-1}	$(O-C)$ km s^{-1}
46485.64	−0.46	23.7	0.5	51925.78	1.47	23.6^{Camb}	0.4
47285.58	−0.18	20.1	0.6	52041.55	1.51	21.7^{Camb}	−1.5
47287.48	−0.18	20.3	0.8	52106.40	1.54	21.6^{Camb}	−1.6
47601.60	−0.06	13.5	−0.5	52292.74	1.60	23.9^{Camb}	1.0
47609.55	−0.06	13.6	−0.2	52329.67	1.62	22.7^{Camb}	−0.1
47870.72	0.03	12.3	0.0	52360.62	1.63	24.1^{Camb}	1.3
47964.64	0.07	13.6	−0.7	52388.57	1.64	23.1^{Camb}	0.4
47969.58	0.07	13.9	−0.5	52411.54	1.65	21.9^{Camb}	−0.7
48266.75	0.17	20.4	0.7	52444.42	1.66	21.4^{Camb}	−1.1
48671.67	0.32	22.8	0.3	52482.39	1.67	20.7^{Camb}	−1.7
49000.75	0.43	23.7	0.5	52688.69	1.75	22.5^{Camb}	1.1
49034.60	0.45	24.4	1.2	52717.58	1.76	22.0^{Camb}	0.8
49426.66	0.59	22.6	−0.4	52745.57	1.77	22.3^{Camb}	1.3
49476.51	0.60	22.5	−0.4	52781.37	1.78	22.3	1.5
49782.68	0.71	21.2	−0.7	52785.53	1.78	22.1^{Camb}	1.4
49874.54	0.74	21.6	0.2	52810.48	1.79	19.3^{Camb}	−1.2
50125.71	0.83	18.3	−0.9	52815.45	1.79	19.9^{Camb}	−0.6
50176.58	0.85	17.9	−0.6	52822.36	1.79	20.2	−0.2
50192.56	0.86	17.1	−1.2	52841.39	1.80	19.8^{Camb}	−0.5
50198.55	0.86	17.5	−0.7	53013.79	1.86	18.3^{Camb}	0.1
50327.30	0.91	16.6	0.7	53087.58	1.89	17.7	0.8
50479.71	0.96	12.1	−0.4	53094.64	1.89	16.9^{Camb}	0.1
50610.45	1.01	12.4	1.0	53117.62	1.90	16.2^{Camb}	−0.1
50656.38	1.02	11.5	−0.3	53144.53	1.91	15.6^{Camb}	−0.2
50837.70	1.09	14.9	−0.8	53169.48	1.92	16.2^{Camb}	1.0
50936.59	1.12	17.9	0.2	53219.37	1.93	14.6^{Camb}	0.5
50974.43	1.14	18.5	0.2	53261.28	1.95	12.4	−0.8
50978.45	1.14	18.7	0.3	53365.77	1.99	11.3^{Camb}	−0.2
51005.45	1.15	19.4	0.6	53392.75	2.00	10.9^{Camb}	−0.4
51186.74	1.21	20.6	−0.2	53441.70	2.01	11.4^{Camb}	−0.1
51321.38	1.26	20.2	−1.5	53446.58	2.01	12.2	0.7
51541.78	1.34	22.4^{Camb}	−0.2	53479.58	2.03	11.9^{Camb}	−0.1
51607.69	1.36	23.6^{Camb}	0.8	53505.53	2.04	13.2^{Camb}	0.7
51640.60	1.37	22.7^{Camb}	−0.2	53524.41	2.04	12.6	−0.2
51665.52	1.38	23.3^{Camb}	0.4	53535.43	2.05	13.3^{Camb}	0.2

Table 4 Orbital elements of HR 1304, HR 1908 and HD 126947. In Col. 3, T is the epoch of periastron passage.

Name	P days	T (JD) 2400000+	ω deg.	e	K_1 km s^{-1}	V_0 km s^{-1}	$a_1 \sin i$ Gm	$f(m)$ M$_\odot$	$\sigma_{(O-C)}$ km s^{-1}
HR1304	699.30	45469.4	134.5	0.125	4.45	−26.81	42.5	0.0063	0.24
	±0.28	±12.9	±6.7	±0.014	±0.07	±0.05	±0.7	±0.0003	
HR1908	1150.69	46337.1	236.8	0.284	7.61	−115.27	115.4	0.0464	0.56
	±0.97	±10.1	±3.3	±0.017	±0.14	±0.09	±2.9	±0.0034	
HD126947	2812.3	47781.2	181.6	0.432	5.96	+19.85	207.8	0.0453	0.76
	±9.4	±21.9	±3.5	±0.021	±0.15	±0.11	±8.3	±0.0051	

For a given value of the orbital inclination i, and the value of μ derived from the previous relationship, the mean linear separation a of the components can be computed by the relationship: $a = a_1 + a_2 = a_1 \ \sin i \times (1 + 1/\mu)/\sin i$, where $a_1 \sin i$ is estimated from the orbit (Table 4). We have shown (Carquillat et al 1982) that the value of a is then not very sensitive to the assumed value of i, even when i varies over a large range. Assuming the statistically most probable value of $i = 60°$, and taking into account the uncertainties on M_1 and π, we obtain: $a = 2.2 \pm 0.15$ au, or in angular separation $a = 23.6 \pm 2.8$ mas.

With $i = 60°$, we would have $\mu \sim 0.18$ and $a_1 \sim 4.2$ mas, which corresponds to the amplitude of the motion of the primary relative to the center of gravity of the system. This amplitude is not negligible with respect to the parallax as measured by Hipparcos ($\pi = 10.7$ mas) and one can wonder whether the parallax determination was not affected by this motion. In a recent study, Pourbaix & Jorissen (2000) have shown that the Hipparcos parallax determination of binary systems was indeed perturbed by the relative orbital motion for the systems whose orbital periods are close to one year. This effect is negligible for systems with $P > 1.5$ yr (see Fig. 9 of their paper). As the period of

HR 1304 is 1.9 yr, we can trust Hipparcos parallax value. This will also be the case for HR 1908 and HD 126947 which have longer periods (see Table 4).

3.2 HR 1908 (HIP 26386)

3.2.1 Intrinsic parameters of the primary

The *Hipparcos Catalogue* gives $V = 5.97$, $B - V = 1.592$ and $\pi = 3.97 \pm 0.82$ mas. Thus HR 1908 is localized at a distance $d = 252(-43, +65)$ pc from the Sun, and its absolute magnitude is $M_V = -1.04 \pm 0.46$. Moreover the star is quoted in the *Hipparcos Catalogue* (see Vol.11) as an "unsolved variable" with a magnitude variation of small amplitude (0.036 Hp mag.). Two slightly different spectral types are reported in the literature for this star: K4 II (Keenan & Keller 1953) and K5 III (Roman 1955). At its galactic coordinates (194°, −11°), Lucke (1978)'s maps for interstellar reddening imply $E(B - V) = 0.05$, and thus an absorption of ∼0.15 mag. in the V band. Such absorption would reduce the magnitude and colour of the system to $V = 5.82$ and $B - V = 1.54$, and its absolute magnitude to $M_V = -1.19 \pm 0.46$. Like HR 1304, HR 1908 does not show any correlation dip from the secondary star in the CORAVEL traces, and the spectrum is not reported as composite, i.e. with the presence a hot secondary. That implies that $\Delta m_V \gtrsim 2$, and $-1.2 \lesssim M_{V1} \lesssim -1.0$. Those parameters ($M_{V1}$ and $B - V$) are consistent with a classification ∼K5 II–III, i.e. a compromise between the two published spectral types for HR 1908.

Like HR 1304, HR 1908 is a star with an active chromosphere (Wilson 1976, Strassmeier et al. 1993). Notice that the value of M_V quoted by Wilson, $M_V(K) = -0.1 \pm 0.2$, is also in disagreement with the value derived from Hipparcos, in the same sense as we found for the previous star (i.e., its luminosity appears underestimated). Also, like HR 1304, HR 1908 is a star with high spatial velocity (Roman 1955), which is not surprising in view of the value we find for the systemic velocity: $V_0 = -115$ km s^{-1} (see Table 4).

3.2.2 Minimum mass and separation of the companion

A procedure similar to that used for HR 1304 gives us an estimate of the theoretical mass $M_1 = 2.5 \pm 0.7$ M$_\odot$ of the primary K star, which is based upon its evolutionary status according to M_V and $B - V$. Thus, the values of $f(m)$ and $a_1 \sin i$ (Table 4) lead to $M_{2\,\rm min} = 0.80 \pm 0.15$ M$_\odot$, that corresponds to the spectral type K0 V (Schmidt-Kaler 1982), and to an estimate of the separation of components (assuming $i = 60°$), $a = 3.24 \pm 0.30$ au or, in angular separation, $a = 12.8 \pm 3.8$ mas, when the uncertainty in the parallax is taken into account.

3.3 HD 126947 (HIP 70772; NQ Vir)

3.3.1 Intrinsic parameters of the primary

For this star, the *Hipparcos Catalogue* gives the following parameters: $V = 7.37$, $B - V = 1.653$, $\pi = 1.71 \pm 0.97$ mas. Notice that here the parallax is of poor accuracy: $\sigma_\pi/\pi = 0.567$ and, consequently, it simply provides a one-sigma lower limit of the distance d at about 400 pc, with a rough estimate of the absolute magnitude: $M_V \sim -1.5 \pm 1.3$.

The spectral type is only approximately given in SIMBAD which gives "M…" while the *Hipparcos Catalogue* (Vol. 11) quotes M3 III: and refers to …SIMBAD! The M3 III type is analogous to the gM3 given by Wilson & Joy (1950), and the suspicion must arise that it is actually the same type disguised as an MK classification. Indeed, the observed colour index seems consistent with the one expected for a spectral type M3 (i.e. $(B - V)_0 = 1.61$, according to Schmidt-Kaler). In a rough approximation, neglecting the influence of the unseen companion and the interstellar absorption, the absolute magnitude corresponds to a luminosity class II–III, but the large error bar includes as well both the classes II and III.

HD 126947 was recognized by Hipparcos as a "(new, unsolved) variable star" with an amplitude of variation of 0.19 magnitude; it received the denomination "NQ Vir" (Kazarovets et al. 1999).

3.3.2 Minimum mass and separation of the companion

For $(B - V)_0 = 1.61$, Flower (1996)'s tables give $\log T = 3.574$, i.e. $T \approx 3750$ K, $CB = -1.60$. With those values, and M_V as given above, the theoretical diagram of Schaller et al. for solar metallicity leads to an estimate of the primary mass: $M_1 = 2.5 \pm 1$ M$_\odot$. Assuming that value for M_1, we can derive the values of $M_{2\,\rm min}$ and a in the same way as we did for the other objects. We find: $M_{2\,\rm min} = 0.8 \pm 0.2$ M$_\odot$ and $a = 5.9 \pm 0.7$ au.

The physical parameters that we have mentioned in this whole section (Sect. 3) are listed in Table 5. We also give estimates of the theoretical radii R of the primaries (last column of Table 5) that will be used in the next section. Those values of R were derived from the radiation law given by Schmidt-Kaler (1982), i.e. $\log(R/R_\odot) = -0.2 M_{\rm bol} - 2 \log T + 8.47$.

4 Rotational velocities and rotation–revolution synchronism

It is well known that dissipational tidal effects tend to brake the rotations of stars and to reduce the eccentricities of their orbits. The final equilibrium state towards which most binary systems evolve corresponds to a circular orbital motion with a synchronism between the spins and the revolution period for both stars.

Table 5 Physical parameters derived from observational and theoretical data.

Name	V	$B-V$	$v \sin i$ km s^{-1}	π mas	M_V	$\log T_{\rm eff}$	BC	M_1 M$_\odot$	$M_{2\,\rm min}$ M$_\odot$	R_1 R$_\odot$
HR1304	5.47	0.86	4.7	10.74	0.64	3.71	−0.26	2.5	0.37	9.4
			±1.0	±0.54	±0.12			±0.5	±0.05	±0.5
HR1908	5.82	1.54	3.9	3.97	−1.19	3.59	−1.28	2.5	0.80	61
			±1.0	±0.82	±0.46			±0.7	±0.15	±13
HD126947	7.37	1.65	5.5	1.71	−1.47	3.57	−1.60	2.5	0.8	88
			±1.0	±0.97	±1.25			±1.0	±0.2	±50

Hut (1981) showed that, during that evolution, the eccentricity is the parameter which generally evolves the most slowly. For systems starting with an orbit with a large eccentricity, the other parameters relax much more quickly and reach a state of pseudo-equilibrium, characterized by an orbit of non-zero eccentricity. The values of the parameters corresponding to that state can be computed by letting the system dissipate its internal energy by tidal interaction, while keeping its non-zero eccentricity constant. In the long run, the eccentricity decreases slowly towards zero which is the final state of equilibrium.

Let us consider a binary, having a circular orbit, whose components rotate in synchronism with its orbital motion. Let V_e be the equatorial rotational velocity of the considered component, in km s^{-1}, P the orbital period in days and R its radius in solar radii. We have the basic relationship:

$$V_e \times P = 50.6 \times R \qquad \text{or} \qquad R = (V_e \times P)/50.6 \quad (1)$$

In the current case, only the projected rotational velocity, $v \sin i$ (in fact $V_e \sin i$), is known from the observations (here, the profile of the correlation dip). Then the relationship (1) becomes:

$$R \geq (v \sin i \times P)/50.6 \quad (2)$$

And for a given star belonging to a binary system, the relationship (1) is a necessary condition for synchronism: that is the Kitamura & Kondo (1978) test. In short, if the expected radius of the star verifies (2), it may be synchronized, if not, the star rotates too fast for synchronism.

For eccentric orbits, the test refers to the 'pseudo-synchronous' state. In that case, the period involved in Kitamura & Kondo's test is not the orbital period P itself but the 'period of pseudo-synchronism', $P_{\rm ps}$, corresponding to the state of pseudo-equilibrium that we presented in the beginning of this section. The value of the parameter $P_{\rm ps}$ is a function of P and of the eccentricity e (see Hut (1981) and Paper X, formula (2)). For the three systems concerned, we obtain $P_{\rm ps} = 638.4$, 768.9 and 1249.2 days for HR 1304, HR 1908 and HD 126947, respectively.

We can then apply the test (2), with $P = P_{\rm ps}$, and the values of $v \sin i$ published by de Medeiros & Mayor (1999) for HR 1304 and HR 1908, and the one deduced by S. Udry from our correlation dips for HD 126947 (Table 5). It gives: $R \gtrsim 59 R_\odot$, $R \gtrsim 59 R_\odot$, and $R \gtrsim 136 R_\odot$ for HR 1304, HR 1908 and HD 126947, respectively. Finally we can compare those values to the theoretical radii quoted in Table 5 (column 11): it appears that HR 1908 has probably reached the pseudo-synchronous state, whereas the other two stars rotate too rapidly to be in that state.

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References

Baranne, A., Mayor, M., & Poncet, J.L.: 1979, Vistas Astron., 23, 279
Beavers, W.I., Eitter, J.J.: 1986, ApJS 62, 147
Carquillat, J.-M., Ginestet, N., Pédoussaut, A.: 1971, Sciences, Tome II-N°4, 251
Carquillat, J.-M., Nadal, R., Ginestet, N., Pédoussaut, A.: 1982, A&A, 115, 23
Carquillat, J.-M., Jorissen, A., Udry, S., Ginestet, N.: 1998, A&AS 131, 49
Carquillat, J.-M., Prieur, J.-L., Udry, S.: 2005 AN 326, 31 (Paper X)
de Medeiros, J.R., Mayor, M.: 1999, A&AS 139, 433
ESA: 1997, *The Hipparcos and Tycho Catalogues*, ESA SP-1200, ESA Publications Division, Noordwijk
Flower, P.J.: 1996, ApJ, 469, 355
Glebocki, R., Musielak, G., Stawikowski, A.: 1980, Acta Astron. 30, 453
Hut, P.: 1981, A&A, 99, 126
Jorissen, A., Van Eck, S., Mayor, M., Udry, S.: 1998, A&A 332, 877
Kazarovets, E.V., Samus, N.N., Durlevich, O.V., Frolov, M.S., Antipin, S.V., Kireeva, N.N., Pastukhova, E.N.: 1999, IBVS 4659, 1
Keenan, P.C., Keller, G.: 1953, ApJ 117, 241
Keenan, P.C., Barnbaum, C.: 1999, ApJ 518, 859
Kitamura, M., Kondo, M.: 1978, Ap&SS 56, 341
Lucke, P.B.: 1978, A&A 64, 367
Nadal, R., Carquillat, J.-M., Pédoussaut, A., Ginestet, N.: 1983, A&AS, 52, 293 (Paper I).
Pourbaix, D., Jorissen, A.: 2000, A&AS 145, 161
Roman, N.G.: 1955, ApJS 2, 195
Schaller, G., Schaerer, D., Meynet, G., Maeder, A.: 1992, A&AS, 96, 269

Schmidt-Kaler, Th.: 1982, in Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, K. Schaifers & H.H. Voigt eds., New Series, Gr. VI, Vol. 2b (Springer-Verlag, Berlin), pp 1–35
Strassmeier, K.G., Hall, D.S., Fekel, F.C., Scheck, M.: 1993, A&AS 100, 173
Udry, S., Mayor, M., Queloz, D.: 1999, in *Precise Stellar Radial Velocities*, ASP Conferences Ser., 185, 367
Wilson, R.E., Joy, A.H.: 1950, ApJ 111, 221
Wilson, R.E.: 1953, *General Catalogue of Stellar Radial Velocities*, Carnegie Institution Washington Publ. 601
Wilson, O.C.: 1976, ApJ 205, 823