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Investigation of the Praesepe cluster*

III. Radial velocity and binarity of the F5-K0 Klein-Wassink stars

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Abstract. Coravel observations of 103 F5-K0 stars in the Praesepe cluster yielded 24 spectroscopic binaries (3 are non-members), and 20 orbits were determined, with periods from 4 to 7400 days. Based on a complete sample in the colour range $0.40 \leq B-V \geq 0.80$ (80 stars, including KW 244 = TX Cnc), the companion star fraction CSF = 0.45. The percentage of spectroscopic binaries with P < 1000$^{\rm d}$ is 20% (16/80). The combined photometric and spectroscopic analysis showed that 12 among 18 single-lined spectroscopic binaries are located within the "single" star sequence in the $(V, B-V)$ diagram and cannot be detected by the photometric analysis in the UBV system. In addition, seven photometrically analysed binaries were not detected with the radial velocity observations, but are confirmed members. The number of single:binary:triple stars is 47:30:3.

Key words: Galaxy: open clusters and associations: individual: Praesepe – stars: binaries: spectroscopic

1. Introduction

Observations of star-forming regions (SFR) have demonstrated that stars form mainly in clusters and associations, and have a large number of companions. Numerical simulations have also shown that the presence of primordial binaries influences the dynamical evolution of star clusters. Therefore binarity is a basic information to describe properly the results of star-formation processes and the stellar population in open clusters. Technical developments in the domain of radial-velocity scanner, speckle interferometer and adaptive optics imager have permitted to obtain in the recent years a wealth of interesting observations which shed new light on the old, and so far not solved, question of the similarity, or difference, of the binary frequency in star clusters.

Duchêne (1999) has reexamined the evidence from SFR and concluded that four SFR have a larger rate of binaries than open clusters. However, both kinds of stellar systems are not compared exactly in the same period or separation intervals. Most recent observations in SFR were performed with speckle interferometry or adaptive-optics imaging (see Duchêne (1999) for references). Among the nearby open clusters, only the Hyades (Mason et al. 1993a; Patience et al. 1998) and Pleiades (Bouvier et al. 1997) have been observed to detect binaries in the range of separation 0.″05 - 0.″50. The speckle interferometry survey of Mason et al. (1993b) hardly reached the brighter F5 stars and there is little overlap with the sample discussed in this paper. Conversely, long term radial-velocity surveys have been undertaken (Mermilliod 1997; Stefanik & Latham 1992) to monitor main-sequence late-type stars in nearby open clusters, while very few data have been published for star-forming regions.

This paper is the third one in this series devoted to the investigation of Praesepe (NGC 2632, M44, α (B1950) = 8^h $37^{\rm m}.2$, δ (B1950) = +20° 10). In the first paper (Mermilliod et al. 1990) we identified 48 new members in the cluster corona, out to 4 degrees and found 10 spectroscopic binaries. Six orbits were determined. In the second paper (Mermilliod et al. 1994) we presented the orbital elements of three spectroscopic binaries in triple systems (KW 365, KW 367 and KW 495). All the material has been used by Raboud & Mermilliod (1998b) to study the radial structure of Praesepe. It has been shown that the spectroscopic binaries are slightly more concentrated toward the cluster centre than single stars. Furthermore, they found that the mass function of the primary of spectroscopic binaries is different from that for the single stars, confirming a result also found in the Pleiades (Raboud & Mermilliod 1998a).

Few radial velocities for solar-type dwarfs in Praesepe have been published so far. Bolte (1991) observed 14 stars to check the binarity status of stars that appeared as photometric double stars in the colour-magnitude diagram, having in mind the interpretation of the second-sequence stars in globular clusters. Barrado y Navascués et al. (1998) have obtained a number of radial velocities (mostly one per star) for a sample of G, K and M stars in Praesepe to study the stellar activity. The agreement of their radial velocities with our measurements is very good. Very recently, Abt & Willmarth (1999) published radial-velocity observations of 16 A-type stars on the upper main sequence and determined new orbits for 5 stars.

The sample and the observations are described in Sect. 2, the results and orbits are presented in Sect. 3. Binarity in Praesepe is discussed in Sect. 4.

* based on observations collected at the Haute-Provence Observatory (France)

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2. Observations

2.1. The sample

The initial observing programme included all 88 known F5 - K0 members in the region studied by Klein-Wassink (1927). The original limiting magnitude was $B = 12.5$. In 1977, the membership estimates were mainly based on the proper motions from Klein-Wassink (1927) and the UBV photometry of Johnson (1952).

Three F5 V stars (KW 295, KW 478, KW 555) did no produce any correlation dip. Although their rotational velocities ($V \sin i$) are not known, they are probably larger than about 45 km s^{-1}, as is frequent for early-F stars. In addition, no radial velocities are available for these stars. KW 244 (TX Cnc, V = 10.02, $B-V$ = 0.62) is a short period eclipsing binary (Whelan et al. 1973). It could not be observed with the Coravel because of its rotation, but will be included in the binary statistics presented below.

2.2. Coravel observations

The observations were obtained with the CORAVEL radial-velocity scanner (Baranne et al. 1979) installed on the Swiss 1-m telescope at the Haute-Provence Observatory (OHP) for stars later than spectral type F5 and brighter than B = 12.5. Between November 1978 and December 1996, four to nine observations per star were obtained. Binaries were observed more often to derive orbital elements. From January 1993 on, 16 fainter stars (B $<$ 13.5) were added to the sample and observed, mainly for the purpose of determining rotational velocities. One or two observations have been obtained. They are listed in Table 1 for sake of completeness, because few radial velocities have been so far published for these faint members.

The OHP radial velocities were corrected for zero-point differences to place them in the system defined by Mayor and Maurice (1985). The integration times ranged from about 200 to as much as 1500 seconds, the average being about 400 seconds. The errors on well-exposed individual measurements usually were smaller than 0.5 km s^{-1}. However, for a few stars with large rotation ($v \sin i \simeq 30$ km s^{-1}) the errors may reach 2 km s^{-1}, depending on the width of the correlation function. The mean value of $\sigma(O-C)$ for the 18 binaries is 0.73 km s^{-1}.

The KW numbers (Klein-Wassink 1927), the V magnitudes, the mean radial velocities V_r, the standard errors ϵ (in km s^{-1}), the number of measurements n, the time intervals ΔT covered by the observations, the probability $P(\chi^2)$ that the scatter is due to chance (Mermilliod & Mayor 1989) are collected in Table 1. The remarks SB1O or SB2O refer to single-lined and double-lined binaries for which orbits have been determined, PHB to binaries detected photometrically in the colour-magnitude diagram, VB to visual binaries.

Individual observations can be requested from the first author. The whole CORAVEL dataset is currently being recalibrated for possible zero-point error and color effect. All the individual data will then be published in a comprehensive catalogue of observations in Praesepe.

Table 1. CORAVEL results for KW stars in Praesepe

KW	m_V	V_r	ϵ	E/I	n	ΔT	$P(\chi^2)$	Rem
9	11.39	34.85	0.35	1.94	5	3986	0.005	PHB
16	9.18	34.33	1.71	5.56	22	5858	0.000	SB2
23	11.29	34.98	0.23	1.20	5	5793	0.224	
27	11.44	34.69	0.20	1.09	5	5793	0.327	
30	11.40	35.45	0.23	0.63	4	4458	0.756	
31	9.79	34.99	0.23	1.36	8	5504	0.076	PHB
32	11.65	35.53	0.27	0.69	3	2977	0.621	
47	9.87	34.94	0.13	21.93	34	4058	0.000	SB1O
49	10.66	34.71	0.28	1.29	5	6594	0.156	
55	11.41	39.94	0.10	65.47	32	3256	0.000	NM
58	11.26	34.35	0.22	1.12	5	6175	0.291	
70	11.84	34.84	0.18	1.11	6	6175	0.292	
90	10.84	35.72	0.20	1.23	7	6175	0.178	PHB
100	10.55	33.89	0.21	0.98	7	7263	0.462	
127	10.80	34.31	0.12	26.32	33	5848	0.000	SB1O
142	9.29	35.00	0.23	21.18	55	5557	0.000	SB2O
155	9.41	34.86	0.44	1.05	11	4762	0.382	
162	10.58	34.90	0.40	1.64	5	6594	0.031	
164	11.31	34.35	0.29	1.27	4	4458	0.184	
181	10.53	34.49	0.10	59.08	44	5853	0.000	SB1O
182	10.35	34.17	0.15	0.88	9	7272	0.631	PHB
184	11.56	34.95	0.11	32.13	39	5049	0.000	SB2O
196	10.74	34.99	0.23	1.01	5	5173	0.398	
208	10.66	34.12	0.29	1.29	5	6594	0.162	
213	11.81	34.34	0.21	0.97	4	4460	0.418	
217	10.23	33.64	0.33	1.63	8	6976	0.008	
218	9.34	36.74	1.22	1.14	4	4024	0.276	
222	10.11	34.29	0.24	1.19	7	6965	0.209	
227	9.49	34.77	0.41	1.64	7	6532	0.013	
238	10.29	34.28	0.36	1.13	10	6965	0.074	
239	9.66	36.66	0.54	1.12	8	4760	0.292	
250	9.79	36.45	0.74	1.00	6	2509	0.425	
257	11.01	35.13	0.44	2.12	6	7230	0.000	PHB
258	10.24	54.69	0.11	14.62	31	3724	0.000	NM
268	9.89	35.75	0.13	13.34	44	4459	0.000	SB1O
275	9.96	34.45	0.17	1.35	10	7272	0.060	PHB
287	10.37	34.09	0.10	5.31	28	7207	0.000	SB1O
288	10.70	35.32	0.25	1.32	6	6976	0.132	
293	9.85	36.61	0.56	0.89	7	3670	0.574	
297	11.64	37.14	0.27	2.43	16	6118	0.000	SB1
301	11.17	34.11	0.35	1.72	5	6175	0.020	
304	11.52	33.53	0.26	0.44	4	4457	0.903	
309	11.63	34.42	0.21	0.66	4	3668	0.729	
322	10.87	35.08	0.45	3.91	17	7228	0.000	SB1
325	10.60	34.63	0.11	12.40	30	6139	0.000	SB1O
326	11.35	34.28	0.19	0.89	5	3665	0.535	
332	9.56	33.44	0.44	0.89	8	6259	0.597	
334	11.00	36.35	0.32	1.78	7	7230	0.005	PHB
335	11.02	34.62	0.23	1.15	5	5793	0.264	
336	11.46	35.21	0.25	1.11	4	3665	0.294	
341	10.30	36.13	0.38	2.00	8	6177	0.000	SB1
365	10.18	27.21	2.31	26.64	51	4728	0.000	Triple
367	10.69	var	8.39	42.35	82	6591	0.000	Triple
368	11.49	34.87	0.09	25.25	28	4756	0.000	SB1O
371	10.10	34.83	0.40	1.07	6	3605	0.339	PHB
392	10.76	34.57	0.25	1.43	6	6176	0.072	
396	9.85	34.15	0.34	0.83	5	3607	0.604	

Table 1. (continued)

KW	m_V	V_r	ϵ	E/I	n	ΔT	$P(\chi^2)$	Rem
399	10.97	33.32	0.37	2.30	8	6175	0.000	SB1
403	11.71	34.39	0.37	1.85	4	3667	0.016	
411	9.32	35.63	1.42	1.66	3	1037	0.063	
416	9.59	34.49	0.11	37.84	40	5115	0.000	SB1O
418	10.47	33.87	0.27	1.45	6	6176	0.066	
421	10.15	34.87	0.22	1.00	6	6177	0.418	
425	11.42	40.48	0.32	1.52	7	6174	0.035	NM
432	11.05	32.99	0.21	0.96	4	5792	0.452	
434	11.41	34.34	0.13	45.73	21	3256	0.000	SB1O
439	9.43	34.92	0.12	3.76	34	6231	0.000	SB1O
454	9.88	34.89	0.32	0.61	6	6230	0.867	
458	9.71	33.64	0.33	1.51	7	7272	0.034	VB, 0.″2
466	10.99	33.45	0.26	1.26	5	6174	0.195	
476	11.62	34.70	0.27	1.26	4	3667	0.199	
488	11.44	34.69	0.24	1.13	4	3665	0.287	
495	9.97	32.73	0.15	0.81	31	5114	0.138	SB3O
496	9.57	33.68	0.22	0.78	11	6212	0.826	SB2
498	11.78	33.83	0.23	0.58	4	3667	0.797	
508	10.77	34.23	0.64	6.32	26	6174	0.000	SB1O
533	11.58	35.00	0.18	1.62	14	6171	0.001	SB2
537	11.65	33.95	0.21	1.04	4	3666	0.363	
539	11.18	34.25	0.52	4.88	20	6171	0.000	SB1O
540	11.03	36.80	0.14	4.80	24	6171	0.000	SB1O
542	11.72	33.60	0.22	1.03	4	3666	0.363	
546	11.62	37.78	0.27	0.74	2	684	0.457	
548	10.01	-9.14	0.15	0.95	6	5081	0.483	NM
553	10.15	27.16	0.25	32.82	48	5166	0.000	NM
557	10.38	4.94	0.36	1.58	4	3991	0.061	NM
Fainter stars								
48	12.32	34.69	0.37		1			
52	12.28	35.05	0.39		1			
79	12.08	36.03	0.40		1			PHB
236	12.94	36.08	0.52	0.15	2	2	0.878	Triple?
246	12.01	26.83	1.18	4.27	2	684	0.000	SB1
263	12.01	34.00	0.40		1			
313	12.20	34.80	0.37		1			
344	12.10	34.39	0.37		1			
349	12.23	34.26	0.36		1			
353	12.35	33.85	0.39		1			
417	12.35	36.72	0.39		1			
430	12.06	35.20	0.27	0.18	2	1035	0.858	
448	12.15	34.98	0.38		1			
471	12.15	35.07	0.35		1			
474	12.12	32.36	0.36		1			PHB
492	12.13	33.93	0.39		1			
530	12.26	77.18	0.39	1.71	4	3357	0.035	NM
547	11.99	39.25	1.25	5.99	3	1035	0.000	SB1

3. Results

3.1. Membership

The radial-velocity results summarized in Table 1 confirm the membership of most stars, with seven exceptions. KW 55, 258, 425, 530, 548, 553 and 557 are clearly (more than 7 σ) non-members, although the membership probabilities from proper motions (Jones & Cudworth 1983) for KW 55 (P = 0.98), KW 258 (P = 0.94) and KW 425 (P = 0.86) are quite high. KW 55, KW 258 and KW 553 are spectroscopic binaries, and their systemic velocities (+39.94, +54.7 and +27.2 km s^{-1}, respectively) differ from the mean cluster velocity by at least 7 km^{-1}. The scatter of the $(O-C)$ residuals doest not support any long term variability which would indicate that these stars are in triple systems. KW 425, KW 530 and KW 553 are well below the ZAMS in the colour-magnitude diagram, while KW 548 and KW 557 are above the main sequence band.

3.2. Spectroscopic binaries

Thirty spectroscopic binaries and triple systems (27 members and 3 non-members) have been discovered among Praesepe F5 - K0 stars. Twenty orbits have been determined (17 members, 3 non-members). The shortest period is 3.ᵈ93 and the longest 7365.ᵈ. The orbital elements of a few binaries could not be determined either because the expected period is longer than twenty years, or because the frequency of observations did not permit to reobserve several times the double-lined patterns, the radial velocity being otherwise constant at the cluster velocity (KW 16, 496, 533). None of the stars considered as non variable show any trend with time, only star KW 162 shows a slight change from +36.3 km s^{-1} in 1978 to +34.5 km s^{-1} in 1990, with values of +35.0 and +35.5 in 1982 and 1986. The evidence remains marginal. We can conclude that the undiscovered binaries will have radial-velocity amplitude smaller than about 2 km s^{-1} and periods longer than, at least, 15 years.

The orbital elements for 20 new orbits are presented in Table 2, and the in-phase radial-velocity diagrams are presented for each binary. To the 19 KW stars, the elements for VL 1025 have been added. This star is slightly outside the Klein-Wassink area and its binarity has been detected in Paper I (Mermilliod et al. 1990). An orbit has now been determined and the elements are included at the end of Table 2.

Orbital elements for the spectroscopic binaries KW 365, KW 367 and KW 495 belonging to triple systems have been published by Mermilliod et al. (1994). The periods given in Table 2 for KW 367 correspond to the short (Aab) and long period (Aab x B), respectively.

The diagram of the eccentricity vs logarithm of the periods (Fig. 6) shows the clear transition from circular to elliptical orbits at about 8 days. KW 181 (P = 5.ᵈ86, e = 0.36) is an exception. There is so far no indication that this star is a triple system. Its original eccentricity must have been quite large, and it had not enough time to reduce it to 0 (Duquennoy et al. 1992).

3.3. Individual stars

KW 16: Double lines have been observed on December 14, 1993, with a velocity difference of 43 km s^{-1}. The 21 velocities of the blend vary between +28 and +43 km s^{-1}, but no period could be determined. The width of the correlation function varies also. The double-lined status is in agreement with the position of the star in the CMD.

Table 2. Orbital parameters

KW	Period	T	e	γ	ω	K_1	K_2	f(m)	a sin i	$\sigma(O-C)$	n_{obs}
47	34.619	8989.69	0.406	34.94	289.8	19.01		0.0189	8.27	0.72	34
	.002	.25	.009	.13	1.6	.18		.0008	.11		
55	5.98533	9002.06	0.00	39.94		34.73		0.0260	2.858	0.57	32
	.00003	.01	.004	.10		.14		.0003	.011		
127	13.2803	9002.61	0.226	34.31	130.7	17.82		0.0072	3.170	0.61	33
	.0001	.08	.009	.12	2.5	.19		.0003	.040		
142	45.9746	9972.36	0.223	34.90	56.7	32.50	33.92	0.1725	20.90	2.67	55
	.0019	.41	.012	.28	3.3	.52	.48	.0089	.35		
181	5.866276	8998.266	0.357	34.49	228.9	47.13		0.0520	3.552	0.65	44
	.000006	.006	.003	.10	.5	.14		.0006	.015		
184	47.438	8969.58	0.341	34.95	68.2	23.46	24.17	0.0529	14.39	0.94	39
	.002	.15	.007	.11	1.3	.23	.24	.0029	.18		
258	260.41	4802.6	0.394	54.69	194.9	11.95		0.0358	39.3	0.55	31
	.13	1.2	.015	.11	2.2	.29		.0034	1.3		
268	144.340	4838.50	0.649	35.75	285.3	13.25		0.0153	20.00	0.67	44
	.013	.33	.008	.13	1.5	.20		.0011	.49		
287	7365.	6249.	0.62	34.09	72.9	4.86		0.0431	388.	0.46	28
	325.	38.	.03	.09	4.0	.17		.0099	41.		
325	896.9	9164.	0.117	34.63	146.5	8.79		0.0619	107.6	0.52	30
	1.4	18.	.020	.11	8.0	.15		.0038	2.3		
367	3.057311	9998.9	0.000	33.41		52.88	66.16				88
	.000002	1.9	.005	.20		.14	.37				
367	1659.	8025.	0.762	33.41	230.5	8.32		0.0318	136.		88
	14.	10.	.024	.20	4.6	.90					
368	76.5643	9478.18	0.212	34.87	12.8	14.53		0.02275	149.47	0.47	28
	.0045	.48	.008	.09	2.5	.13		.00076	.17		
416	25.84234	9978.406	0.432	34.49	318.88	26.94		0.03850	8.635	0.60	40
	.00016	.038	.005	.11	.84	.16		.00098	.073		
434	3.932626	9998.105	(0.000)	34.34		33.27		0.01504	1.7991	0.50	20
	.000012	.015	.005	.13		.18		.00025	.0098		
439	457.8	9332.	0.17	34.92	34.	2.62		0.00082	16.2	0.60	34
	1.4	27.	.06	.12	23.	.19		.00021	1.4		
508	647.64	9477.1	0.496	34.19	171.1	4.72		0.0046	36.5	0.55	26
	.77	5.7	.039	.13	5.0	.28		.0012	3.2		
539	5551.	6966.	0.533	34.03	49.1	4.04		0.0236	263.	0.42	20
	221.	94.	.049	.18	6.8	.25		.0079	36.		
540	1149.5	9082.	0.669	36.75	356.0	4.05		0.0033	48.	0.53	24
	6.5	12.	.080	.13	5.5	.91		.0032	16.		
553	40.6649	9969.23	0.342	27.16	266.2	47.47		0.375	24.95	1.57	47
	.0014	.11	.008	.25	1.2	.33		.011	.25		
VL 1025	2657.	7203.	0.481	33.95	275.2	6.22		0.0448	199.	0.52	22
	26.	18.	.029	.11	4.3	.21		.0075	12.		

KW 236: If it is a member, this star is probably a triple system: it shows a dip at the cluster velocity and a well marked secondary dip.

KW 287: This binary has quite a long period, and the first cycle has not yet been completely covered. However, a reasonably well determined orbit has been computed, because both extrema have been well observed.

KW 297: The null probability P(χ^2) of this star is mostly due to the first velocity in January 1981 (34.4 km s^{-1}). But the present mean velocity is around 37.5 km s^{-1}, which deviates from the cluster mean. It is probably a very long period binary.

KW 322: A very preliminary orbit has been obtained, with a period of about 10000 days. One complete cycle has not been yet covered and the uncertainties on the elements are therefore rather large. The elements are not included in Table 2

KW 367: This is a double-lined binary for which an orbit has already been determined (Mermilliod et al. 1994) and the systemic velocity was found to be variable. This star has been frequently observed and an orbit for the long period system has been determined. The elements are included in Table 2. The two periods are thus $3\overset{\rm d}{.}057$ for the close system and $1659\overset{\rm d}{.}$ for the longer one. The elements for the short periods are very similar to the first published ones. The present values has been obtained with

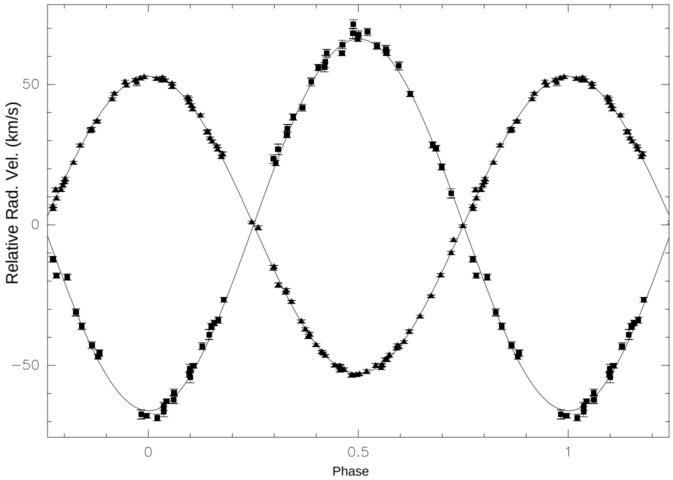

Fig. 1. Radial-velocity curves for the SB2 system in KW 367.

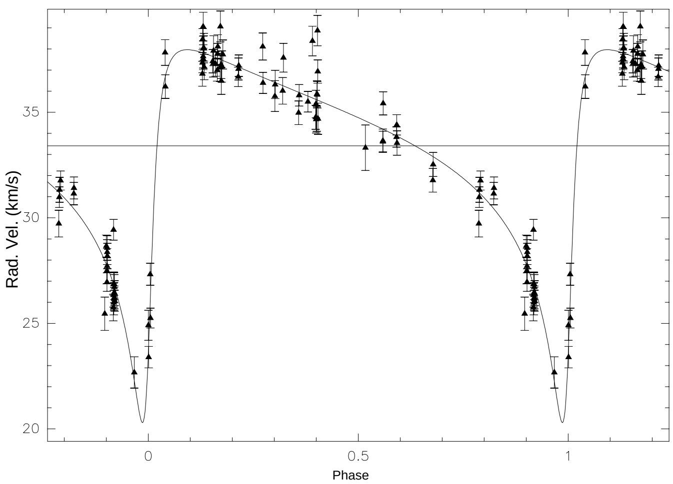

Fig. 2. In phase systemic-velocity variation for the SB2 in KW 367.

additional observations and a simultaneous solution for the two orbits. The radial-velocity curves are displayed in Figs. 1 and 2. The third component has not been convincingly seen in the correlation functions, although a few dips, similar to those of the secondary of the SB2, but with completely different velocities could be tentatively attributed to the secondary of the long system. If this fact is confirmed, the secondary could also be a spectroscopic binary itself. However, as deduced from the CM diagram, most of the light comes from the SB2 and the other system does not seem to contribute much light.

KW 399: The peak to peak amplitude is 2.68 $\mathrm{km\,s^{-1}}$ and is due to two low velocities obtained in February 1982 and January 1983. The last observation was made in 1991 and more recent data are necessary to judge the binary status of this star.

KW 496: Line doubling has been observed on three nights in 1981, 1983 and 1990, but the velocity is stable for the 30 other observations. The velocity separation is close to 20 $\mathrm{km\,s^{-1}}$.

KW 533: Line doubling has been observed on January and February 1987 and on February 1988, with a velocity separation of the order of 25 $\mathrm{km\,s^{-1}}$. Since that time, the velocity is constant at the cluster mean velocity. This is probably another long period binary.

3.4. Binary frequency

We limit our analysis to the stars listed in the first part of Table 1 which corresponds to the colour interval 0.40 $< B-V <$ 0.80. All stars have been observed at least 4 times, and the star census is supposed to be complete. We count 80 stars, including KW 244 (TX Cnc). We find 16 single-lined spectroscopic binaries (SB1), 5 double-lined binaries (SB2), including KW 244, 8 photometrically analysed binaries (PHB: star well above the ZAMS, $\delta V > 0.45$ mag, but not detected as spectroscopic binaries), 3 triple systems, one visual binary.

The overall rate in this colour interval is 30% (24/80) and that for the Pleiades was 19% (17/88). Due to the size of the samples, the statistical *a posteriori* significance of this difference is at the 10% level. The rate of binaries with periods shorter than 1000^d is 20% (16/80), by counting the short-period spectroscopic binaries in the 3 triple systems. This value is slightly larger than in the Pleiades (13%: 11/88) in a similar colour interval, and is significant at the 18% level, and than in the nearby G dwarf sample of Duquennoy & Mayor (1991): 13% (21/164), with a significance at the level of 14%. In Praesepe, 67% (16/24) of the binaries have periods shorter than 1000^d. The longest period determined from our material is 7365 days. This means that the detection of binaries with periods shorter should be quite complete. The proportion of single:binary:triple systems is 47:30:3 for Praesepe. That obtained for the Pleiades in the range 0.40 $< B-V <$ 0.90, i.e. slightly larger, was: 56:30:2.

The values of the multiple-system fraction is $MSF = (b+t)/(s+b+t)$ = 0.41 (33/80) and the companion star fraction, $CSF = (b+2t)/(s+b+t)$ = 0.45 (36/80), where s means single, b, binary and t, triple. For a sample of 162 stars in the Hyades, Patience et al. (1998) obtained $MSF = 0.41 \pm 0.05$ and $CSF = 0.46 \pm 0.05$. Taking into account that a more extensive binary search has been performed in the Hyades, the agreement is pretty good, and shows that the multiplicity rates are not very different between the Hyades and Praesepe. At least, it cannot explain the striking difference in the X-ray source detection between the two clusters (Randich & Schmitt 1995, Barrado y Navascués et al. 1998).

3.5. Mass ratios

Mass ratios have been computed for the spectroscopic and photometric binaries in various ways. For photometric binaries, a photometric deconvolution has been attempted. The resulting values are given in Table 3: V_a, C_a, M_a are V mag., $B-V$ colour and mass of the primary respectively, and V_b, C_b, M_a are the V mag., $B-V$ colour and mass of the secondary. When the stars were at the upper binary limit or slightly above, $V_a = V_{ab}$ - 0.75 mass ratios have been set at 0.99. For spectroscopic binaries located well within the single star sequence, the minimum mass (Min) has been computed from the spectroscopic orbit and the maximum mass (Max), under the assumption that the secondary

Table 3. Deduced mass ratios

KW	V_a	V_b	C_a	C_b	M_a	M_b	q	Max	Min
9	11.60	13.27	0.75	1.09	0.95	0.73	0.77		
16	9.72	10.29	0.43	0.51	1.27	1.16	0.92		
31	10.54		0.56		1.11		0.99		
47	9.87		0.48		1.22		>0.29	0.58	0.36
90	11.10	12.77	0.65	0.98	1.03	0.78	0.76		
127	10.81		0.60		1.07		>0.23	0.40	0.23
142	10.06		0.49		1.19		0.99		
181	10.57	13.61	0.55	1.18	1.12	0.68	0.61		0.51
182	10.97	11.22	0.63	0.68	1.04	1.00	0.96		
184	12.38		0.90		0.83		0.99		
268	9.89		0.47		1.23		>0.27	0.58	0.33
275	10.66	10.78	0.57	0.59	1.10	1.08	0.98		
287	10.54	12.49	0.54	0.92	1.12	0.82	0.73		0.48
297	11.88	13.38	0.80	1.12	0.90	0.71	0.79		
322	11.03	13.05	0.63	1.05	1.04	0 75	0.72		
325	10.69	13.33	0.58	1.10	1.09	0.72	0.66		0.55
334	12.20	12.98	0.67	1.04	1.01	0.75	0.75		
367	11.02	12.17	0.63	0.85	1.04	0.87	0.83		
368	11.51		0.73		0.95		0.35	0.33	0.33
399	10.95		0.63		1.05			0.40	
416	9.59		0.41		1.31		>0.38	0.59	0.50
434	11.39		0.71		0.97		>0.29	0.35	0.28
439	9.45		0.40		1.34		>0.09	0.60	0.12
458	10.47		0.55		1.12		0.99		
496	10.09	10.71	0.48	0.59	1.20	1.08	0.90		
508	10.78		0.59		1.08		>0.18	0.25	0.19
533	12.34		0.90		0.83		0.99		
540	11.13	13.71	0.65	1.21	1.02	0.67	0.65	0.40	0.16
				Corona binaries					
KW									
549	10.15	14.04	0.48	1.30	1.19	0.63	0.52		0.13
556	10.55	14.77	0.55	1.39	1.12	0.58	0.52		0.85
VL									
142	10.53	12.35	0.54	0.89	1.13	0.84	0.75		0.66
184	11.85		0.79		0.93		>0.10	0.3	0.09
1025	11.75	13.84	0.77	1.24	0.92	0.65	0.71		0.43
Art									
1271	11.34	11.34	0.71	0.71	0.97	0.97	0.99		
1780	11.22	11.22	0.69	0.69	0.99	0.99	0.99		

is 5 mag. fainter than the primary. This limit corresponds to an effect of 0.01 mag on the V magnitude. A difference of 4 mag. may appear more appropriate. In this case, the maximum mass would be larger and the mass interval for the secondary would be wider. The two mass values give a reasonnable estimate of the secondary masses. Values of the mass ratios q tabulated in Table 3 show that photometric detection produces mass ratios larger than 0.60, while the lower limit of the mass ratios for the single-lined spectroscopic binaries is around 0.20.

The distribution of q, by bins of 0.2 $M_\odot$ is 0.8–1: 12, 0.6–0.8: 9, 0.4–0.6: 7, 0.2–0.4: 7. There is a slight increase toward values of q larger than 0.7, but the distribution for $q < 0.5$ may be incomplete, because the orbits with very long periods have not been determined yet.

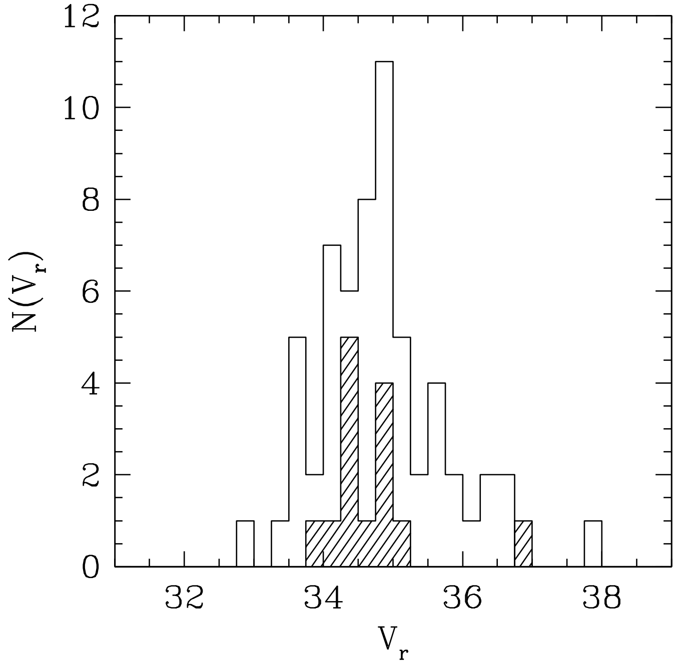

Fig. 3. Radial-velocity distribution for "single" stars and spectroscopic binary (shaded histrogram).

3.6. Cluster mean velocity

We have computed Praesepe mean velocity from 46 "single" stars and found a value of 34.53 $\pm$ 0.12 (s.e.) km s^{-1}. The standard error is 0.81 km s^{-1}. The mean value of 14 spectroscopic binaries (excluding KW 540) is 34.68 $\pm$ 0.11 km s^{-1}, with a standard error of 0.40 km s^{-1}.

The observed velocity dispersion, 0.40 km s^{-1} for the binaries and 0.81 for the single stars would indicate, if taken at face value, that the velocity dispersion of the binaries, more centrally concentrated than the single stars, is only half of the dispersion of the single stars. This result is in agreement with what is expected from the dynamics of star clusters. However, one should be careful and take into account the velocity dispersion due to unknown binaries. Fig. 3 shows the histogram of the stellar mean velocity and illustrates this effect. The shaded area corresponds to the spectroscopic binaries for which an orbit has been determined.

4. Colour-magnitude diagram

The colour-magnitude diagram for the F5 - K0 stars (Fig. 7) clearly shows that binary stars are distributed all over the main sequence band. They are not only found near the upper binary limit (0.75 mag above the ZAMS), but also among the "single" stars. Nine binary stars are found at $\Delta V > 0.70$ mag, 10 are found among the single stars and 7 in the intermediate band. Therefore, any photometric detection of binary stars in a colour-magnitude diagram will miss about 40% of the spectroscopic binaries.

There is however no one to one correspondance between the photometrically detected and the spectroscopic binaries. For (B-

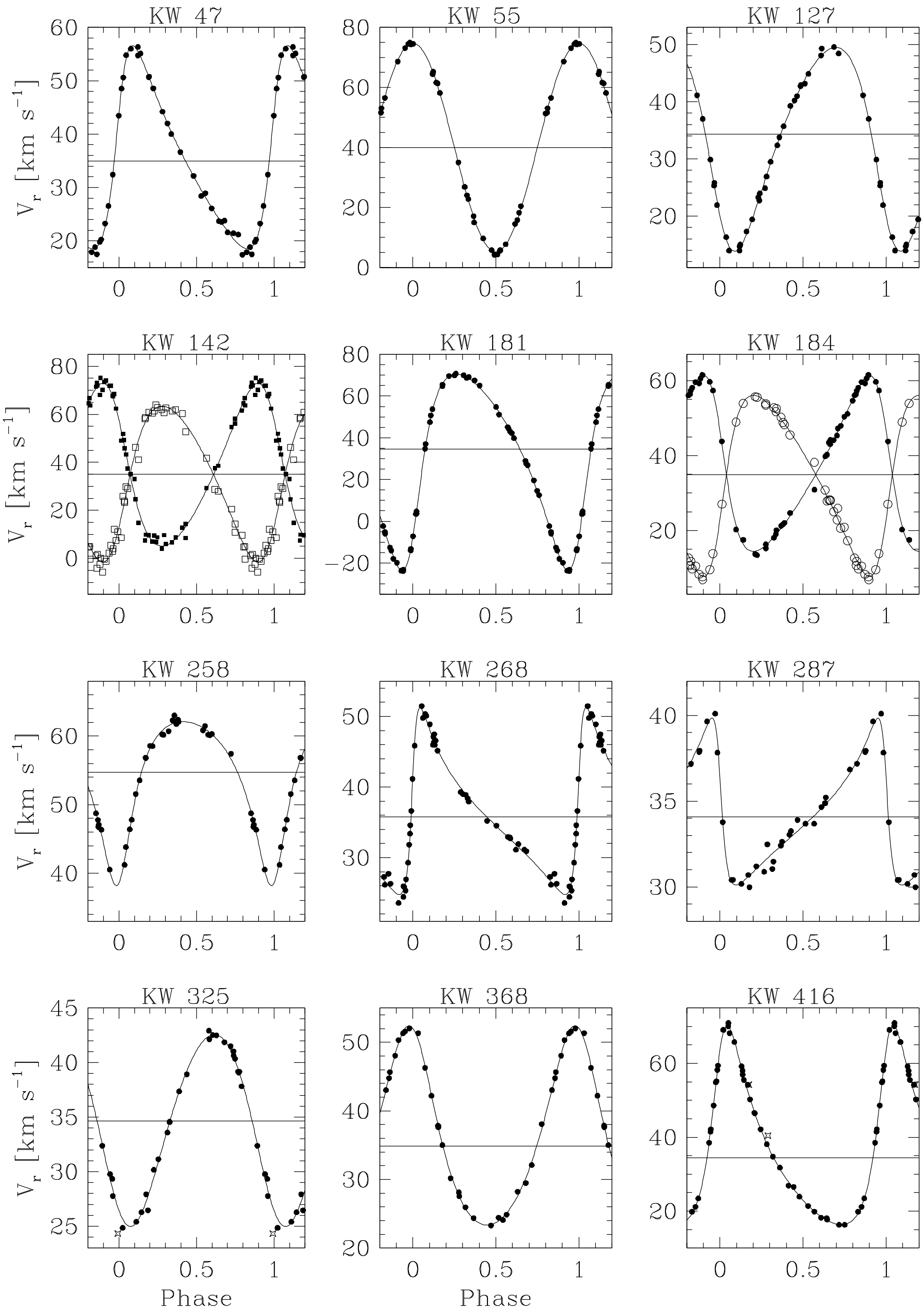

Fig. 4. Radial-velocity curves for twelve spectroscopic binaries. For SB2s, filled circles are for the primaries and open circles for the secondaries.

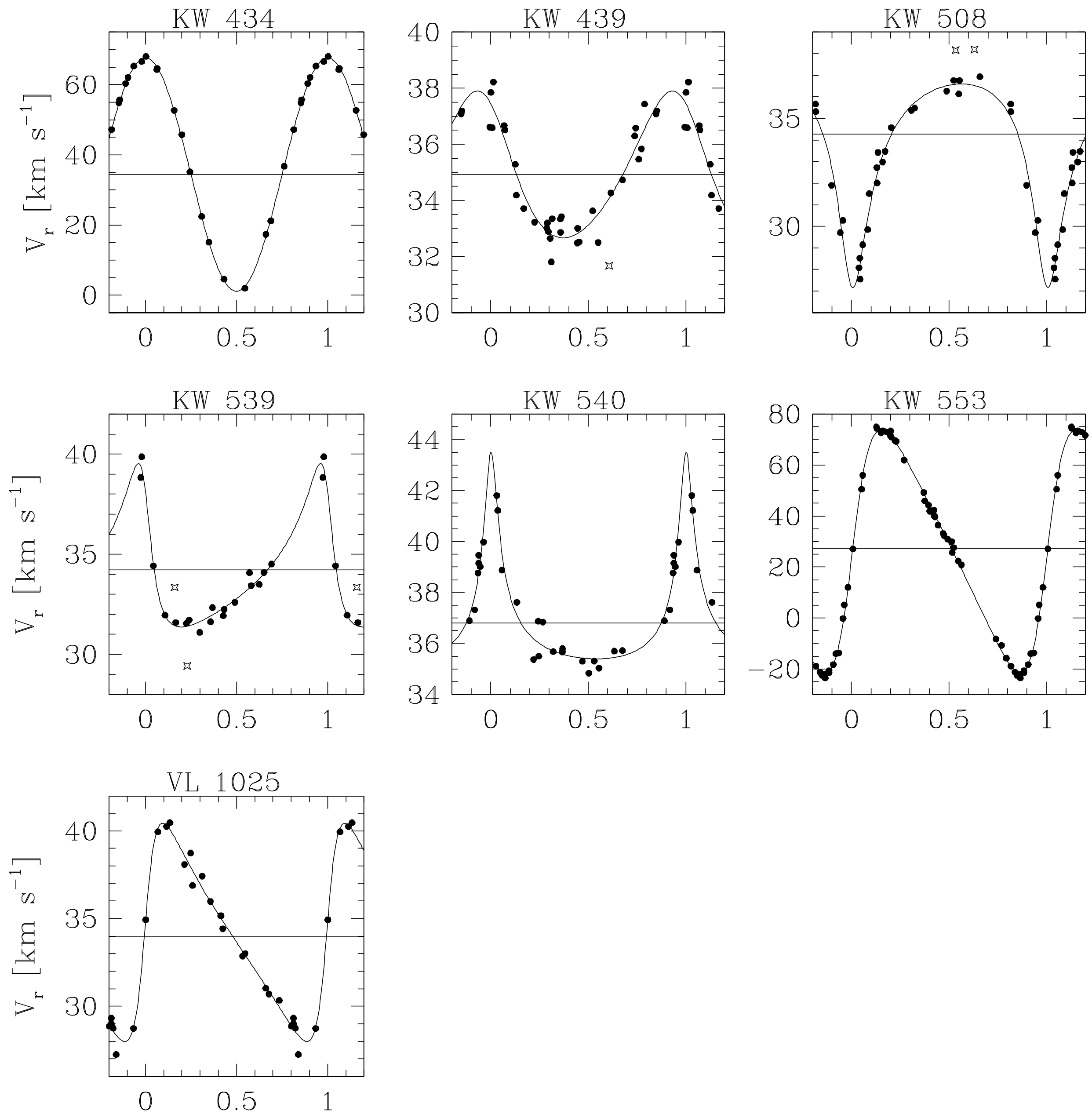

Fig. 5. Radial-velocity curves for seven spectroscopic binaries. Open diamonds represent observations rejected in the orbital solutions.

V) < 0.90, seven obvious photometric double stars have not been detected as spectroscopic binaries. A similar situation has been met in the Pleiades (Mermilliod et al. 1992). Adaptive optics observations have permitted to resolve a number of the Pleiades photometric binaries (Bouvier et al. 1997). A similar survey of 150 stars in Praesepe made in 1998 will permit to answer this question (Bouvier et al. 1999).

In a similar way, it is quite possible that apparently single stars have low-mass companions at large distance which do not produce perceptible effect on the joint magnitudes or on the radial velocities. Data in Table 3 suggest that very few binaries with mass ratios smaller than 0.3 have been detected, although the precision of our radial-velocity observations allows us to determine orbits with semi-amplitudes around 2.5 $\mathrm{km\,s^{-1}}$, see for example KW 439.

To test the presence of a variation of the number of spectroscopic binaries along the main sequence, we have applied the test of Wilcoxon-Mann-Whitney. The test shows that, in our sample, binaries are more frequent among stars with small $B-V$, but the level of significance is 8%. Therefore, we cannot definitely discard the possibility that this trend is not intrinsic, but simply comes from random noise.

In the interval $0.4 < B-V < 0.55$ the star distribution is clearly bimodal: on the one hand five stars show the maximum magnitude effect: three SB2 (KW 16, KW 142, KW 496), one visual binary (KW 458) and one photometric binary (KW 31).

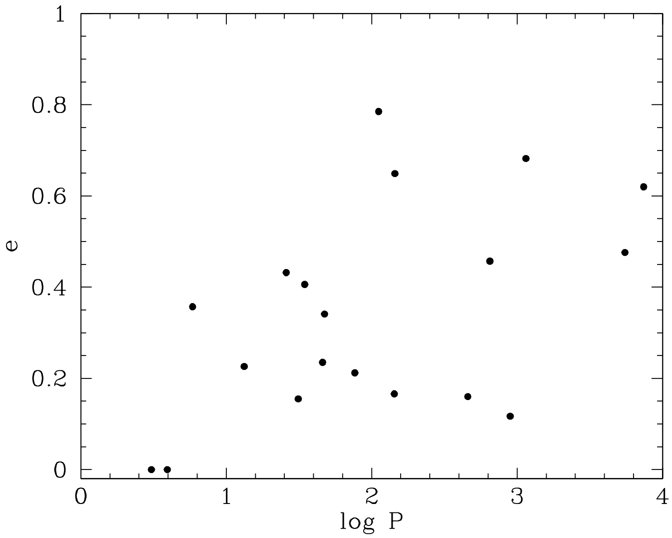

Fig. 6. Eccentricity - period diagram.

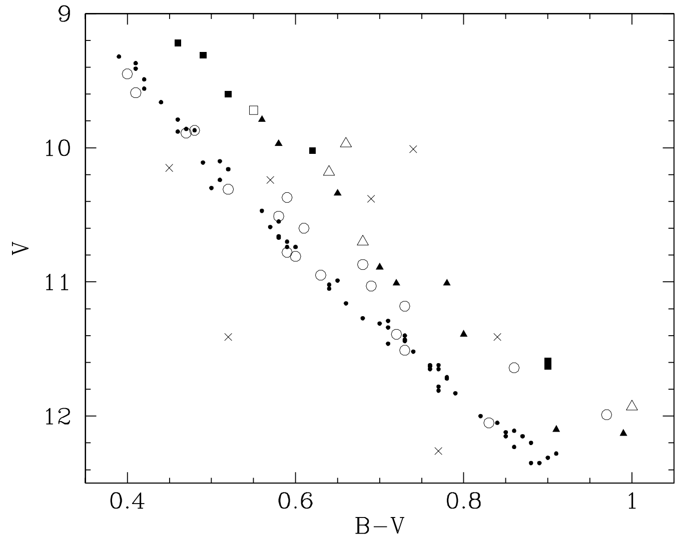

Fig. 7. Colour-magnitude diagram of the F5-K0 stars in Praesepe. The solid and dashed curves represent the ZAMS and the binary upper limit respectively. Symbols are as follows: points: single stars, open circles: SB1s, filled squares: SB2s, open square: visual binary, open triangles: triple systems, filled triangles: photometric binaries, crosses: non-members. Notice that 10 among 17 single-lined binaries are located within the "single" star sequence.

Twenty-one stars define the main-sequence locus, four binaries (KW 47, KW 268, KW 416, KW 439) are photometrically indistiguishable from true single stars.

The interval $0.55 < B-V < 0.75$ is much richer in binary types. It contains the three triple systems discussed by Mermilliod et al. (1994). In KW 495, all three components are seen in the correlation functions and the position in Fig. 7 is in good agreement with that expected for a triple system. KW 365, in which one single star and the SB primary are seen is very close to the 0.75 upper limit, so the contribution of the third body seems to be small. Then, the position of KW 367, a double-lined system with a variable systemic velocity is surprisingly located 0.25 mag below the upper binary limit. Because two components are seen, the third one should not contribute much light. There are five single-lined binaries (KW 181, 287, 322, 325, 540) located between 0.20 and 0.50 mag above the ZAMS, with three other stars (KW 90, 334, 541) occupying the same position, without spectroscopic detection. One (KW 182) is close to the upper binary limit. Finally, in this colour interval, one finds also the double-lined contact binary (KW 244, TX Cnc) which could be not observed with Coravel due to the high rotation induced by the short period.

In the redder colour interval ($0.75 < B-V < 0.90$) the binarity is again well marked. Six stars are at least 0.50 mag above the ZAMS: two SB2s (KW 184, KW 533), two photometric binaries (KW 9, KW 257) and one single-lined binary (KW 297).

In total, eleven single-lined binaries show no photometric effects of duplicity and are completely indistinguishable from single stars. They are even often on the lower side of the single-star locus.

5. X-ray sources

Because the survey of Randich et al. (1995) covers an area of 4°x4° all the Klein-Wassink area has been observed. We have looked at the detection of the various kinds of stars: SB2s detected: 5/6, SB1s detected: 6/17, triples detected: 2/3, photometric binaries detected: 4/8, single stars detected: 8/57.

From the periods determined so far, it is difficult to derive firm conclusions. Most short periods binaries $P < 6^d$ have been detected, but KW 368 ($P = 76\overset{d}{.}5$) has also been detected although there is no photometric evidences from the companion. Several SB1s with much longer periods and half of the photometric binaries are also detected. But the triple system KW 365 is not. The 8 single stars detected could also be binaries, with low-mass companions and large separation which would explain why they have not been discovered in the radial-velocity survey.

6. Conclusions

The present results contribute to the recent effort to investigate the duplicity in open clusters from various techniques and in various cluster environments. So far only radial velocity can detect binaries with periods smaller than 1000 days which represents 64% of the spectroscopic binary sample in Praesepe. An adaptive-optics survey of 150 G and K stars in Praesepe will provide further information on the general duplicity in Praesepe (Bouvier et al. 1999), and will allow a better comparison of the properties of the Hyades. The limiting separation is around $0\overset{\prime\prime}{.}1$, which, at the distance of Praesepe, 180 pc (Robichon et al. 1999), corresponds to 54 yrs for two solar-mass stars and 76 yrs for two stars of 0.5 $M_{\odot}$. There will still be a gap in the coverage for periods between 20 yrs and 50 yrs. With an age of about 700 Myr, the binary properties of these two clusters are probably not representative any more of the primordial binary-parameter distribution.

The frequency of binaries in Praesepe is slightly larger than that found in the Pleiades (Mermilliod et al. 1992) in a similar colour interval, but the difference is significant at the 10% level. Thus we cannot totally exclude that both clusters have similar statistical properties. Detailed comparison with the Hyades is awaiting the publication of the results obtained by Stefanik &Latham (1992). But it seems that it is not possible to explain the X-ray flux differences between the Hyades and Praesepe on the basis of difference in duplicity as it has been proposed by Randich & Schmitt (1995) and Barrado y Navascués et al. (1998).

The combination of photometric and spectroscopic data results in a powerful tool to analyse binary stars in open clusters. For example, ten stars which would be classified as single on a photometric basis have been found to be binaries from their radial velocities, and seven stars which do not exhibit velocity variations appear to be binary stars when their photometry is taken into account. Thus, binary analysis is more complex than previously thought.

Based on simulations, Kroupa & Tout's (1992) results tend to favour a fraction of binaries close to unity. The present results have demonstrated the presence of numerous binaries among the so-called single stars, but much work remains to be done to detect companions in systems with $q < 0.3$. Such a detection is difficult in the visible, near-infrared photometry may help. As concerns radial velocities, instruments providing the precision needed to detect such low-mass companions are now in use, but the investment in observing time would be rather heavy and should extend over many years. However open clusters like the Pleiades and Praesepe are among the best targets to study the multiplicity of solar-type and low-mass main-sequence stars, to build a much more complete distribution of mass-ratios and orbital elements.

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References

Abt H.A., Willmarth D.W., 1999, ApJ 521, 682
Barrado y Navascués D., Stauffer J.R., Randich S. 1998, ApJ 506, 347
Baranne A., Mayor M., Poncet J.-L. 1979, Vistas in Astron. 23, 279
Bolte M. 1991, ApJ 376, 514
Bouvier J., Duchene G., Mermilliod J.-C., Simon T. 1999, in prep.
Bouvier J., Rigaut F., Nadeau D. 1997, A&A 323, 139
Duchêne G. 1999, A&A 341, 547
Duquennoy A., Mayor M. 1991, A&A 248, 485
Duquennoy A., Mayor M., Mermilliod J.-C. 1992, in "Binaries as Tracers of Stellar Formation", Eds. A. Duquennoy & M. Mayor, (Cambridge Univ. Press), p. 52
Johnson H.L. 1952, ApJ 116, 640
Jones B.F., Cudworth K.M. 1983, AJ 88, 215
Klein-Wassink W.J. 1927, Publ. Kapteyn Astron. Lab. no 4
Kroupa P., Tout C.A. 1992, MNRAS 259, 223
Mason B.D., McAlister H.A., Hartkopf W.I., Bagnuolo W.G. 1993a, AJ 105, 220
Mason B.D., Hartkopf W.I., McAlister H.A., Sowell J.R. 1993b, AJ 106, 637
Mayor M., Maurice E. 1985, inIAU Coll. 88, Eds A.G.D. Philip & D.W. Latham, L. Davis Press (Schenectady, N.Y.), p. 35
Mermilliod J.-C. 1997, Mem. Soc. Astr. It. 68, 853
Mermilliod J.-C., Duquennoy A., Mayor M. 1994, A&A 283, 515
Mermilliod J.-C., Mayor M. 1989, A&A 219, 125
Mermilliod J.-C., Rosvick J.M., Duquennoy A., Mayor M. 1992, A&A 265, 513
Mermilliod J.-C., Weis E.W., Duquennoy A., Mayor M. 1990, A&A 235, 114
Patience J., Ghez A.M., Reid I.N., Weinberger A.J., Mattews K. 1998, AJ 115, 1972
Raboud D., Mermilliod J.-C. 1998a, A&A 329, 101
Raboud D., Mermilliod J.-C. 1998b, A&A 333, 897
Randich S., Schmitt J.H.M.M. 1995, A&A 298, 115
Robichon N., Arenou F., Mermilliod J.-C., Turon C. 1999,A&A 345, 471
Stefanik R.P., Latham D.W. 1992, ASP Conf. Ser. 32, 173
Whelan J.A.J., Worden S.P., Mochnacki S.W. 1973, ApJ 183, 133