Astron. Astrophys. 319, 481–486 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Red giants in open clusters

VI. Orbits of ten spectroscopic binaries*,**

J.-C. Mermilliod[1], **J. Andersen**[2], **and M. Mayor**[3]

[1] Institut d'Astronomie de l'Université de Lausanne, CH-1290 Chavannes-des-Bois, Switzerland
[2] Niels Bohr Institute for Astronomy, Physics, and Geophysics, Astronomical Observatory, Juliane Maries Vej 30, DK-2100 Cøpenhagen, Denmark
[3] Observatoire de Genève, CH-1290 Sauverny, Switzerland

Received 11 July 1996 / Accepted 23 July 1996

Abstract. We present new orbits for ten (single-lined) spectroscopic binaries in seven open clusters: NGC 2489, 2567, 3033, 5822, 6134, 6664 and IC 2488 based on 243 individual radial velocities obtained with the southern CORAVEL scanner. The orbital periods range from 98.5 to 3566 days. The shortest-period orbit is circular, as expected. Seven of the binaries are confirmed cluster members, one is a possible member, and two are clearly non-members. Maximum masses from photometric separation and minimum masses from the spectroscopic orbits define the mass of the secondaries within an interval of M_{max} - M_{min} = 0.5 $M_{\odot}$. NGC 6664 #54 seems to have a rather massive secondary (M $>$ 3 $M_{\odot}$), but the UBV colours appear normal for a luminous red giant, while significantly bluer $(B-V)$ and $(U-B)$ colours would be expected. It could be a triple system, the secondary being itself a short period binary. This paper brings the number of orbits published in this programme to 53, 45 of which are confirmed red-giant cluster members and 8 are non-members.

Key words: cluster: open – binaries: spectroscopic – stars: fundamental parameters

1. Introduction

Open clusters present a large variety of spectroscopic binaries among their red giant members, with periods covering a wide interval from 40 to more than 7000 days (the longest orbital period we have determined so far) and a wide range of secondary masses. Several composite red giants with a marked effect on their colours due to the presence of a late B- or A-type star on the upper main sequence (Mermilliod & Mayor 1989, Paper I) have been found, but in many systems the secondary is not visible, neither photometrically nor spectroscopically. In such cases we suppose that the secondary star is either a main sequence star at least five magnitudes fainter than the primary, or a white dwarf. From the present data it is not possible to estimate the ratio of main sequence- to white dwarf secondaries, but the fact that the observed orbital eccentricities are generally normal (e $>$ 0.15), in contrast to the case of barium stars which show predominantly small eccentricities (Jorissen & Boffin 1992), suggests that the fraction of white dwarf secondaries is small. The abundance of red giant binaries in open clusters contrasts with the paucity of spectroscopic binaries discovered so far among red giants in globular clusters.

Analysis of the distribution of orbital elements for the first sample of 100 orbits (Mermilliod 1996) has shown that the shortest period at any primary mass is determined by the Roche limit at the red giant tip. A star evolving along the ascending red giant branch reaches its largest radius at the red giant tip. If it fills its Roche lobe, mass will be transferred to the secondary and its evolution is interrupted. Thus, the red giant binary will survive beyond the red giant tip phase only if the orbital period is longer than a critical period defined by the condition that the size of the Roche lobe is equal to the maximum radius of the red giant. Computations of these critical periods for various masses from 1.5 to 6 $M_{\odot}$ show good agreement with the shortest periods observed (Mermilliod & Mayor 1996). The shortest period determined by us so far (41.5 days for NGC 2477 #1025, unpublished orbit) is in good agreement with the mass (~ 2 $M_{\odot}$) and maximum radius of this star as deduced from the evolutionary tracks of Schaller et al. (1992). In this mass domain, stars with about 2 $M_{\odot}$ show the shortest ascending path before the onset of helium burning.

The period-eccentricity diagram for the red giants shows a well-marked transition from circular to eccentric orbits (Mer-

Send offprint requests to: J.-C. Mermilliod

* Based on observations collected with the Danish 1.54-m telescope at the European Southern Observatory, La Silla, Chile

** Table 3 is only available in electronic form at the CDS via anonymous ftp to cds.u-strasbg.f (130.79.128.5) or via http://cdsweb.u-strasbg.fr/abstract.html

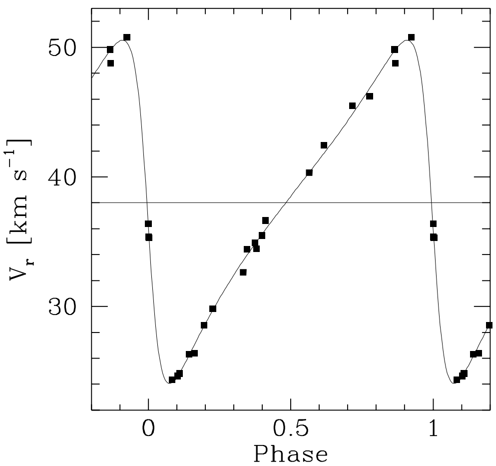

Fig. 1. Radial-velocity curve for LJ 25 in NGC 2489.

Table 1. Star positions and identifications

Cluster	No	α_{2000}	δ_{2000}	Remarks
NGC 2489	25	7 56 20.1	-30 05 01	
NGC 2567	104	8 18 18.1	-30 40 17	
NGC 3033	12	9 48 29.3	-56 24 53	
	19	9 48 42.3	-56 22 57	
NGC 5822	3	15 04 14.2	-54 25 48	CpD -53° 6231
	312	15 04 35.9	-54 332 4	CpD -54° 6305
NGC 6134	8	16 27 44.1	-49 09 49	
	34	16 27 55.9	-49 08 11	
NGC 6664	54	18 36 33.0	-08 15 32	Arp E
IC 2488	25	9 27 12.0	-56 41 57	CpD -56° 2185

milliod & Mayor 1992). A mass-period diagram plotted for the same sample of 100 orbits also shows clearly that the cut-off period for circular orbits is a function of the primary mass and increases with mass for stars more massive than about 2 $M_\odot$ (Mermilliod & Mayor 1996).

Raboud & Mermilliod (1994) have looked for effects of mass segregation in a study of 88 binary red giants, which were compared with 260 single red giants in 14 clusters of different ages. No statistically significant effect has been found, except for the well known case of M67 (Mathieu & Latham 1986). The explanation may either lie in incomplete survey of the cluster members in terms of radial distance from the cluster centre, as shown by simulations, or result from an age effect, most clusters of the sample being too young. Or the clusters may have lost their most massive short period central binaries if their periods were shorter than the Roche critical period mentioned above.

Orbital elements for 43 spectroscopic binaries in clusters have been published in earlier papers in this series. The present paper presents five additional orbits for red giant spectroscopic binaries in three clusters which have already been analysed in previous papers: NGC 5822 (Mermilliod et al. 1990), NGC 6134 (Claria & Mermilliod 1992) and NGC 6664 (Mermilliod et al. 1987), and five orbits for new binaries in NGC 2489, 2567, 3033 and IC 2488.

As in Paper II (Mermilliod et al. 1989), to which the reader is referred for a more detailed scientific justification of this programme, we shall discuss here only the binary stars. Open cluster results not presented in previous papers will be discussed later in this series.

2. Observations

A total of 243 radial-velocity observations were made of the ten programme stars during the period February 1983 through July 1995 with the photoelectric radial-velocity scanner CORAVEL (Baranne et al. 1979) on the Danish 1.54-m telescope at European Southern Observatory, La Silla, Chile. Its southern location, very good pointing accuracy and relatively large collecting area make this telescope well suited for the cluster programme. The limiting magnitude is B = 15.0. Integration times varied from 3 min. to about 20 min. depending on star brightness and seeing conditions. The positions and identifications of the binary red giants are listed in Table 1. References for the star numbering are given in Sect. 3 where individual systems are discussed.

The radial velocities are on the southern system defined by Mayor & Maurice (1985), which is a natural system for the southern CORAVEL and corresponds to that of the fainter ($V >$ 4.3) IAU standard stars. Errors for the individual observations are derived following the precepts of Baranne et al. (1979) and are generally below 0.5 km s^{-1} for all the stars discussed here. In all ten systems, the radial-velocity variations are large enough ($4 < K < 30$ km s^{-1}) to be clearly significant. The individual radial-velocity observations (Table 3) are available in electronic form only at the CDS via anonymous ftp (130.79.128.5). All the binaries discussed here are single-lined objects because the brighter and hotter A and early F-type companions usually show no dip, while the fainter secondary stars (G- and K-type dwarfs) are too faint to be detected.

UBV magnitudes and colours for the individual stars, the number of CORAVEL observations, and the time interval covered by them are given in Table 2 together with the orbital elements determined. No UBV magnitudes and colours are known for IC 2488 #25, but the Henry Draper Extension catalogue (HDE 300105) gives the spectral type G5 for this star. The periastron time T_O is expressed as T_O - 2440000.

3. Results for individual systems

3.1. NGC 2489

NGC 2489 is an intermediate-age cluster for which UBV photographic data have been published by Lindoff & Johansson (1968) and UBV CCD data by Ramsay & Pollaco (1992). Seven red giants in the cluster field have been observed. One (LJ 3) is non-member, and one (LJ 25) turned out to be a binary member. Twenty-three observations were obtained over an interval of 3968 days, which represents 2.5 cycles. While the phases between 0.1 and 0.95 are well covered (Fig. 1), the phases between

Table 2. General data and orbital elements for ten spectroscopic binaries

Cluster	N2489	N2567	N3033		N5822		N6134		N6664	I2488
Star no.	25	104	12	19	3	312	8	34	54	25
V	11.96	10.79	11.99	11.34	10.31	9.91	11.77	11.14	10.81	10.5
B-V	1.40	0.95	1.92	1.06	1.06	0.85	1.41	1.44	2.10	
U-B	1.32	0.63	1.90	0.85	0.76	0.85	1.20	1.36	2.39	
ΔT [d]	3968	2866	4104	4104	4480	4481	3588	2871	3999	3267
P [d]	1581.1	98.547	793.0	2122.9	3556.	977.86	702.7	257.83	739.31	520.57
	7.9	.009	2.9	8.0	29.	.61	1.2	.21	.63	.28
T_O [HJD]	9375.7	9413.92	8925.	6167.	9476.	7946.53	8830.0	9259.8	8476.6	9178.9
	3.0	.11	16.	12.	68.	.65	2.6	1.7	2.8	3.8
V_O [km/s]	37.97	35.79	-0.58	26.73	-29.65	-31.69	-27.00	-26.12	18.15	14.26
	.17	.09	.11	.10	.07	.10	.11	.10	.13	.12
K [km/s]	13.25	30.06	6.46	8.51	4.09	18.08	8.93	8.87	21.69	21.12
	.29	.13	.20	.17	.09	.21	.38	.22	.19	.21
e	0.56	0.000	0.19	0.36	0.19	0.728	0.50	0.42	0.31	0.153
	.02	.004	.02	.03	.02	.005	.03	.01	.01	.008
ω [°]	95.2		305.2	84.3	105.2	220.93	157.6	326.2	29.6	48.6
	1.8		6.2	2.6	6.9	.90	1.9	2.5	2.0	2.8
f(m) [$M_\odot$]	0.22	0.278	0.021	0.112	0.0237	0.194	0.0336	0.014	0.673	0.491
	.03	.004	.002	.011	.0021	.011	.0062	.001	.025	.017
asini [Gm]	239.	40.7	69.1	233.1	196.0	166.8	74.6	28.56	209.6	149.4
	10.	.2	2.7	8.1	6.9	3.4	4.7	.94	2.7	1.8
σ [km/s]	0.52	0.57	0.44	0.41	0.31	0.48	0.40	0.39	0.50	0.49
N_{obs}	23	42	24	19	23	25	21	21	21	24

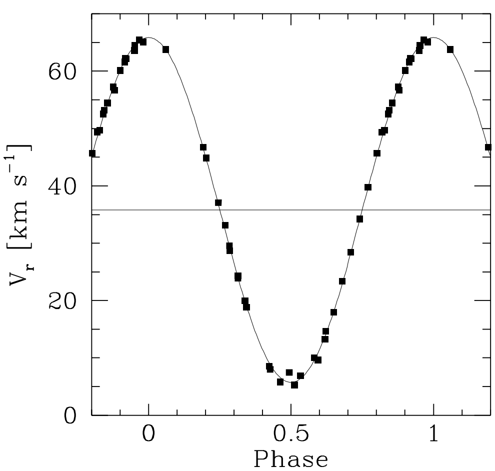

Fig. 2. Radial-velocity curve for L104 in NGC 2567.

0.95 and 0.1 are represented by two points only. Both extrema have been observed, and the orbit appears well defined.

The minimum mass for the secondary from the mass function is 1.5 $M_\odot$, assuming that the mass of the red giant primary is about 2.5 $M_\odot$. However, since the secondary does not produce any visible effect on the combined colours it should also be at least 5 mag. fainter and hence have a maximum mass of about 1 $M_\odot$. These conclusions are mutually inconsistent, but the actual luminosity of the secondary is quite uncertain because the Lindoff & Johansson (1968) UBV colours are based on photographic data, and the isochrone does in fact not fit the colour-magnitude diagram well, neither with CCD nor photographic data. New photometric data within a radius of $\sim$ 8 arcmin and a determination of metallicity would be useful.

3.2. NGC 2567

NGC 2567 is a young open cluster which has been studied by Lindoff (1968) in UBV photographic and by Ramsay & Pollaco (1992) in UBV CCD. Six red giants have been selected as candidates and one (L104) turned out to be a spectroscopic binary. The orbit is circular (Fig. 2), which is expected because the period is shorter than 100 days. Although the distribution in phase of the observations is not quite uniform, the orbit is well determined, thanks to the large number of measurements obtained (42). L104 is definitively a cluster member.

With an age of log t $\simeq$ 8.55, the mass of the red giant is $\sim$ 3.0 $M_\odot$ and the secondary has a mass of some 2.1 $M_\odot$, as deduced from the photometric separation. Again, the data are photographic and the errors of the colours may be rather large. Therefore the real effect on the colour of the system is also uncertain. The minimum mass from the spectroscopic mass function is 1.85 $M_\odot$. These two values would give a mass for the secondary around 2.0 $M_\odot$.

The red giant binary L104 is located at the periphery of the cluster rather than close to the cluster centre. Due to the young age of this cluster, significant mass segregation is not expected according to the results of Raboud & Mermilliod (1994).

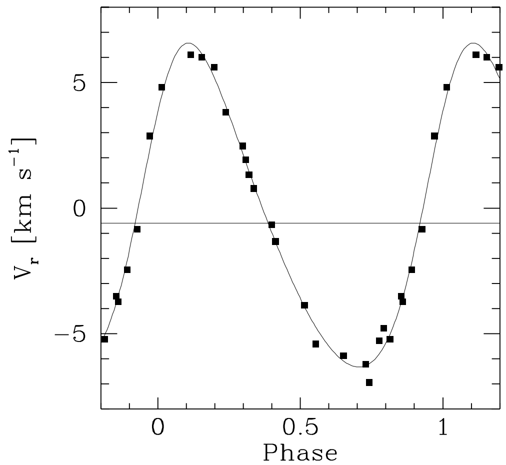

Fig. 3. Radial-velocity curve for VM 12 in NGC 3033.

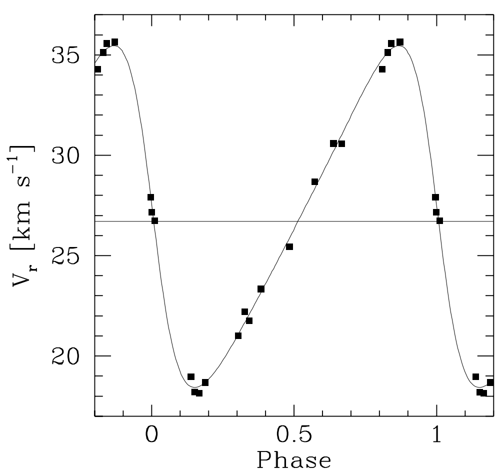

Fig. 4. Radial-velocity curve for VM 19 in NGC 3033.

3.3. NGC 3033

NGC 3033 is a poorly studied open cluster. Vogt & Moffat (1972) have published UBV data for 19 stars. Two red giants have been observed with CORAVEL (VM 12 and 19), and both turned out to be binaries. Since the systemic velocities are different, however, only one of them at most can be a member of the cluster. Star VM 12 is too red to be a member, but VM 19 has about the right magnitude. Its $B-V$ colour is somewhat too blue, which could be due to the presence of its companion. Since the mean velocity of the cluster is not known, it is not possible to decide upon the membership of VM 19 with certainty, and it will be considered as a possible member only.

The radial-velocity curves for VM 12 and VM 19 are shown in Figs. 3 and 4. For VM 19, 1.9 cycles have been covered by the observations spanning an interval of 4104 days. Due to its sparseness, the global parameters of this cluster (distance, diameter, age, composition, etc.) are quite uncertain, and a more detailed discussion will await further observations.

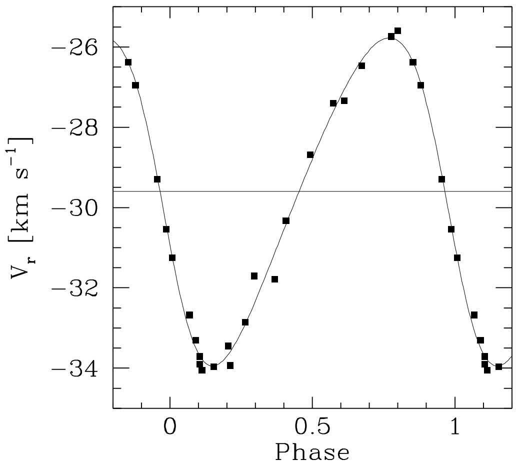

Fig. 5. Radial-velocity curve for Boz 3 in NGC 5822.

3.4. NGC 5822

NGC 5822 was discussed in Paper III (Mermilliod & Mayor 1990). The radial-velocity observations of 28 red giants confirmed the membership of 21 stars, and eight spectroscopic binaries were discovered. Four orbits (for Boz 2, 31 80 and 151; Bozkurt 1974) were published in Paper II (Mermilliod et al. 1989). Orbits have now been determined for two more binaries: Boz 3 (Fig. 5) and Boz 312 (Fig. 6). In addition, the variability of stars Boz 4 and 276, suspected in Paper III from the available data, has now been confirmed; however, no orbit can be determined yet, because the periods are quite long and the first cycle has not yet been completed for any of them.

The minimum mass from the spectroscopic orbit for the secondary of Boz 3 is 0.5 $M_{\odot}$, by assuming a primary mass of 2.2 $M_{\odot}$. The upper mass limit derived from the photometric separation is 0.9 $M_{\odot}$ since Boz 3 shows no visible effect due to its companion, which we therefore assume is some 5 magnitudes fainter. With a magnitude difference of 5 magnitudes, the combined magnitude of the binary would be less than 0.01 mag. brighter than that of the primary alone.

The eccentricity of Boz 312 is the highest of this sample and we are indebted to H. Lindgren and Bo Reipurth for obtaining the critical observations close to the minimum which led to the revision of our preliminary orbit. The UBV colours of Boz 312 ($B-V$ = 0.87, $U-B$ = 0.51) are appreciably bluer than the bulk of the red giants in NGC 5822 ($B-V$ = 1.05, $U-B$ = 0.70). The photometric separation gave a primary mass of 2.2 $M_{\odot}$ and a secondary mass of 1.8 $M_{\odot}$. In addition, the minimum mass from the spectroscopic mass function f(m) = 0.194 is 1.3 $M_{\odot}$. Thus, the secondary mass should be between 1.3 $M_{\odot}$ (sin i = 1) and 1.8 $M_{\odot}$ (sin i = 0.807, corresponding to an inclination of 54°).

3.5. NGC 6134

A discussion of the 24 red giants in the intermediate-age open cluster NGC 6134, based on new photometric data in the UBV, DDO and Washington systems, and CORAVEL radial veloc-

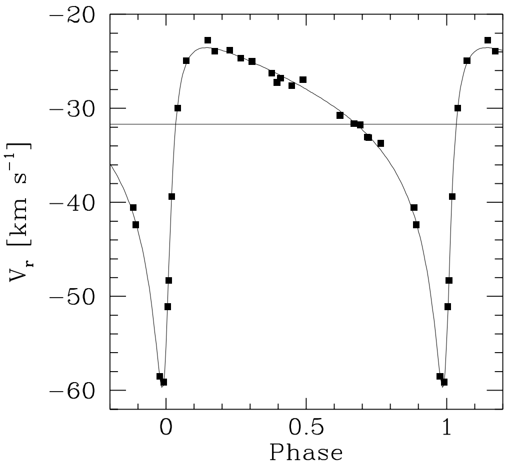

Fig. 6. Radial-velocity curve for Boz 312 in NGC 5822.

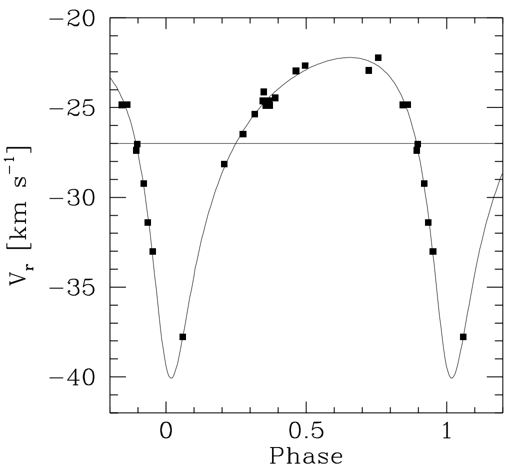

Fig. 7. Radial-velocity curve for L8 in NGC 6134.

ities, was published by Claria & Mermilliod (1992). Several spectroscopic binaries were discovered, but no orbital elements were published because only preliminary results were available at that time. The observations were pursued and reliable orbits eventually determined (Figs. 7 and 8). The systemic velocities of both stars L8 and L34 (star numbering from Lindoff 1972) are very close to the mean cluster velocity (-26.0 ± 0.24 km s^{-1}), and both are cluster members.

The minimum secondary masses deduced from the spectroscopic mass function for L8 and L34 are 0.6 and 0.4 $M_\odot$ respectively, and neither star shows any clear effect due to the companion. If the secondaries are assumed to be main sequence stars at least 5 magnitudes fainter than the primary, the maximum masses are 0.9 and 1.0 $M_\odot$ respectively, again confining the the secondary mass within an interval of ∼0.5 $M_\odot$.

3.6. NGC 6664

NGC 6664 contains the Cepheid EV Sct, and radial-velocity observations of 5 red giants and the Cepheid were discussed by Mermilliod et al. (1987). The membership of the Cepheid

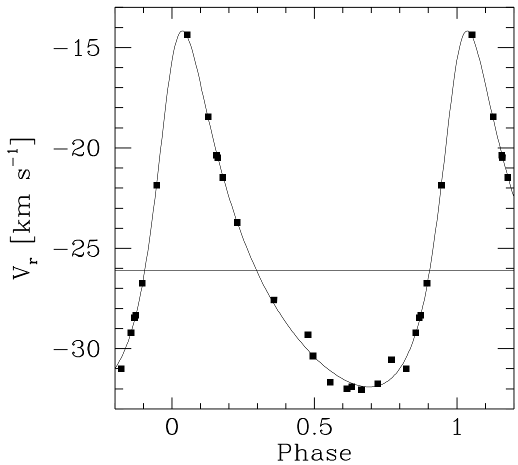

Fig. 8. Radial-velocity curve for L34 in NGC 6134.

variable was not very well established due to the uncertain velocity of one of the giants, star #54 = Arp E (Arp 1958). Further observations have showed that star #52 = Arp C (Arp 1958) is also a binary and a probable member.

The mean velocity now determined for star #54 (18.1 ± 0.1 km s^{-1}) is in good agreement with that of star #51 = Arp B (Arp 1958) (18.9 ± 0.3 km s^{-1}) and the Cepheid EV Sct itself (17.8 ± 0.2 km s^{-1}) as published by Mermilliod et al. (1987). Thus, the new results tend to support the membership of both the Cepheid EV Sct and the two red giants (Arp B and D) in the open cluster NGC 6664.

The radial-velocity curve of NGC 6664 #54 (Fig. 9) is rather well defined because the extrema have been well covered. Some phases could not be sampled because the period is close to two years. The mass function f(m) is quite large (0.673). With a primary mass of about 4.5 $M_\odot$ the minimum mass of the secondary is 3.5 $M_\odot$. With such a massive companion, the combined colours of the binary system should place it in the middle of the Hertzsprung gap, and it is surprising that this is not observed: the UBV colours seem normal for a luminous red giant when reddening is taken into account. No MK type has been published for this star, and no double dip has been observed to indicate that the companion is also a red star. It is, however, true that the observed colour-magnitude diagram shows large scatter, probably due to differential reddening. A plausible explanation is that the secondary is itself a short period spectroscopic binary, formed by two early F-type stars, which would explain the important mass and the non-detection of the secondary, and the limited colour effect due to the large magitude difference. This star would therefore be a highly hierarchised triple system.

3.7. IC 2488

The first UBV study of IC 2488 was performed by Pedreros (1987). He derived a distance of 1450 pc and a colour excess E(B-V) = 0.26. The age is close to that of the Pleiades (log t = 8.0). No UBV data were known when the programme was initiated, so the red giant candidates were selected for observation on

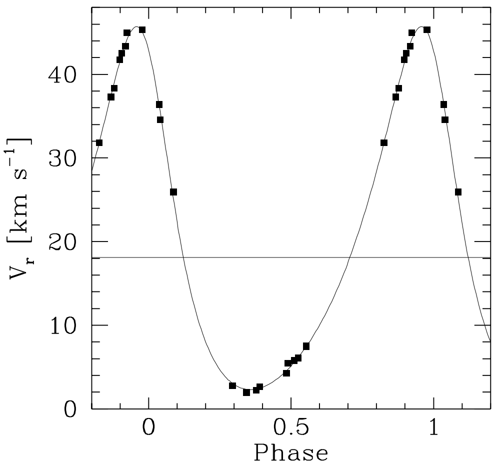

Fig. 9. Radial-velocity curve for star #54 in NGC 6664.

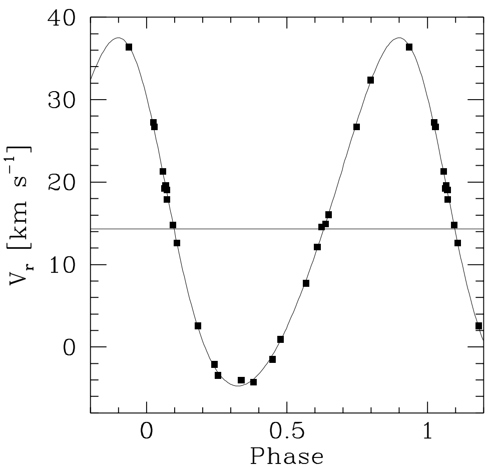

Fig. 10. Radial-velocity curve for star P25 in IC 2488.

the basis of the classification given in the Henry Draper Extension catalogue. Thirteen red giants in the cluster field have been observed, but only three are true cluster members and one (P25) has been discovered to be a binary. Unfortunately, its systemic velocity differs by some 17 kms^{-1} from the cluster mean velocity, so P25 is undoubtedly a non-member and no further analysis will be attempted. Fig. 10 shows its radial-velocity curve.

4. Conclusion

We have presented the first spectroscopic orbits for ten red giants in the fields of seven open clusters, continuing the publication of the results of a long-term observing programme started in 1983 in the southern hemisphere. The total number of spectroscopic binaries amongst cluster red giants that can be reached with the present instrumentation remains appreciable, and observations of stars in the sample continues with the aim to accumulate a sufficient number of orbits for meaningful analysis of the orbital element distributions and their possible dependence on the ages and masses of the primary stars, or the masses and other dynamical properties of the parent clusters.

Acknowledgements. It is a pleasure to thank H. Lindgren and Bo Reipurth for an important observation of NGC 5822 #312 in February 1990. We are also grateful to B. Nordström for obtaining measurements for several stars of this programme. The work of JCM and MM has been supported by continuous grants from the Swiss National Foundation for Scientific Research (FNRS), while JA thanks the Danish Natural Science Research Council, the Carlsberg Foundation, and the Danish Board for Astronomical Research for support of this research.

References

Arp H.C. 1958, ApJ 128, 166
Baranne A., Mayor M., Poncet J.-L. 1979, Vistas in Astron. 23, 279
Bozkurt S. 1974, Rev. Mex. Astron. Astrofis. 1, 89
Claria J.J., Mermilliod J.-C. 1992, A&AS 95, 429
Jorissen A., BoffinH.J.M. 1992, in: *Binaries as Tracers of Stellar Formation*, eds. A. Duquennoy & M. Mayor (Cambridge: Cambridge University Press), p. 110
Lindoff U. 1968, A&AS 4, 587
Lindoff U. 1972, A&AS 7, 231
Lindoff U., Johansson K. 1968, Ark. Astr. 5, 45
Mathieu R.D., Latham D.W. 1986, AJ 92, 1364
Mayor M., Maurice E. 1985, In: IAU Coll. 88, eds A.G.D. Philip, & D.W. Latham, L. Davis Press, (Schenectady, N.Y.), p. 35
Mermilliod J.-C. 1996, ASP Conf. Ser. 90 (in press)
Mermilliod J.-C., Mayor M. 1989, A&A 219, 125 (Paper I)
Mermilliod J.-C., Mayor M. 1990, A&A 237, 61 (Paper III)
Mermilliod J.-C., Mayor M. 1992, in: *Binaries as Tracers of Stellar Formation*, eds. A. Duquennoy & M. Mayor (Cambridge: Cambridge University Press), p. 183
Mermilliod J.-C., Mayor M. 1996, 9th Cool Stars and Stellar System Conf. (in press)
Mermilliod J.-C., Mayor M., Andersen J., Nordström B., Lindgren H., Duquennoy A. 1989, A&AS 79, 11 (Paper II)
Mermilliod J.-C., Mayor M., Burki G. 1987, A&AS 70, 389
Pedreros M. 1987, AJ 94, 92
Raboud D., Mermilliod J.-C. 1994, A&A 289, 121
Ramsay G., Pollaco D.L. 1992, A&AS 94, 73
Schaller G., Schaerer D., Meynet G., Maeder A. 1992, A&A 96, 269
Vogt N., Moffat A.F.J. 1972, A&AS 9, 97

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.