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Red giants in open clusters*

IX. NGC 2324, 2818, 3960 and 6259

J.-C. Mermilliod[1], J. J. Clariá[2], J. Andersen[3], A. E. Piatti[2], and M. Mayor[4]

[1] Institut d'Astronomie de l'Université de Lausanne, 1290 Chavannes-des-Bois, Switzerland
[2] Observatorio Astronómico, Laprida 854, 5000 Córdoba, Argentina
[3] Niels Bohr Institute for Astronomy, Physics, and Geophysics, Astronomical Observatory, Juliane Maries Vej 30, 2100 Copenhagen, Denmark
[4] Observatoire de Genève, 1290 Sauverny, Switzerland

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Abstract. We present accurate radial velocities and photoelectric *UBV* photometry for 73 and 57 red-giant candidates, respectively, in the intermediate-age open clusters NGC 2324, 2818, 3960 and 6259. These data confirm the membership of 47 stars, 12 of which (26%) are spectroscopic binaries; three preliminary orbits have been determined in NGC 3960. From Washington photometry of 8 red giant members, the metallicity of NGC 6259 is found to be $[Fe/H] = 0.06 \pm 0.08$. At the age of these clusters, most of the red giants are observed in the core-helium (clump) burning phase, the general morphology of which is well reproduced by theoretical models with convective overshooting. However, a number of bona fide cluster giant members are found significantly to the red of the isochrones fitting the rest of the CMD of these and a few other clusters. Some of these stars are binaries, but others seem to be single. In either case, their red colours and/or low luminosities remain unexplained by current stellar evolution theory.

Key words. cluster: open – individual: NGC 2324, NGC 2818, NGC 3960, NGC 6259 – binary: spectroscopic – star: evolution – star: red giant

1. Introduction

Colour-magnitude diagrams (CMDs) of open clusters are fundamental observational constraints on theoretical models of stellar evolution. In particular, the detailed morphology of the red-giant clump feature contains valuable information on the size and physical state of helium cores at the onset of core helium burning. Critical comparisons of theory and observation are, however, usually difficult because of inadequate photometry and, even more, lack of precise membership and duplicity information for individual stars in the red-giant region of the typical cluster CMD. In this situation, potentially informative deviations from an overall isochrone match to the average giant location cannot be substantiated. This paper presents part of the results from a long-term effort to provide radial-velocity and photometric data for red giants in open clusters which will alleviate these deficiencies.

Previous papers in this series (Mermilliod & Mayor 1990; Clariá et al. 1999; Girardi et al. 2000b) have shown that the distribution of red giants in the CMD of certain open clusters presents peculiar, but nonetheless real features. Isochrones computed in the standard manner are often not able to reproduce the observed star clumps. For instance, Girardi et al. (2000b) showed that the apparently peculiar, detailed clump morphology of the clusters NGC 752, NGC 7789, and NGC 2660 could be understood by noting that the masses of the clump giants in these clusters are just straddling the limit between non-degenerate and degenerate core helium ignition (the helium flash), and assuming that effects such as rotation or mass loss caused small variations in the mass of their helium cores at their arrival on the ZAHB.

In this paper we substantiate an earlier finding (Mermilliod & Mayor 1989, 1990) that some clusters contain a small number of red giants with well-established membership credentials – some double, some apparently single – which lie significantly to the red of an otherwise well-defined giant branch. It seems equally difficult to understand the properties of these stars in terms of either

Send offprint requests to: J.-C. Mermilliod,
e-mail: Jean-Claude.Mermilliod@obs.unige.ch

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Table 1. Basic cluster properties.

NGC	RA (2000)	Dec	$m-M$	$E(B-V)$	[Fe/H]	$\log t$
2324	7 04.2	+01 03	12.30	0.04	−0.52	8.85
2818	9 16.0	−36 38	12.50	0.18	−0.17	8.97
3960	11 50.9	−55 42	12.20	0.29	−0.27	9.03
6259	17 00.7	−44 40	13.25	0.66	+0.10	8.30

active single-star models or as binary systems composed of a normal red giant and another star from anywhere on the cluster sequence.

This paper provides improved radial-velocity and photometric data for the determination of the membership of candidate red giants in four intermediate-age clusters, and for the study of their colour-magnitude diagrams. A number of spectroscopic binaries were discovered, but due to the relative faintness of the objects and the scheduling of observing runs in Chile, only three orbits have been completed so far.

2. Observations

The coordinates and other characteristics of the four clusters observed are given in Table 1. The distance modulus and the color excess have been redetermined from the available data by taking into account the correction to the ZAMS position as a function of the cluster metallicity according to the relation of VandenBerg & Poll (1989): δM_V ([Fe/H]) $= -$[Fe/H] (1.44+0.362 [Fe/H]). These values differ from those presently included in the WEBDA database, which are best reproduced if [Fe/H] is set to 0. The [Fe/H] data we use come from the list of abundances recalibrated by Gratton (2000).

Red giant candidates were selected on the basis of the photometric data available at the start of the programme in 1983, taking into account the effects of any main-sequence companion on the combined colours.

No mean radial velocities have been published so far for NGC 2324, NGC 2818 and NGC 6259, while Friel & Janes (1993) give a velocity of -12 km s^{-1} for NGC 3960, based on 6 stars.

2.1. Radial-velocity measurements

Radial-velocity observations were obtained with the CORAVEL instrument (Baranne et al. 1979) at the 1.54-m Danish telescope at ESO, La Silla, Chile. At least two observations, typically spanning 3–4 years, were obtained through the period 1983–1994 for the non-variable stars. The radial velocities are on the system defined by Udry et al. (1999) from high-precision radial-velocities obtained with the ELODIE spectrograph (Baranne et al. 1996). This calibration corrects for all systematic effects of the CORAVEL system.

The individual observations (Table 2) are available in electronic form from the Strasbourg service for published tables (`cdsarc.u-strasbg.fr (130.79.1228.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/375/30`). Our mean results for individual stars in the four clusters are summarized in Table 3 (NGC 2324), Table 4 (NGC 2818), Table 5 (NGC 3960) and Table 7 (NGC 6259).

2.2. UBV and Washington photometry

Photoelectric UBV measurements of 14 giant candidates in the open cluster NGC 2324, 19 in NGC 2818, 6 in NGC 3960 and 20 in NGC 6259 were carried out between 1985 and 1994 with the 1.0 m telescopes at La Silla and Cerro Tololo Inter-American Observatory (CTIO), both located in Chile. A single-channel photoelectric photometer was used in these observatories in conjunction with dry-ice cooled RCA 31034 (Quantacon) and Hamamatsu R943-02 Ga-As photomultipliers, respectively, with pulse-counting electronics. Mean extinction coefficients for La Silla and CTIO were used and typically 12–18 standard stars from the lists of Cousins (1973, 1974) and Graham (1982) were nightly observed to transform to the standard UBV system. The results of the UBV photometry are listed in Tables 3–5 and 7, respectively.

Photoelectric photometry in the Washington system was also obtained for 10 giant candidates in NGC 6259 with the CTIO 1.0 m telescope in March 1985. The CMT_1T_2 filters recommended by Canterna (1976) were employed together with a Ga-As RCA 31034 photomultiplier cooled with dry ice and pulse counting electronics. Mean CMT_1T_2 extinction coefficients for CTIO were used in the reductions. Standard stars selected from the list of Canterna (1976) were used to place the observations in the standard Washington system. External mean errors of the UBV and Washington photometries range between 0.01 and 0.02 mag; these errors are essentially equal for all nights. The results of the Washington photometry are listed in Table 8.

3. Results

The observational results are summarized in Tables 3–5 and 7. Their general layout is as follows: Cols. (1) and (2) give star identification numbers in the systems specified below for each cluster; only one numbering system is used for NGC 3960, with obvious consequences for the column numbers in Table 5. Columns (3) and (4) then list right ascensions and declinations (J2000), mainly extracted from the GSC, and Cols. (5) to (8) give the V, $B-V$ and $U-B$ magnitudes and colours and the number of observations. The mean radial velocities and associated mean errors, the number of observations, time interval (days) spanned by the observations, and the probability $P(\chi^2)$ that the scatter is due to observational errors only, are given in Cols. (9) to (13). Finally, the remarks in Col. (14) identify cluster members (M), possible members (M?), non-members (NM), and spectroscopic binaries (SB). $P(\chi^2) < 0.005$ is the criterion adopted for certain detection of spectroscopic binaries.

3.1. NGC 2324

The adopted numbering system (Col. (1) in Table 3) is from Cuffey (1941), while Col. (2) gives the identifications by Becker et al. (1976). Most earlier photometric data for this cluster are photographic (Hoag et al. 1961; Rahim & Hassan 1967; Becker et al. 1976); V, $B-V$ data in Table 3 without indication of the number of observations are from Becker et al. (1976). The average difference in the photometry, in the sense (this paper – earlier), is $\Delta(V) = 0.116 \pm 0.046$, $\Delta(B-V) = -0.040 \pm 0.051$, compared with the photographic data by Becker et al. (1976), for 14 stars. No previous radial-velocity observations have been reported for NGC 2324.

The separation of cluster members and field stars is unambiguous from the radial velocities in Table 3. Star #280 is probably a spectroscopic binary ($P(\chi^2) = 0.002$), and therefore the mean velocity tabulated just represents the mean based on the available observations, but not the true systemic velocity. Because it falls well on the red-giant track it has been considered as a possible member. The radial velocity of #121 deviates from the cluster mean by 6 $\mathrm{km\,s^{-1}}$ (some 10 σ) and has been constant over 2864 days. Although it could be a binary member with a very long period and/or eccentric orbit, we consider it a non-member in the present study. Its position in the colour-magnitude diagram (Fig. 4) is compatible with membership, but most radial-velocity non-members share this property.

From the 5 red giants with constant radial velocities, we compute a mean cluster velocity of $< V_{\mathrm{r}} > = +41.81 \pm 0.25$ $\mathrm{km\,s^{-1}}$ (s.e. of the mean). From the available observations, three spectroscopic binaries are identified, all apparently with periods in excess of 3000 days. The binary frequency is $3/8 = 37\%$.

3.2. NGC 2818

NGC 2818 was first observed photometrically by Tifft et al. (1972). Pedreros (1989) and Surendiranath et al. (1990) obtained UBV and VI_{c} CCD data respectively. Geisler et al. (1992) published Washington photometry of 19 red giants and derived a metallicity of [Fe/H] $= -0.31$. Stetson (2000) produced a list of BVR magnitudes and colours for 178 stars in the standard field of NGC 2818. The average differences in the photometry, in the sense (this paper – earlier), is $\Delta(V) = -0.023 \pm 0.040$, $\Delta(B-V) = 0.019 \pm 0.020$ (10 stars), and $\Delta(U-B) = 0.023 \pm 0.044$ (7 stars), compared with the CCD data by Pedreros et al. (1989), and $\Delta(V) = 0.012 \pm 0.006$, $\Delta(B-V) = 0.022 \pm 0.016$ for 8 stars in common with Stetson's (2000) recent CCD data.

Table 4 presents our results. The adopted numbering system (1) is from Pedreros (1989) for the three stars with numbers smaller than 1000, and from Tifft et al. (1972) for the numbers larger than 1000. Column (2) displays the identifications by Pedreros (1989). V and $B-V$ for stars #138, 296, 297 and 1053 not observed by us are from Pedreros (1989).

The separation of the members and field stars is unambiguous, as 15 stars have radial velocities within 1.2 σ of their mean, while all others are far from that value. From the 12 red giant members with constant radial velocities, we compute a mean cluster velocity of $< V_{\mathrm{r}} > = +20.69 \pm 0.29$ $\mathrm{km\,s^{-1}}$ (s.e. of the mean). Three spectroscopic binaries have been discovered. The binary frequency is thus $3/15 = 20\%$. Due to the limited number of observations obtained for each star, the detection of binaries is probably still incomplete, although member star identification is already definitive.

3.2.1. Membership of the planetary nebula

According to the catalogue of Durand et al. (1998), the radial velocity of the planetary nebula seen within the cluster area is -0.9 ± 2.9 $\mathrm{km\,s^{-1}}$, close to that obtained by Tifft et al. (1972), +8 $\mathrm{km\,s^{-1}}$. Tifft et al. concluded that the planetary nebula was probably associated with the cluster, based on their cluster velocity of $+3 \pm 20$ $\mathrm{km\,s^{-1}}$ derived from stars 1104 and 1118. The difference between the reliable radial velocity of the planetary nebula obtained by Meatheringham et al. (1988), -1.0 ± 3.0 $\mathrm{km\,s^{-1}}$, and our new cluster mean velocity, $+20.69 \pm 0.29$ $\mathrm{km\,s^{-1}}$, does not support this contention. Pedreros (1989) distance estimates are consistent with such an association, but Acker (1978) and Pottasch (1983) determined distances of 1.4 and 1.8 kpc respectively, using distance scales based on interstellar extinction, while the distance modulus given in Table 1 corresponds to a distance of 2.4 kpc for the cluster. These disagreements make the planetary-nebula membership very unlikely.

3.3. NGC 3960

Janes (1981) has published BV photolelectric data for 98 stars and BV photographic data for 219 stars in NGC 3960. The average difference in the photometry, in the sense (this paper – earlier), is $\Delta(V) = 0.015 \pm 0.014$, $\Delta(B-V) = -0.019 \pm 0.016$ from six stars in common with the photoelectric data by Janes (1981). Geisler et al. (1992) obtained Washington photometry for 14 red giants and derived a [Fe/H] value of -0.68, while Friel & Janes (1993) determined [Fe/H] $= -0.34$ from medium-resolution spectra. The latter authors also determined radial velocities for 6 of the red giants.

Table 5 presents our results. The adopted numbering system (1) is from Janes (1981), as are the BV data without $U-B$ values. Radial velocities from Friel & Janes (1993) are reproduced in Col. (13).

Five of the stars are spectroscopic binaries, and three preliminary orbits have been determined. The orbital parameters are presented in Table 6 and the radial-velocity curves are displayed in Figs. 1, 2 and 3. Although we have only 12, 14 and 12 observations respectively for the three

Table 3. *UBV* and CORAVEL data for red giants in NGC 2324.

No (1)	B (2)	RA (2000) (3)	Dec (4)	V (5)	$B-V$ (6)	$U-B$ (7)	n (8)	V_r (9)	ϵ (10)	N (11)	ΔT (12)	$P(\chi^2)$ (13)	Rem (14)
19	135	7 04 51.16	+1 02 55.7	13.482	1.090	0.622	2	+41.25	0.44	2	2531	0.712	M
67	57	7 04 13.54	+1 02 03.7	13.601	1.053	0.544	2	+42.00	0.49	3	2141	0.964	M
91	79	7 04 08.20	+1 05 18.3	13.17	1.07			+39.78	3.54	12	3329	0.000	M, SB
118	50	7 04 03.71	+1 00 13.6	13.423	1.099	0.547	3	+42.05	1.44	8	3329	0.000	M, SB
134	56	7 04 14.72	+1 01 05.6	13.330	1.096	0.705	2	+42.11	1.78	10	3331	0.000	M, SB
136	32	7 04 16.22	+1 01 11.3	12.491	1.240	0.935	3	+41.23	0.27	3	2140	0.890	M
161	80	7 04 01.11	+1 06 02.4	13.382	1.046	0.575	3	+42.29	0.39	3	2138	0.308	M
215	47	7 04 00.27	+0 58 15.9	12.561	1.462	1.285	3	+42.27	0.26	3	2139	0.400	M
280		7 04 22.52	+1 06 13.6	13.71	1.07			+38.00	1.31	4	2519	0.002	M?, SB
50	106	7 04 02.24	+1 02 20.3	12.887	1.131	0.725	3	+9.50	1.29	5	1784	0.000	NM, SB
75	27	7 04 18.85	+1 02 36.6	12.360	1.309	1.161	3	+5.22	0.34	2	343	0.309	NM
86	16	7 04 14.69	+1 04 48.6	13.816	1.045	0.680	2	+10.47	0.53	2	345	0.458	NM
103	93	7 03 57.88	+1 04 16.1	13.213	1.097	0.686	3	+91.96	0.60	2	345	0.212	NM
121	52	7 04 05.81	+1 00 34.6	13.570	1.055	0.460	3	+47.82	0.24	7	2864	0.520	NM?
147	18	7 04 21.98	+1 04 32.9	13.361	1.007	0.400	4	−11.15	1.49	2	345	0.046	NM
183	37	7 04 11.21	+0 59 41.5	12.876	1.244	0.985	3	+19.35	0.48	2	342	0.228	NM
276	130	7 04 26.70	+1 00 13.9	12.93	0.77			−5.02	0.46	2	342	0.226	NM

Table 4. *UBV* and CORAVEL data for red giants in NGC 2818.

No (1)	P (2)	RA (2000) (3)	Dec (4)	V (5)	$B-V$ (6)	$U-B$ (7)	n (8)	V_r (9)	ϵ (10)	N (11)	ΔT (12)	$P(\chi^2)$ (13)	Rem (14)
138	138	9 16 10.67	−36 36 13.6	13.68	0.96			+20.54	0.37	2	1417	0.670	M
296	296	9 16 03.55	−36 39 50.8	13.60	1.02			+20.24	0.40	2	1418	0.575	M
297	297	9 16 03.97	−36 39 50.8	13.40	1.04			+20.36	0.42	2	1418	0.344	M
1004	D	9 16 12.61	−36 34 46.7	12.182	1.128	0.724	2	+21.51	7.89	4	3325	0.000	M, SB
1044	64	9 16 02.99	−36 34 35.0	13.731	1.012	0.608	2	+19.74	0.48	3	2177	0.204	M
1053	84	9 15 59.37	−36 34 57.1	13.34	0.89			+22.83	2.14	6	2156	0.000	M, SB
1063	119	9 16 04.57	−36 35 49.7	13.834	1.022	0.589	2	+21.08	0.58	2	1789	0.271	M
1069	167	9 16 08.76	−36 36 48.6	13.664	1.025	0.659	2	+19.61	0.49	2	1790	0.783	M
1135	287	9 16 12.61	−36 39 42.8	13.857	0.999	0.748	3	+23.17	0.45	2	1789	0.605	M
1156	225	9 16 18.86	−36 38 08.8	13.885	1.032	0.547	2	+20.65	0.61	2	1114	0.762	M
1159	W	9 16 17.56	−36 37 53.5	12.559	1.098	0.845	2	+19.54	0.86	7	3263	0.000	M, SB
2038		9 15 56.55	−36 40 51.7	13.568	1.055	0.712	2	+21.58	0.61	3	2176	0.019	M
2130		9 16 30.87	−36 34 20.7	12.541	1.347	1.303	2	+20.21	0.44	2	1114	0.310	M
2142		9 16 27.82	−36 36 24.5	13.794	1.014	0.657	2	+20.26	0.49	2	1114	0.903	M
3035		9 15 52.34	−36 30 44.5	13.346	1.035	0.755	2	+22.02	0.66	2	1797	0.129	M
1003	59	9 16 14.62	−36 34 27.6	13.393	1.157	0.912	2	+60.84	0.56	2	1795	0.260	NM
1126	311	9 16 07.59	−36 40 10.3	13.551	1.173	0.664	3	+67.56	0.52	2	1789	0.287	NM
1161	F	9 16 17.56	−36 37 53.5	12.702	1.498	1.633	3	+32.20	0.43	2	1114	0.954	NM
2035		9 16 03.38	−36 40 19.1	13.059	1.102	0.756	2	−15.52	4.73	4	2176	0.000	NM, SB
2139		9 16 34.85	−36 36 00.5	12.910	1.020	0.667	2	+35.04	0.42	2	1114	0.475	NM
2147		9 16 36.01	−36 37 47.9	13.406	1.226	1.088	2	+59.83	0.82	2	1114	0.046	NM
3034		9 15 50.23	−36 30 36.0	13.125	1.133	0.868	2	+9.06	0.41	2	1797	0.600	NM
3074		9 16 37.81	−36 33 00.2	13.657	1.253	1.190	2	+68.92	0.69	1			NM

binaries, the orbits are already well determined and only one stable solution was found for each system. The eccentricity for #275 has been fixed to 0.00, consistent with its short period (Mermilliod & Mayor 1992, 1996)

From the radial velocities, two of the stars (#55 and 297) are obvious non-members. Eliminating these, the two binaries without orbits, and star #18, we find a mean cluster velocity of $< V_r > = -22.56 \pm 0.17$ km s^{-1} (s.e. of the mean) from the remaining 6 single stars and 3 binaries with orbits. Star #18 deviates from this value by 4.29 km s^{-1} or $\sim 7.7\sigma$, allowing for the uncertainty of both velocities. Including star #18 changes $< V_r >$ to -22.08 km s^{-1}, with #18 still nearly 3σ off. We conclude that #18 is a field star or perhaps a long-period cluster binary; more radial-velocity data are needed for a conclusive result regarding the membership status of this star.

Table 5. *UBV* and CORAVEL data for red giants in NGC 3960.

No	RA (2000)	Dec	V	$B-V$	$U-B$	n	V_r	ϵ	N	ΔT	$P(\chi^2)$	Litt	Rem
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
18	11 50 21.91	−55 42 21.6	12.65	1.62			−18.27	0.31	3	742	0.416		M?
24	11 50 28.26	−55 41 36.6	13.294	1.205	0.828	2	−20.31	0.63	6	3997	0.000	−13	M, SB
28	11 50 26.75	−55 40 28.3	13.003	1.182	0.744	3	−22.48	0.26	4	3256	0.990	−9	M
41	11 50 36.00	−55 42 06.2	13.168	1.282	0.993	3	−22.57	0.24	4	3254	0.377	−6	M
43	11 50 33.20	−55 42 37.1	13.607	1.305	0.888	2	−22.52	0.87	7	4798	0.000		M, SB
44	11 50 37.42	−55 41 03.3	12.682	1.201	0.874	2	−21.42	0.28	5	3997	0.257		M
47	11 50 41.25	−55 40 54.6	13.65	1.17			−22.38	0.31	4	2261	0.412	−22	M
50	11 50 37.73	−55 40 14.7	13.126	1.183	0.733	3	−22.31	0.23	12	4799	0.000	−9	M, SBO
91	11 50 26.15	−55 39 45.3	13.32	1.17			−23.19	0.20	15	4799	0.000		M, SBO
102	11 50 26.24	−55 43 51.5	11.50	1.70			−22.69	0.20	4	3257	0.928		M
275	11 50 33.40	−55 38 54.0	13.45	1.35			−22.50	0.19	12	4798	0.000		M, SBO
286	11 50 38.33	−55 39 45.6	13.17	1.20			−23.02	0.33	4	3256	0.208		M
55	11 50 50.52	−55 40 12.0	13.55	1.31			+28.83	0.26	4	3256	0.442		NM
297	11 50 43.57	−55 38 41.4	12.34	1.41			+9.50	0.26	3	2192	0.449	+21	NM

Table 6. Orbital elements of three stars in NGC 3960.

Element	50	91	275
P [d]	328.77	209.12	96.899
	.30	0.25	.018
T [HJD-2440000]	9583.6	9830.2	9939.42
	7.9	3.0	.34
e	0.16	0.36	0.000
	.02	.03	fixed
γ [km s^{-1}]	−22.31	−23.19	−22.50
	.23	.20	.19
ω [°]	262.95	359.6	
	9.1	5.0	
K [km s^{-1}]	12.92	11.98	18.91
	.34	0.67	.23
$f(m)$ [$M_\odot$]	0.0708	0.0301	0.0680
	.0065	.0061	.0025
$a \sin i$ [Gm]	57.6	32.1	5.52
	1.8	2.2	.31
σ(O–C) [km s^{-1}]	0.54	0.54	0.61
$n_{\rm obs}$	12	14	12

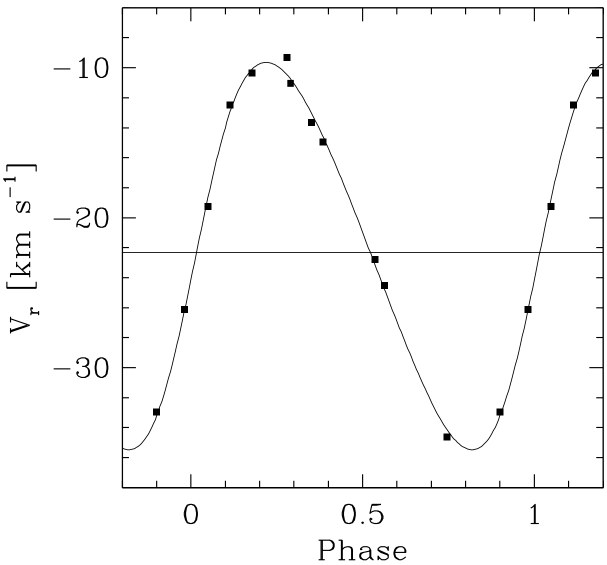

Fig. 1. Radial-velocity curve for star 50 in NGC 3960.

3.4. NGC 6259

NGC 6259 was first observed by Hawarden (1974) who obtained photoelectric *UBV* photometry for 24 stars and *BV* photographic data for 163 stars. Anthony-Twarog et al. (1989) obtained further *BV* photographic data for 443 stars. Recently, Piatti et al. (1998) published VI_c CCD data for 226 stars. These are the only data available for this cluster. The average difference in the photometry, in the sense (this paper − earlier), is $\Delta(V) = 0.038 \pm 0.032$, $\Delta(B-V) = -0.017 \pm 0.031$, for 9 stars in common with the data by Anthony-Twarog et al. (1989), and $\Delta(V) = 0.016 \pm 0.027$ from 9 stars in common with Piatti et al. (1998).

Table 7 presents our results. The adopted numbering system (1) is based on Hawarden's (1974) while Col. (2) gives the identifications by Anthony-Twarog et al. (1989). V, $B-V$ data without indication of the number of observations are from the photographic data of Anthony-Twarog et al. (1989).

Stars with three or more radial-velocity observations are from the original sample, while those with only one observation were added to the observing list after the publication of the paper by Anthony-Twarog et al. (1989). It appears probable from Hawarden's map that the entire cluster area was not covered and that the sample of red giant candidates is therefore incomplete. The area studied by Anthony-Twarog et al. (1989) is probably also not large enough.

For the stars with three observations, the membership decision is again quite obvious, while we cannot decide from a single observation only whether stars #1335, 2221 and 2301 are binaries or non-members. They are therefore excluded from the computation of the cluster mean

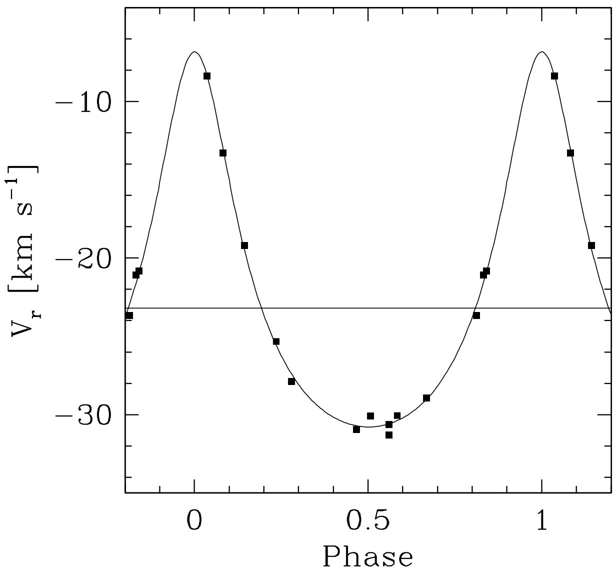

Fig. 2. Radial-velocity curve for star 91 in NGC 3960.

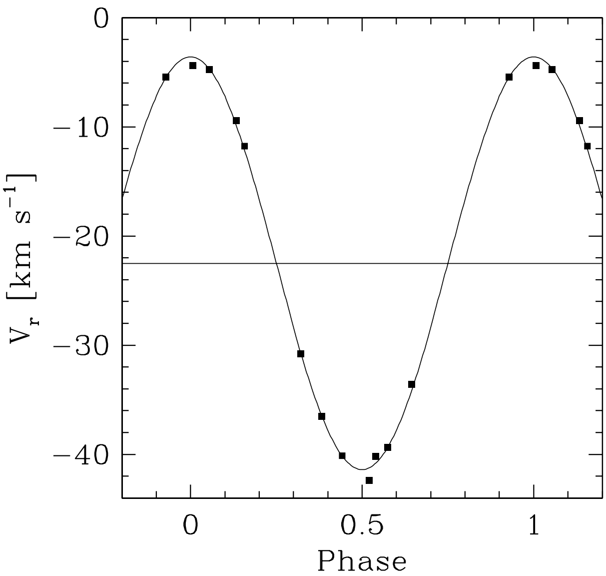

Fig. 3. Radial-velocity curve for star 275 in NGC 3960.

velocity, which is equal to: $< V_{\rm r} > = -33.70 \pm 0.19$ km s^{-1} (s.e. of the mean). Somewhat surprisingly, no probable spectroscopic binaries have been detected, although we would normally have detected some from 3 observations over 4 years. But none of the values of $P(\chi^2)$ is anywhere near zero, and only the three stars mentioned above differ significantly from the cluster mean velocity. It is probable that continued observations of the known sample of stars, as well as any red-giant candidate located outside Anthony-Twarog et al. (1989) area that might have been missed so far, could help to identify the missing binaries.

3.5. Washington photometry

The Washington photometric data obtained for 10 stars in NGC 6259 are displayed in Table 7. The first column contains Hawarden (1974) identification numbers. The following columns give the CMT_1T_2 measurements, together with the standard deviations of individual measurements σ (in mag) on the second line, and the number of measurements (N).

Before the cluster metal abundance can be derived, corrections for reddening must be made. Therefore, the observed colour indices were dereddened using $E(B-V) = 0.66$ (see Sect. 4.4) and the colour-excess ratios given by Geisler et al. (1991). The Washington system provides five independent metallicity parameters, denoted Δ_j ($j = 1$, 2, 3, 4, 5), which gather information from the blue-green and green-red spectral regions. The abundance-sensitive parameter Δ is defined as the difference between the observed colour $(C-M)$, $(M-T_1)$ or $(C-T_1)$ and the solar-abundance colour at the observed (T_1-T_2) [or $(M-T_2)$], where all colours refer to dereddened values. For example, $\Delta_1 = \Delta(C-M)_{T_1-T_2} = (C-M)_0 - (C-M)_*$, where $(C-M)_0$ is the observed $(C-M)$ value corrected for reddening and $(C-M)_*$ is the solar-abundance $(C-M)$ for a star with the observed (reddening-corrected) (T_1-T_2).

Geisler et al. (1991) described a procedure for correcting the decrease in abundance sensitivity with temperature and established empirical calibrations of the abundance indices $\Delta'_1 - \Delta'_5$ with [Fe/H]. These Δ' indices can be calculated from the Δ indices using Eq. (2) of Geisler et al. (1991). In particular, $\Delta' = \Delta$ for stars with $0.4 < (T_1-T_2)_0 < 0.57$ or $1.0 < (M-T_2)_0 < 1.45$. The resulting mean values and standard deviations of the mean from eight radial velocity members of NGC 6259 are:

$< \Delta'_1 > = < \Delta'(C-M)_{T_1-T_2} > = 0.058 \pm 0.021$
$< \Delta'_2 > = < \Delta'(M-T_1)_{T_1-T_2} > = 0.020 \pm 0.016$
$< \Delta'_3 > = < \Delta'(C-T_1)_{T_1-T_2} > = 0.058 \pm 0.020$
$< \Delta'_4 > = < \Delta'(C-M)_{M-T_2} > = 0.022 \pm 0.017$
$< \Delta'_5 > = < \Delta'(C-T_1)_{M-T_2} > = 0.025 \pm 0.016$.

Using the abundance calibration of Geisler et al. (1991), the above mean Washington indices yield $[{\rm Fe/H}]_1 = 0.04 \pm 0.01$, $[{\rm Fe/H}]_2 = -0.13 \pm 0.09$, $[{\rm Fe/H}]_3 = 0.13 \pm 0.04$, $[{\rm Fe/H}]_4 = 0.11 \pm 0.07$ and $[{\rm Fe/H}]_5 = 0.11 \pm 0.06$. The average of the five Washington abundance estimates, $[{\rm Fe/H}] = 0.06 \pm 0.08$ (s.d.), indicates that NGC 6259 has nearly solar metal content. This value is in good agreement with the metallicity tabulated by Gratton (2000) and reproduced in Table 1.

3.6. Mean radial velocities

Table 9 summarises for each cluster the values of the mean radial velocity, the standard errors of the mean, the number of stars observed, the number of confirmed members, and the number of binaries discovered so far.

4. Colour-magnitude diagrams

Isochrones from the models of Girardi et al. (2000a) for $z = 0.008$ or $z = 0.019$ have been fitted to the entire colour-magnitude diagrams of the four clusters. The isochrones reproduce quite well the main sequence

Table 7. *UBV* and CORAVEL data for red giants in NGC 6259.

No	AT	RA (2000)	Dec	V	$B-V$	$U-B$	n	V_r	ϵ	N	ΔT	$P(\chi^2)$	Rem
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1013	4307	17 00 28.27	−44 38 53.6	12.512	1.768	1.724	2	−33.86	0.52	3	1446	0.043	M
1030	4344	17 00 36.23	−44 37 25.1	12.462	1.786	1.663	2	−33.82	0.32	3	1446	0.307	M
2029	4204	17 00 46.68	−44 38 22.1	12.303	1.739	1.659	2	−32.69	0.35	3	1446	0.846	M
2046	4209	17 00 45.54	−44 37 20.8	11.97	0.83			−34.34	0.52	3	1446	0.520	M
2209	2209	17 00 53.98	−44 43 39.4	12.903	1.766	1.707	2	−33.70	0.49	1			M
3001	4101	17 00 38.59	−44 41 33.3	12.202	1.797	1.855	5	−34.57	0.48	3	1446	0.104	M
3007	3203	17 00 57.08	−44 40 42.1	12.621	1.697	1.567	3	−33.76	0.49	3	1446	0.097	M
3017	2117	17 00 51.50	−44 41 29.8	12.683	1.671	1.418	4	−34.49	0.35	3	1446	0.475	M
4014	1123	17 00 38.59	−44 41 33.3	12.807	1.779	1.556	4	−33.54	0.29	3	1446	0.944	M
4024	1232	17 00 29.88	−44 41 42.6	12.218	1.748	1.770	4	−35.16	0.29	3	1446	0.770	M
4027	1313	17 00 24.28	−44 41 47.0	12.591	1.738	1.485	5	−33.15	0.34	3	1446	0.300	M
1335	1335	17 00 27.03	−44 43 09.7	12.444	1.737	1.662	2	−36.99	0.57	1			M?
2221	2221	17 00 56.75	−44 42 37.4	13.242	1.499	1.252	2	−39.76	0.59	1			M?
2301	2301	17 01 09.62	−44 41 21.8	11.189	1.893	2.088	3	−42.73	0.47	1			M?
1035	4339	17 00 32.61	−44 37 00.5	11.75	0.97			−13.70	0.28	3	1446	0.585	NM
1220	1220	17 00 29.46	−44 41 15.5	12.576	1.810	1.624	2	+10.51	0.65	1			NM
2014	3237	17 00 55.65	−44 40 04.8	12.938	1.418	1.370	2	−14.58	2.05	11	3974	0.000	NM, SB
3351	3351	17 01 08.75	−44 39 34.3	12.909	1.472	1.302	2	−10.04	0.62	1			NM
4039	1254	17 00 34.84	−44 43 01.5	11.778	2.067	2.263	2	−24.38	0.22	7	1133	0.095	NM
2024	3346	17 01 03.61	−44 38 32.1	13.938	1.440		2						NM
2335	2335	17 00 56.60	−44 44 46.8	13.397	1.602	1.400	2						NM?
3347	3347	17 01 05.60	−44 38 42.4	13.945	1.474		2						NM

Table 8. Washington photometry for NGC 6259.

No	$C-M$	$M-T_1$	T_1-T_2	T_1	N
	σ	σ	σ	σ	
1013	2.057	1.400	0.942	11.581	4
	.012	.005	.009	.006	
2014	1.663	1.119	0.766	11.209	2
	.002	.005	.006	.002	
2029	2.020	1.381	0.944	11.399	2
	.006	.005	.007	.002	
3001	2.161	1.431	0.976	11.296	4
	.017	.003	.001	.008	
3007	1.944	1.354	0.927	11.712	2
	.003	.021	.007	.001	
3017	1.938	1.361	0.920	11.778	4
	.003	.011	.008	.005	
4014	2.082	1.435	0.966	11.867	4
	.006	.002	.002	.002	
4024	2.047	1.387	0.949	11.299	4
	.010	.006	.007	.010	
4027	2.047	1.384	0.957	11.696	4
	.014	.012	.006	.005	
4039	2.496	1.675	1.155	10.697	2
	.010	.001	.001	.003	

morphology and mean red giant locations. However, small adjustments to the isochrones were made to pass through the observed points of the red giants. A precise simultaneous fit to both the main sequence and the red giants is difficult to obtain, due to uncertainties in the exact value of α and in the conversion between theoretical and observed parameters, and to any small differences in chemical composition which also shift the main-sequence and giant tracks differently. The distance moduli and colour excesses reproduced below are the values used to get the best match with the observations.

Table 9. Mean radial velocities, membership and duplicity.

NGC	$< V_r >$	ϵ	n_{obs}	n_M	n_{SB}
2324	+41.81	0.25	17	8	3
2818	+20.69	0.29	23	15	3
3960	−22.56	0.17	14	12	5
6259	−33.70	0.19	14	9	

4.1. NGC 2324

A very good fit is obtained for NGC 2324 with an isochrone for $\log t = 8.90$ and $z = 0.019$, for $m - M = 12.95$ and $E(B-V) = 0.02$. Geisler et al. (1992) derived [Fe/H] $= -1.01$ from 11 giants observed in the Washington system. Friel et al. (1995) obtained [Fe/H] $= -0.31$ from moderate dispersion spectroscopy. However, already an isochrone for $z = 0.008$ would require a negative reddening, which is clearly not acceptable. We expect the true metallicity of NGC 2324 to be closer to solar, although the [Fe/H] value quoted in Table 1 is equal to -0.52.

The theoretical isochrone reproduces quite well the distribution of the observed points. Only star #215 is markedly off to the red side of the curve. Its radial-velocity credentials regarding membership and constancy are impeccable (and we have not found a way to combine two cluster stars to match the position of #215 in the CMD). Based on the current data, this discrepancy appears real.

4.2. NGC 2818

The fit of the Girardi et al. (2000a) isochrone to the CCD colour-magnitude diagram of NGC 2818 from Stetson (2000) is also quite good. The adopted parameters are: $m-M = 12.97$, $E(B-V) = 0.18$, $\log t = 9.00$, $z = 0.008$). The isochrone reproduces also quite well the observed distributions of the red giants, because in NGC 2818 they are nearly all located where the models predict them, i.e. within the bluest part of the loop. The reddest star #2130 is probably at the tip of the first ascending giant branch, although the models do not reproduce its position correctly.

The positions of the spectroscopic binaries appear to be consistent with the effects of a turnoff secondary star on the combined colours, but we do not have orbital elements to compute the secondary masses and prove this explanation correct.

4.3. NGC 3960

The metallicity of NGC 3960 is intermediate between that of the available isochrones, i.e. $z = 0.019$ and $z = 0.008$. Therefore these isochrones will not fit the observed colours directly: The $z = 0.008$ isochrone for $\log t = 9.00$ has to be reddened to reproduce the colour-magnitude diagram, while that for $z = 0.019$ must be shifted to the blue. The best fit is reached with the following parameters: $m-M = 12.65$, $E(B-V) = 0.33$, $\log t = 9.00$. Due to the artificial colour correction, the reddening appears a bit larger than that deduced by Janes (1981): $E(B-V) = 0.29$.

Due to the wider amplitude of the loops, the Girardi et al. (2000a) isochrone better reproduces the clump morphology than an isochrone from the Geneva models (Schaller et al. 1992). However, four confirmed radial-velocity members are much redder than the theoretical tracks. The two faintest stars (#43 and 275) are binaries, but, although other binaries in similar positions have been found in NGC 2360 (Mermilliod & Mayor 1990) and NGC 6940 (Mermilliod & Mayor 1989), duplicity does not by itself readily explain their locations. As mentioned above, #18 may still prove to be a binary or non-member, but there seems to be no obvious explanation for the position of #102.

4.4. NGC 6259

NGC 6259 is younger than the other three clusters. The best agreement for the whole colour-magnitude diagram constructed from the available photoelectric data and the photographic data of Anthony-Twarog et al. (1989) is obtained with the following set of parameters: $m-M = 13.45$, $E(B-V) = 0.66$, $\log t = 8.45$, $z = 0.019$. With the above parameters, the isochrone reproduces nicely the clump position, but fails to reach the three stars located above the clump.

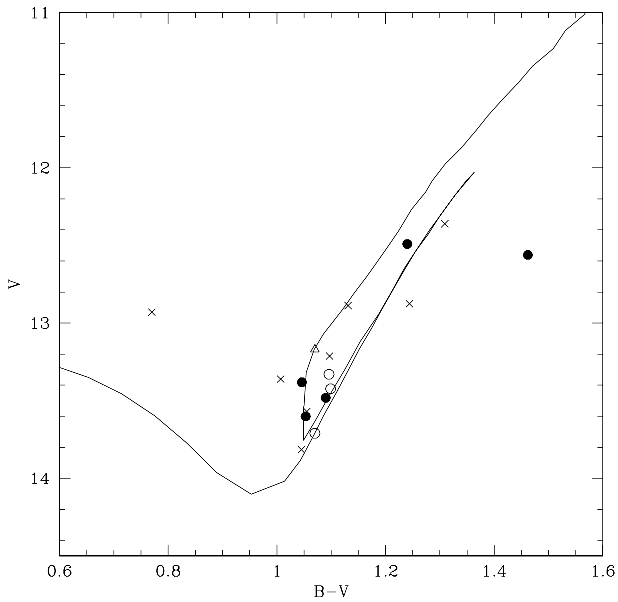

Fig. 4. The red-giant region in NGC 2324. The isochrone (Girardi et al. 2000a) is for $\log t = 8.90$ and $z = 0.019$. Symbols are as follows: *filled circles*: member with UBV per data, *open circles*: spectroscopic binaries, *open triangles*: members with BV photographic data, *crosses*: non-members. Note that many definite radial-velocity non-members are found among the confirmed clump stars. However, the outlying star #215 ($V = 12.56$, $(B-V) = 1.46$) is a definite radial-velocity member.

Two stars with uncertain membership from their radial velocities (#2221 and 2301) can be considered as non-members from their position in the colour-magnitude diagram, while star #1335 could be a clump member. The three stars with photoelectric photometry but no radial velocities (#2024, 2335, 3347) appear to be most probably non-members because they are too faint. It would be interesting to search for more red giant members in the cluster area to improve the definition of the empirical isochrone.

5. Conclusion

Our new radial velocities and photometric data have permitted us to confirm the membership of 47 red giants among the 73 stars observed. The colour-magnitude diagrams demonstrate again that secure separation of members and non-members cannot be done from photometry alone: several definite non-members fall precisely within the clump area, especially in NGC 2324.

Twelve spectroscopic binaries have been discovered among the members and four among the non-members, which gives a binary frequency of 26% (12/47) for the members and 17% (4/24) for the non-members.

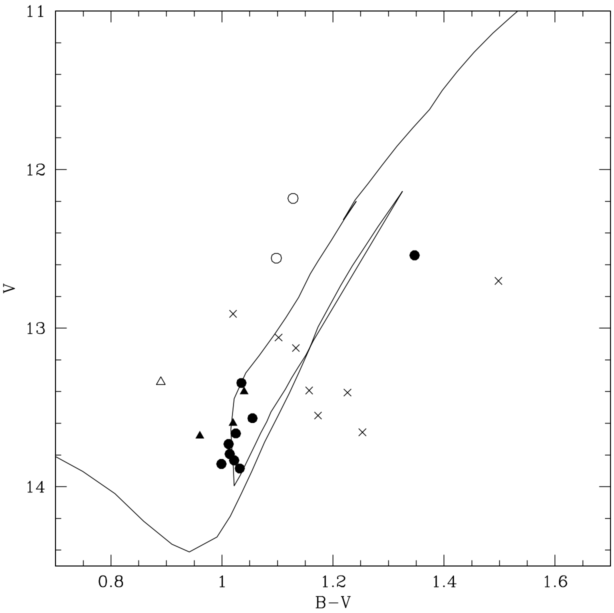

Fig. 5. The red giants in NGC 2818. The location of the cluster stars is well matched by the Girardi et al. (2000a) isochrone for $\log t = 9.00$ and $z = 0.008$. The locations of the spectroscopic binaries can be understood as the effect of the secondary on the colours. Symbols as in Fig. 4; *filled triangles*: members with photoelectric data from the literature.

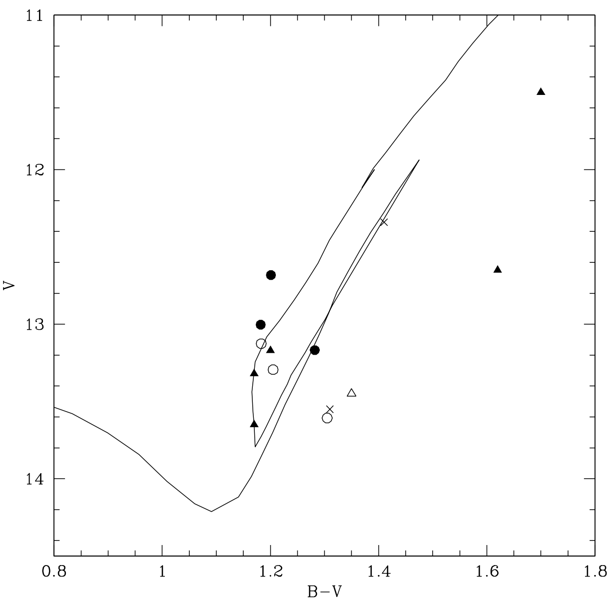

Fig. 6. The red giants in NGC 3960. The Girardi et al. (2000a) isochrone for $\log t = 9.00$ and $z = 0.008$ reproduces the clump morphology rather well, although four stars are located to the red of the track (see text). Symbols as in Figs. 4 and 5.

Three preliminary orbits have been determined, the eccentricity of the short-period system being circular, as expected for $P < 120$ days.

The three clusters NGC 2324, 2818 and 3960 have similar ages (0.8–1 Gyr) but different metallicities. NGC 2324

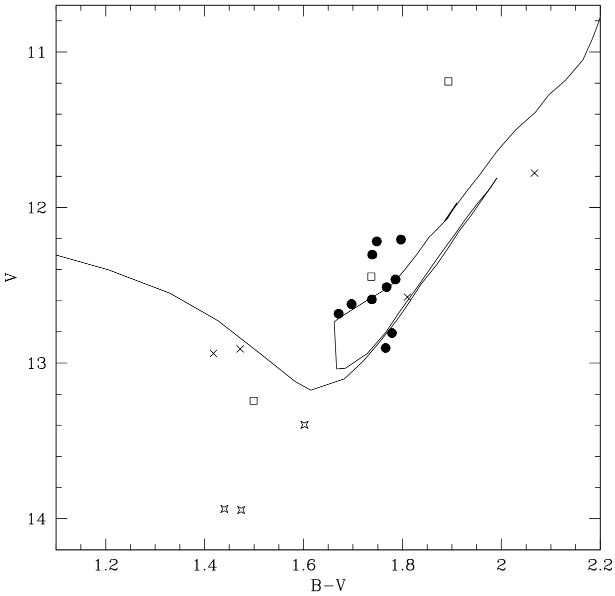

Fig. 7. Red giants in NGC 6259. The (younger) isochrone from Girardi et al. (2000a) for $\log t = 8.45$ and $z = 0.019$ matches only some of the stars. Symbols as in Fig. 4; *open squares* denote stars noted M? and *diamonds* stars with *UBV* data but no radial velocities in Table 7.

is probably near solar ($z = 0.019$) despite the low metallicity determinations; NGC 2818 appears somewhat metal-poor ($z = 0.008$), and NGC 3960 is intermediate between these two values. NGC 6259 is younger than the three other clusters (0.3 Gyr).

The isochrones from Girardi et al. (2000a) reproduce quite well the morphology and the magnitude and colours of the observed clumps. Especially the width of the loop (vertical distance between the ascending giant branch and the core burning track) is correctly predicted by the models. Although the general trend is well reproduced by the models used in this paper, a number of stars are located in abnormal positions which have no known explanation, either in terms of evolution or of binarity.

It would be important to search for additional red giant members in the outer part of these clusters to increase the number of stars describing the empirical evolutionary track and improve the comparison with theoretical models. A comparative spectroscopic study of the clusters with both anomalous and normal red giants would also be worthwhile.

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References

Acker, A. 1978, A&AS, 33, 367
Anthony-Twarog, B. J., Payne, D. M., & Twarog, B. A. 1989, AJ, 97, 1048
Baranne, A., Mayor, M., Poncet, J.-L. 1979, Vistas Astron., 23, 279
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Becker, W., Svolopoulos, S. N., & Fang, C. 1976, Kataloge photographischer und photoelektrisher Helligkeiten von 25 galaktischen Sternhaufen im RGU- und U_cBV System, (Basel)
Canterna, R. 1976, AJ, 81, 228
Clariá, J. J., Mermilliod, J.-C., & Piatti, A. E. 1999, A&AS, 134, 301
Cousins, A. W. J. 1973, Mem. R. Astron. Soc., 77, 223
Cousins, A. W. J. 1974, MNSSA, 33, 149
Cuffey, J. 1941, ApJ, 94, 55
Durand, S., Acker, A., & Zijlstra, A. 1998, A&AS, 132, 13
Friel, E., & Janes, K. A. 1993, A&A, 267, 75
Friel, E. D., Janes, K. A., Hong, L., Lotz, J., & Tavarez, M. 1995, in The formation of the Milky Way, ed. E. J. Alfaro, & A. J. Delgado (Cambridge Univ. Press), 189
Geisler, D., Clariá, J. J., & Minniti, D. 1991, AJ, 102, 1836
Geisler, D., Clariá, J. J., & Minniti, D. 1992, AJ, 104, 1892
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000a, A&AS, 141, 371
Girardi, L., Mermilliod, J.-C., & Carraro, G. 2000b, A&A, 354, 892
Graham, J. A. 1982, PASP, 94, 244
Gratton, R. 2000, ASPC, 198, 225
Hawarden, T. G. 1974, MNRAS, 169, 539
Hoag, A. A., Johnson, H. L., Iriarte, B., et al. 1961, Publ. Us. Nav. Obs. XVII part VII, 347
Janes, K. A. 1981, AJ, 86, 1210
Meatheringham, S. J., Wood, P. R., & Faulkner, D. J. 1988, ApJ, 334, 862
Mermilliod, J.-C., & Mayor, M. 1989, A&A, 219, 125
Mermilliod, J.-C., & Mayor, M. 1990, A&A, 237, 61
Mermilliod, J.-C., & Mayor, M. 1992, in Binaries as Tracers of Stellar Formation, ed. A. Duquennoy, & M. Mayor (Cambridge: Cambridge University Press), 183
Mermilliod, J.-C., & Mayor, M. 1996, in Cool Stars, Stellar Systems and the Sun, ed. R. Pallavicini, & A. K. Dupree, ASPC, 109, 373
Piatti, A. E., Clariá, J. J., & Bica, E. 1998, ApJS, 116, 263
Pedreros, M. 1989, AJ, 98, 2146
Pottasch, S. R. 1983, in Planetary Nebulae, ed. D. R. Flower (Reidel, Dordrecht), IAU Symp., 103, 391
Rahim, M. A., & Hassan, S. M. 1967, Helwan Obs. Bull., No 7
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Stetson, P. B. 2000, PASP, 112, 925
Surendiranath, R., Rao, N. K., Sagar, R., Nathan, J. S., & Ghosh, K. K. 1990, JAA, 11, 151
Tifft, W. G., Connolly, L. P., & Webb, D. F. 1972, MNRAS, 158, 47
Udry, S., Mayor, M., & Queloz, D. 1999, in Precise Stellar Radial Velocities, IAU Colloq. 170, ed. J. B. Hearnshaw, & C. D. Scarfe, ASP Conf. Ser., 185, 367,
VandenBerg, D. A., & Poll, H. E. 1989, AJ, 98, 1451