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Radial velocities and membership of stars in the old, distant open cluster Berkeley 29⋆

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Abstract. Multi slit spectroscopy at the Telescopio Nazionale Galileo was employed to measure radial velocities for 20 stars in the direction of the old open cluster Berkeley 29, the farthest known in our Galaxy. Membership information was derived for stars all along the red giant branch, in particular near its tip, and on the red clump. The sample of bona fide cluster members was used to revise the cluster distance to ~15 kpc, on the basis of an empirical comparison with the red clump in open clusters with known distances. A metallicity [Fe/H] $= -0.74 \pm 0.18$ was also estimated using the colours of spectroscopically confirmed red giant stars.

Key words. Galaxy: disk – Galaxy: open clusters and associations: individual: Berkeley 29 – techniques: radial velocities

1. Introduction

Galactic open clusters are particularly well suited to study the disk of the Milky Way and its history of chemical enrichment, since their distances, ages, and metal abundances can be determined with relative ease. Until a few years ago, however, the data on cluster ages and metallicities were sparse and inhomogeneous, and only recently significant efforts have been dedicated to build large and well studied cluster samples (e.g. Janes & Phelps 1994; Friel 1995; Twarog et al. 1997; Carraro et al. 1998). Our group is undertaking a long-term photometric project to derive a homogeneous set of ages, metallicities, reddening, and distances for a sample of open clusters at various Galactocentric positions. To this end, we use the colour–magnitude diagram (CMD) synthesis technique (see Tosi et al. 1991). Results have been published so far for 15 clusters (e.g., Andreuzzi et al. 2004; Kalirai & Tosi 2004; Tosi et al. 2004, and references therein). This effort is complemented by accurate abundance determinations derived by high-resolution spectroscopy (Bragaglia et al. 2001a,b; Carretta et al. 2004).

Age and distance determinations using the synthetic CMD method are essentially based on reproducing the properties of the red clump, of the main sequence (MS) and of its turn-off (MSTO). For open clusters, which are usually heavily contaminated by foreground and background stars, the separation of cluster members and field interlopers becomes a prerequisite to properly derive the cluster parameters. In particular, it is important to know which stars are real cluster members belonging to the red giant branch (RGB), the red clump, and the MSTO in the cluster CMD. Membership assessment is also important to select targets for follow-up high-resolution spectroscopy to measure detailed chemical abundances.

Multi object spectroscopy at medium resolution represents an efficient way to select samples of confirmed cluster stars in the direction of Galactic open clusters on the basis of their radial velocities. A program has therefore been started to establish the membership of stars in selected open clusters, in particular of stars in the crucial evolutionary phases, by measuring their radial velocities using multi object spectroscopy at the Telescopio Nazionale Galileo.

We present here new results for the old, distant open cluster Berkeley 29 (hereafter Be 29), located towards the Galactic Anticentre: RA(2000) = $06^{h}53^{m}02^{s}$, Dec(2000) = $+16°56'20''$, $l = 197.^{\circ}98$, $b = 8.^{\circ}03$. The photometric catalog is based on the CMD of Kaluzny (1994) and our *BVI* data was acquired with the CCD camera at the 1.5 m ESO/Danish telescope and the SuSI2 imager at the NTT ESO telescope at La Silla, Chile (Tosi et al. 2004). In his paper, Kaluzny (1994) derived an age of about 4 Gyr for Be 29, and a distance from the Sun of 10.5 kpc, making this the farthest known open cluster ($R_{GC} \gtrsim 18$ kpc), hence a crucial object to study the radial variations of disk properties. Carraro & Baume (2003) claimed that the old cluster Saurer A is even more distant from the Galactic centre,

⋆ Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

Table 1. Data for the program stars. Star numbers are taken from our own photometry (Col. 1) and from Kaluzny (1994). The latter ID numbers are also used in the Database for Stars in Open Clusters (BDA, Mermilliod 1995). The *B*, *V*, and *I* magnitudes are from Tosi et al. (2004), and equatorial coordinates are at J2000 (units of right ascension are hours, minutes and seconds, and units of declination are degrees, arcminutes and arcseconds). The classification and evolutionary phase of each candidate member star is given in the last column.

ID	ID_K	*B*	*V*	*I*	RA(2000)	Dec(2000)	Phase
1024	241	16.067	14.458	12.795	6:53:07.132	16:57:12.67	RGB-tip
869	902	18.644	17.739	16.735	6:53:03.048	16:55:28.19	RGB
994	988	16.120	14.585	13.007	6:53:03.886	16:55:15.49	RGB-tip
136	1168	19.352	18.495	17.507	6:53:00.699	16:54:36.48	RGB
626	–	19.403	18.530	17.400	6:52:57.923	16:52:41.28	RGB
72	–	18.216	17.232	16.090	6:52:58.390	16:57:58.75	RGB
949	1076	17.244	16.221	15.103	6:53:01.482	16:55:01.46	RGB
159	412	17.625	16.627	15.574	6:53:01.601	16:56:21.11	clump
258	556	17.583	16.603	15.534	6:53:04.362	16:56:02.86	clump
933	–	17.435	16.447	15.322	6:53:04.486	16:57:44.69	RGB
634	–	18.802	17.908	16.871	6:52:58.788	16:58:01.16	RGB
104	441	19.014	17.945	16.931	6:52:59.759	16:56:17.03	RGB
257	818	17.578	16.608	15.548	6:53:04.320	16:55:39.37	clump
718	1075	18.579	17.658	16.575	6:53:04.514	16:55:00.67	RGB
784	–	18.532	17.650	16.590	6:53:08.116	16:57:47.17	RGB
1009	673	16.004	14.310	12.570	6:53:04.385	16:55:53.93	RGB-tip
993	–	16.320	15.444	14.453	6:53:00.380	16:58:20.27	field
1417	–	99.990	14.818	13.978	6:53:05.051	16:57:32.32	field
456	–	17.096	16.350	15.410	6:53:10.436	16:53:30.44	field
973	761	16.322	15.659	14.899	6:53:03.052	16:55:46.16	field

but more recent independent analyses (Carraro et al. 2004; Tosi et al. 2004) have re-assessed that Be 29 appears indeed to be the outermost open cluster.

Be 29 has a sparse RGB with 3 stars about 2 mag brighter than the red clump that could define the bright end of the RGB, if not its tip. There is no published information on star membership, and even if this cluster is not strongly contaminated by field stars, secure photometric derivation of its distance, age and metallicity requires an appropriate cleaning of the CMD.

Spectroscopic confirmation of member stars is provided for the first time in this paper. Our observations are presented in Sect. 2, and radial velocity measurements are discussed in Sect. 3. A brief discussion of the metallicity of Be 29 based on the sample of spectroscopically confirmed stars is given in Sect. 4. Our results are summarized in Sect. 5.

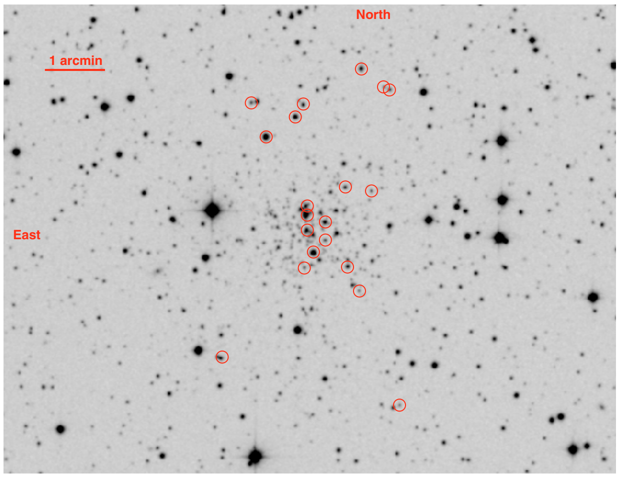

Fig. 1. Map of the field around Be 29: the observed stars are marked by *circles*. North is up, East to the left.

2. Observations and data reduction

Intermediate resolution multi object spectroscopy of stars in Be 29 was obtained using the MOS mode of the low-resolution spectrograph D.O.Lo.Res. at the Telescopio Nazionale Galileo (TNG) on Roque de los Muchachos, Canary Islands, Spain. The VPH grism centered on the Hα spectral region was used, yielding a resolution of 1.38 Å (R = 4750) with 1.″1 (200 μm) slitlets, and a spectral range of about 680 Å around Hα. Be 29 was observed in service mode on the nights of Jan. 11, 21, and 22, 2003. Spectra for 20 stars were obtained in two masks. Three exposures were obtained for each mask, with exposure times ranging from 1800 to 2400 s. A Ne lamp spectrum was acquired immediately before and/or after each science frame for wavelength calibration.

Figure 1 shows the field of Be 29, with the spectroscopically observed stars marked by open circles. Our target stars were chosen on the basis of the observed CMD, using Tosi et al.'s (2004) photometric data; stars in common with Kaluzny (1994) are indicated in Table 1, where all identifications, magnitudes and coordinates for the spectroscopically observed stars are presented. The target stars were selected along the RGB, the red clump, and near the termination of Be 29 RGB (the latter will be referred to in the following as "RGB-tip": this does not

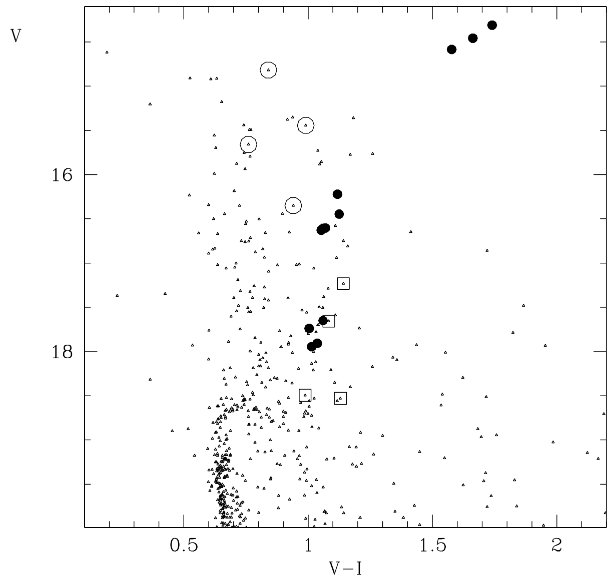

Fig. 2. Colour−magnitude diagram for Be 29 (Tosi et al. 2004), with spectroscopically observed objects marked by larger symbols. *Open circles* indicate field stars, *filled circles* are bona fide members of Be 29, *open squares* are three non members, and one uncertain attribution.

imply that they really define the tip, and is used only to distinguish them from lower RGB stars). We also included in the sample 4 stars that, on the basis of their position in the CMD, are likely field stars. The positions of the observed stars in our $V, V-I$ CMD (Tosi et al. 2004) are shown in Fig. 2.

Two of the 3 RGB-tip stars had been previously observed by our group with FEROS at the ESO 1.5 m telescope (at $R = 48\,000$); their spectra had S/N ratio too low for deriving abundances, but high enough to measure radial velocities of 24.76 and 24.14 km s^{-1} for stars 1009 and 1024, respectively (corrected for the solar system barycentric motion). These two stars with high-precision measurements (having velocity uncertainties not larger than 1 km s^{-1}, including systematic error) are useful as internal radial velocity standard stars.

The six MOS masks were reduced using standard packages in IRAF[1]. The wavelength calibration residuals have rms errors of about 0.01 Å (less than 1 km s^{-1}).

3. Radial velocities

3.1. Velocity measurements

The radial velocities of stars in the field of Be 29 were measured in two ways. First, relative radial velocities (Δv_r) were measured using the cross-correlation package FXCOR in IRAF. The best spectrum of the brightest star in our sample (1009) was used as a template; we also repeated the analysis using another star (1024) and the results were very similar. The cross-correlation was computed in the spectral region 6520−6620 Å, chosen to avoid the presence of strong atmospheric absorption features. All the individual spectra were cross-correlated with the template, obtaining 3 to 6 measures for each star. The formal errors on the single Δv_r provided by the cross-correlation method range from ~1 km s^{-1} to about 20 km s^{-1} in the worst case, with a typical value 4 km s^{-1}. The mean value of the velocity relative to the template, Δv_r, is given for each star in Table 2. Since each mask set has a different barycentric correction, all masks were referred to the velocity system of a reference mask before averaging the radial velocities. The uncertainties were estimated from the standard deviation of the measurements on the individual spectra, σ_{v_r}. The scatter of the single measurements is consistent with the errors of the cross-correlation method. A comparison of the individual Δv_r values for each star with the mean of the individual measurements is presented in Fig. 3a. Observed radial velocities v_r(cc) were obtained by adding the observed velocity of the template spectrum (measured from Hα as below) to the relative velocities, and correcting for the barycentric motion. The results, given in Col. 3 of Table 2, provide the reference data set of this paper.

For comparison, absolute radial velocities were also obtained from direct measurement of the wavelength of absorption lines. In practice, radial velocities were measured from Gaussian fitting to Hα (the only line easily identified in all spectra) for each star, using only the best mask. The radial

Table 2. Results of radial velocity measurements. The values for the relative radial velocities (Δv_r, in Col. 2) are the average of the results of the cross correlation with star 1009 as template. Absolute radial velocities v_r have been obtained by adding the observed velocity of the template spectrum (star 1009), measured from the Hα line. The quoted error σ_{v_r} represents the standard deviation of the mean. Radial velocities derived by cross correlation with the synthetic spectrum as template are given in Col. 6, also corrected for the barycentric motion. In the last column, a "C" flag indicates cluster members, "C:" possible members, and "F" field stars.

ID	Δv_r	v_r(cc,1)	σ_{v_r}	N_{sp}	v_r(cc,2)	Flag
1024	0.16	28.18	3.36	6	30.6	C
869	−7.24	20.78	3.60	6	26.4	C
994	−0.72	27.3	4.31	6	29.8	C
136	49.39	77.41	28.83	6	90.7	F
626	30.53	58.55	9.59	3	56.4	F
72	24.78	52.8	4.37	3	63.2	F
949	−4.54	23.48	3.90	3	28.5	C
159	−3.03	24.99	4.75	3	29.2	C
258	−4.72	23.3	4.20	3	28.3	C
933	−3.45	24.57	4.27	3	31.5	C
634	−0.93	27.09	9.88	3	33.9	C
104	−2.16	25.86	2.82	3	31.4	C
257	6.16	34.18	1.68	3	34.6	C
718	−18.66	9.36	11.60	3	21.3	C:
784	4.20	32.22	6.28	3	36.1	C
1009	0.0	28.02	0.52	6	28.2	C
993	61.23	89.25	8.04	6	93.9	F
1417	60.67	88.69	3.92	6	93.3	F
456	−36.29	−8.27	2.90	6	−7.9	F
973	−27.72	−0.30	4.99	3	5.4	F

[1] IRAF is distributed by the NOAO, which are operated by AURA, under contract with NSF.

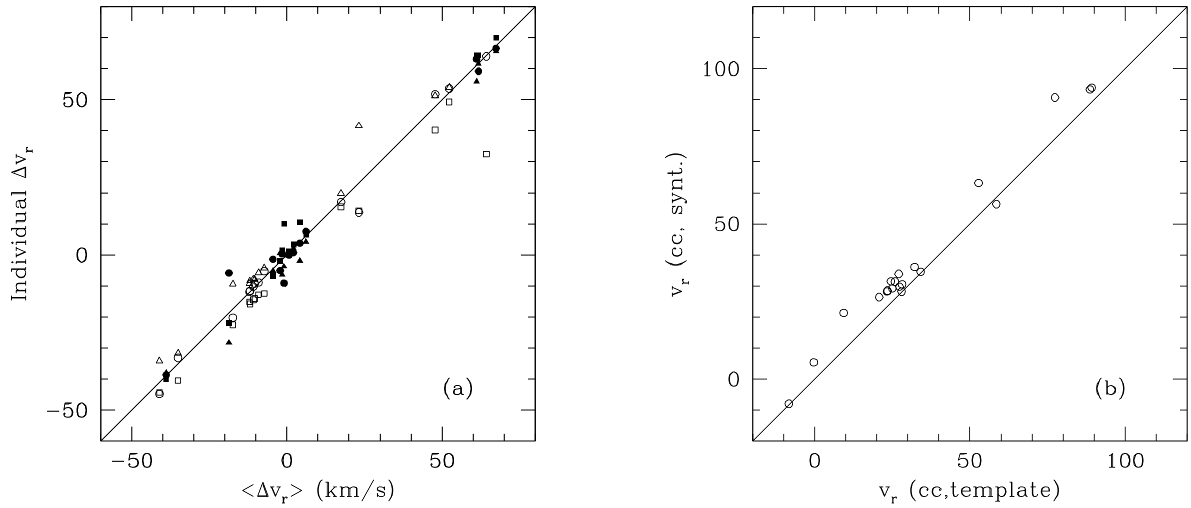

Fig. 3. a) A comparison of the average Δv_r from cross-correlation with star 1009 with individual velocity measurements for each stars (3 to 6 values available). **b)** Comparison of radial velocities obtained from cross-correlation with star 1009 and the synthetic template.

velocities measured from Hα are also given in Table 2, after correction for the barycentric motion, and the value 28.02 km s^{-1} for star 1009 was used as zero point for the cross-correlation derived values.

The zero point of our velocities agrees with previous high-resolution FEROS measurements for stars 1009 and 1024 within 3–4 km s^{-1}. We regard this as an excellent agreement given the limited spectral resolution of our observations and the different sources of systematic error with multislit spectroscopy, in particular centering errors of the targets on the mask slits.

Finally, to further check our results the radial velocities were measured from cross-correlation with a synthetic template in the Hα region for each star in all masks. The correlation between the radial velocities derived from the two cross-correlations is good (Fig. 3b). There is a systematic shift in the radial velocity scales of ~4 km s^{-1} (median difference), with the values estimated from cross-correlation with the template stars being lower. This small residual uncertainty is consistent with the typical cross-correlation errors for our spectral resolution. This is of no consequence in discriminating cluster and field stars, which is the main goal of this paper.

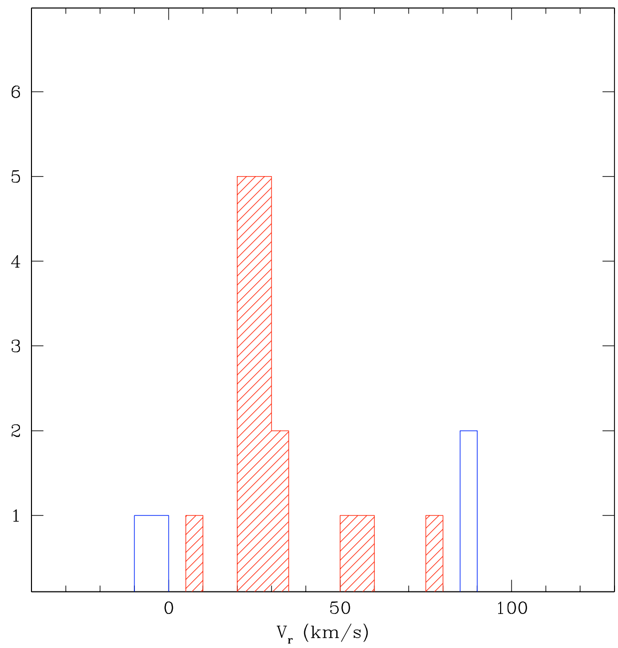

Fig. 4. Histogram of the observed radial velocities (Table 2, Col. 3), using a bin of 5 km s^{-1}. The hatched histogram is for supposed Be 29 members, the open bins indicate the confirmed field stars.

3.2. Membership

The histogram of the measured velocities (Fig. 4) shows a very peaked distribution, with 4 stars in an uncertain position and all the field stars far from the peak. Our results for the membership of stars in Be 29 are summarized in the last column of Table 2.

Of the 16 candidate stars measured in Be 29, 12 turn out to be very likely members, since their velocities are clustered around $\Delta v_r = 0$. One star, 718, has a radial velocity marginally consistent with cluster membership, when considering cross-correlation with star 1009, although the measurements have a large scatter. However, both the velocity estimate from Hα on the best spectrum and cross-correlation with the synthetic template seem to indicate that this is a probable cluster star. Instead, objects 136 (the faintest in our sample), 626, and 72 appear to be field stars.

4. Discussion

Given its Galactic position, it is important to determine with precision the values of the metallicity and reddening, as well as distance, for Be 29. The age and metallicity of Be 29 estimated by Kaluzny (1994) from several photometric parameters, indicate that this cluster is coeval to M 67 (~4 Gyr old) and quite metal-poor, with a metal abundance [Fe/H] ≈ −1.3, and in any case much lower than that of M 67. This conclusion largely rests upon the adopted reddening $E(B-V) = 0.21$

derived from the Burstein & Heiles (1982) reddening maps. By adopting an absolute magnitude $M_V = 0.85$ for the red clump and the above reddening, Kaluzny (1994) obtained a distance modulus $(m - M)_0 = 15.1$ for Be 29, equivalent to a heliocentric distance of 10.5 kpc, making Be 29 the most distant open cluster known. On the other hand, Noriega-Mendoza & Ruelas-Mayorga (1997), by applying a technique for the simultaneous determination of metallicity and reddening, argued for a negligible reddening ($E(B - V) = 0.01$) towards Be 29, and a higher metallicity ([Fe/H] ~ -0.3). If the reddening is low, also the distance to Be 29 must be revised. In fact, the infrared maps of Schlegel et al. (1998) give a reddening $E(B - V) = 0.093$ in the direction of Be 29, lower than that adopted by Kaluzny (1994).

Very recently Tosi et al. (2004) have determined, using different sets of evolutionary tracks and the synthetic colour–magnitude diagram technique, an age of 3.4−3.7 Gyr, an absolute distance modulus of 15.6−15.8 (which translate in a Galactocentic distance of 21.4−22.6 kpc), and a reddening of 0.13−0.10; the metallicity, taken from the best fitting tracks, has a (formal) value of [Fe/H] ~ -0.5 or -0.7. Carraro et al. (2004) have obtained high resolution spectra of two stars, and derived and abundance of [Fe/H] $= -0.44 \pm 0.18$, a reddening of 0.08, an age of 4.5 Gyr, and a Galactocentic distance of 21.6 kpc.

To complement and further check these results, we will try to fully exploit our present data set: the availability of a sample of spectroscopically confirmed members of Be 29 allows us to re-examine the distance and metallicity of the cluster from their photometric data. In particular, our sample of spectroscopically confirmed stars includes 3 stars on the red clump allowing a secure determination of the observed red clump magnitude and colour. In the following we will assume the Schlegel et al. (1998) reddening as our reference value, with an uncertainty of ±0.05 mag, since this is in between the two most recent and precise determinations. The mean magnitude of the red clump from the 3 stars turns out to be $I = 15.55$ with a colour $V - I = 1.06$, in very good agreement with previous determinations (Kaluzny 1994). We note that the observed colour of the red clump in Be 29, once corrected using the Schlegel et al. (1998) value for the reddening, is $(V - I)_0 = 0.95 \pm 0.06$. This is slightly blue for an open cluster (Sarajedini 1999), but not exceptional at all (Percival & Salaris 2003) and goes in the direction of low metallicity. The reddening value adopted by Kaluzny (1994) would imply a red clump as blue as $(V - I)_0 = 0.80$.

To estimate the distance to Be 29, we need to assume an absolute magnitude for the red clump. There is still a debate about the dependence of the red clump luminosity from metallicity and age of a stellar population (see, e.g., Girardi & Salaris 2001; Udalski 2000). To limit the impact of model-dependent assumptions we resorted to an empirical comparison with data for two well-studied open clusters (NGC 2506 and Mel 66), similar enough to Be 29 to represent a good comparison, and to minimize any corrections we choose to apply.

NGC 2506 has a metallicity [Fe/H] $= -0.39$ (Twarog et al. 1997). Using a fit of theoretical main sequences and a comparison to its almost-twin, but slightly metal-richer, NGC 2420, Twarog et al. (1999) estimated an age of about 2 Gyr, and from the distance modulus they derived an absolute magnitude $M_I = -0.48$ and an extinction-corrected colour $(V - I)_0 = 0.94$ for the red clump. Our first approach was to estimate the distance to Be 29 under the hypothesis that it is identical to NGC 2506 (i.e., no age or metallicity corrections were applied to its red clump magnitude). In this case the uncorrected distance modulus is $(m - M)_I = 16.03$ and the extinction-corrected distance modulus $(m - M)_0 = 15.86 \pm 0.09$. Alternatively, we applied a correction to the luminosity of the red clump in Be 29 assuming a metallicity [Fe/H] $= -1.0$ and taking into account the effects of a different age and metallicity. The correction, based on the models of Girardi & Salaris (2001), turns out to be modest as it implies a luminosity $M_I = -0.50$ for the red clump of Be 29. The population correction due to the difference in metallicity is nearly equal, within a few hundredths of magnitude, to that derived using Popowski's (2000) empirical calibration of the red clump luminosity (his Eq. (4)). Using population corrections, the corrected distance modulus becomes $(m - M)_0 = 15.90 \pm 0.09$.

These results are relatively independent of this particular choice of the comparison cluster. Using the open cluster Mel 66 as a template, with the parameters derived by Sarajedini (1999), the results are very similar. Mel 66 is nearly coeval to Be 29, and has a lower than solar metallicity ([Fe/H] $= -0.34$, Twarog et al. 1997). The corrected distance modulus of Be 29 turns out to be $(m - M)_0 = 15.72 \pm 0.09$ assuming that the two clusters are identical, and $(m - M)_0 = 15.85 \pm 0.09$ if we assume a metallicity [Fe/H] $= -1.0$ for Be 29 and apply population corrections. Therefore our analysis implies that Be 29 is located at $\sim$15 kpc from the Sun.

Using this new distance estimate, and a reddening 0.093 with a 0.05 mag uncertainty, we also measured the metallicity of Be 29 by direct comparison of $(V - I)$ colours of its spectroscopically confirmed red giant stars with the ridge lines of red giant branches in Galactic globular clusters (Da Costa & Armandroff 1990). As shown in Fig. 5, the metallicity of Be 29 appears to be intermediate between those of NGC 1851 and 47 Tuc. A quadratic interpolation of the mean colour difference between RGB stars in Be 29 and the ridge lines of globular cluster templates (see, e.g., Held et al. 2001 for details) yielded a new metallicity estimate [Fe/H] $= -1.04 \pm 0.18$ on the Zinn & West (1984) scale, not far from that found by Kaluzny (1994).

This metallicity estimate assumes that Be 29 is coeval to Galactic globular clusters, which is certainly not the case. Since Be 29 has an age lower than 4 Gyr (Kaluzny 1994; Tosi et al. 2004), its mean RGB colour is bluer than that of older Galactic cluster of the same metallicity. We have estimated the effects of an age difference of $\sim$10 Gyr between Be 29 and Galactic clusters by comparing the RGB sample with isochrones of 4 and 14 Gyr and different metallicities (Girardi et al. 2000). The shift in colour of the RGB of Be 29 mimics a metallicity difference of ~0.3 dex. By applying this (model dependent) correction, the colours of the spectroscopically confirmed red giants imply an age-corrected metallicity [Fe/H] $= -0.74 \pm 0.18$.

In conclusion, our analysis also appears to exclude the low reddening and high metallicity derived by Noriega-Mendoza & Ruelas-Mayorga (1997), and favours a lower metallicity.

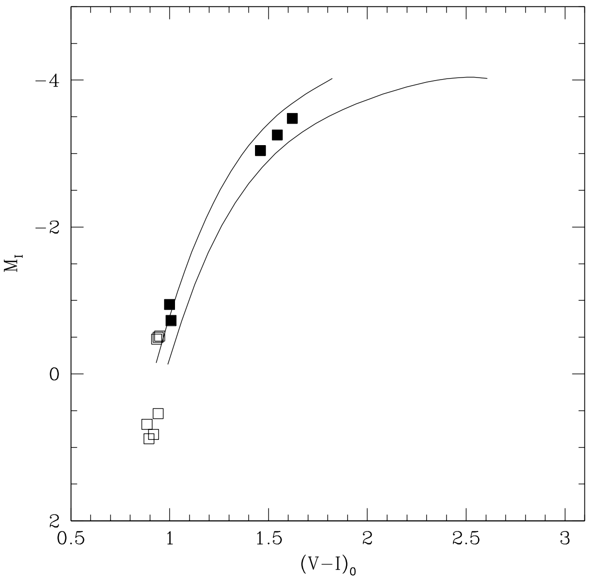

Fig. 5. A comparison of spectroscopically identified members of Be 29 with the fiducial lines of RGB stars in the Galactic globular clusters 47 Tuc and NGC 1851 ([Fe/H] = −0.71 and −1.29 respectively, from Da Costa & Armandroff 1990). For Be 29 we have adopted a reddening $E(B-V) = 0.093$ from Schlegel et al. (1998) and a corrected distance modulus $(m-M)_0 = 15.9$. The stars used to estimate the metallicity of Be 29 are shown as *filled squares*.

The value we find is lower than those found by Carraro et al. (2004) and by Tosi et al. (2004), although consistent with the latter. Further high resolution spectroscopic data are clearly needed to firmly establish the chemical abundances in Be 29.

5. Summary

We have reported radial velocity observations of 20 stars in the direction of the distant, old open cluster Be 29, obtained from multi object spectroscopy at the TNG. On the basis of the radial velocities, we found 12 confirmed cluster members, 1 probable member, and three non members. Thus we have been able to confirm that the 3 stars on the brighter part of the RGB tip, 3 stars in the position of the red clump and 6 stars on the fainter RGB are indeed cluster members.

This information has been used to re-examine cluster properties such as distance and metallicity using only spectroscopically confirmed stars. Our analysis used an empirical comparison of the magnitude and colour of the red clump in Be 29 and similar open clusters with published data to derive a corrected distance modulus $(m-M)_0 = 15.9 \pm 0.1$, corresponding to ~15 kpc.

An estimate of metallicity based on the colours of red giants was obtained by direct comparison with the RGB fiducial lines in Galactic globular clusters, yielding an age-corrected metallicity [Fe/H] = -0.74 ± 0.18, a value supporting the suggestion that Be 29 is moderately metal-poor.

Further constraints must be derived from stars near the MSTO, and this will be the goal of new observations. With our study we have also indicated candidates for detailed chemical analysis based on further high resolution spectroscopy of a larger sample of stars; this requires telescopes of the 10 m class for all stars except the three near the RGB tip.

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