Mon. Not. R. Astron. Soc. **363,** 1247–1256 (2005) doi:10.1111/j.1365-2966.2005.09520.x

Washington photometry of open cluster giants: two moderately metal-poor anticentre clusters

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Accepted 2005 August 12. Received 2005 August 8; in original form 2005 April 27

ABSTRACT

New photometric data in the Washington system are presented for red giant candidates in NGC 1817 and 2251, two open clusters located towards the Galactic anticentre direction. In the case of NGC 2251, the Washington data are supplemented with new *UBV* and David Dunlap Observatory (DDO) photoelectric photometry. Published radial velocities are used to separate field stars from cluster giants. The photometric data yield an effective temperature and metal abundance for each cluster member. Five independent Washington abundance indices yield mean metallicities of [Fe/H] = 0.25 ± 0.04 for NGC 1817 and 2251, respectively. From combined *BV* and DDO data, we also derive $E(B - V) = 0.21 \pm 0.03$ and $[\mathrm{Fe/H}]_{\mathrm{DDO}} = -0.14 \pm 0.05$ for NGC 2251. Both objects are then found to be on the metal-poor side of the distribution of open clusters, their metallicities being compatible with the existence of a radial abundance gradient in the disc. Using the WEBDA Open Cluster data base and the available literature, we re-examined the overall properties of a sample of 30 clusters located towards the Galactic anticentre with the distances, ages and metallicities available. This cluster sample presents no evidence of an abundance gradient perpendicular to the Galactic plane, nor is an age–metallicity relation found. However, a radial abundance gradient of −0.093 dex kpc^{-1} is derived over a Galactocentric distance of 14 kpc, a gradient which is in keeping with most recent determinations. This value practically does not change when all clusters with basic parameters known up to this date are considered.

Key words: methods: observational – techniques: photometric – open clusters and associations: individual: NGC 1817 – open clusters and associations: individual: NGC 2251 – Galaxy: abundances.

1 INTRODUCTION

Open clusters have long been used to trace the structure and chemical evolution of the Galactic disc (Janes 1979; Friel 1995). Because they can be relatively accurately dated and we can observe them at large distances from the Sun, their abundances are an excellent tracer of the metal abundance gradient along the Galactic disc, as well as of several other relevant disc properties such as the age–metallicity relation, the nature of the formation of this region of the Galaxy and even the age of the disc. In particular, open clusters located towards the Galactic anticentre direction are especially important for studying the present and past abundance gradient in the Galactic disc. Although the existence of such a gradient is now relatively well established (see, e.g., Chen, How & Wang 2003 and references therein), how this abundance gradient evolved in the Galactic disc remains one of the unsettled issues concerning the formation and chemical evolution of the Milky Way. An equally important but still unresolved question is the history of this metallicity gradient: was it steeper or flatter in the past? The greater the number of known open clusters with well-determined ages and metallicities, the more precise and detailed the analysis of the metal abundance gradients in the disc as well as its evolution over time will be.

The present paper is devoted to NGC 1817 and 2251, two open clusters located in the Galactic anticentre direction, for which we measure accurate abundances on a uniform scale, using high-quality photoelectric photometry in the Washington system. This study is part of a survey of some poorly studied open clusters, located at different Galactic radii, which has been carried out at Cerro Tololo Inter-American Observatory (CTIO, Chile) since 1992. Another 15 intermediate-age open clusters have already been investigated using the Washington system (Clariá & Mermilliod 1992; Geisler, Clariá & Minniti 1992a; Clariá, Lapasset & Bosio 1993; Clariá

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Table 1. Basic parameters of NGC 1817 and 2251. Coordinates are for the J2000 equinox.

Name	OCL	α (h:m:s)	δ (°, ′, ″)	l (deg)	b (deg)	d (kpc)	Age (Gyr)
NGC 1817	463	05:12:15	+16:41:24	186.1	−13.1	1.5	1.1
NGC 2251	499	06:34:28	+08:22:00	203.6	+0.1	1.3	0.3

et al. 1994a; Clariá, Mermilliod & Piatti 1999; Mermilliod et al. 2001; Clariá et al. 2003), as part of this study. We decided to use the Washington system because of its combination of broad-bands and high metallicity sensitivity provided by the C filter, and the wide colour baseline between C and T_1 filters. The advantages that this system offers in deriving accurate abundances in yellow and red cluster giants have been clearly pointed out by Geisler, Clariá & Minniti (1991). In the case of NGC 2251, we also derive reddening and metal content using combined BV and David Dunlap Observatory (DDO) photometric data. Both objects belong to a rather small group of open clusters located towards the Galactic anticentre direction. Some of the basic parameters of the clusters are summarized in Table 1.

NGC 1817 (C0509+166), also known as Cr 60 (Collinder 1931), is an intermediate-age (Janes & Phelps 1994), moderately concentrated open cluster. The first photometric study was performed by Cuffey (1938) in the B and R bands down to a limiting magnitude of $R = 14$. Later, Purgathofer (1961, 1964), carried out a UBV photographic study reaching $V = 14$. None of these studies, however, reached faint enough to reveal the cluster main sequence clearly. On the other hand, these studies indeed demonstrated the existence of a well-populated red giant branch (RGB). Photographic and photoelectric UBV photometry for 265 stars in the central part of NGC 1817 has been obtained by Harris & Harris (1977, hereafter HH77), who derived $E(B - V) = 0.28$ and a distance of 1.8 kpc from the Sun. Phelps, Janes & Montgomery (1994) defined the morphological age index δV as the magnitude difference between the main-sequence turn-off and the clump in the (V, $V - I$) colour–magnitude diagram, deriving $\delta V = 0.8$ for NGC 1817. This value implies a cluster age of ≈1.3 Gyr (Janes & Phelps 1994), on the basis of which the cluster can be estimated to be of intermediate age. More recently, NGC 1817 was studied by Balaguer-Nuñez et al. (2004) who obtained CCD photometry in the $uvby$–Hβ intermediate-band system down to $V = 22$. They obtained a reddening similar to that of HH77, a distance slightly smaller ($d = 1.5$ kpc), an age of 1.1 Gyr and derived a metallicity of [Fe/H] $= -0.34 \pm 0.26$, using only F and G stars within the validity range of the Shuster & Nissen (1989) calibration.

On the other hand, NGC 2251 (C0632+084) – also designated Cr 101 – is a rich open cluster somewhat younger than the Hyades (Lyngå 1987). The only known photometric study was performed by Hoag et al. (1961, hereafter H61), in the UBV bands. This study includes photoelectric and photographic measurements of 107 stars down to $V = 17$. By using the original data from H61, Loktin, Gerasimenko & Malisheva (2001) determined the following cluster parameters: $d = 1329$ pc, $E(B - V) = 0.186$ and an age of 0.3 Gyr. Based on unpublished DDO photometric data of three red giants, Piatti, Clariá & Abadi (1995, hereafter PCA) obtained [Fe/H] $= -0.17$, while Twarog, Ashman & Anthony-Twarog (1997) revised this value to [Fe/H] $= -0.08$ by adding an offset of 0.09 dex to the value obtained by PCA.

The fact that NGC 1817 and 2251 lie at more than 1 kpc from the Sun in the Galactic anticentre direction makes them interesting objects in terms of the structure and chemical evolution of the outer disc. The determination of their metal abundances will allow us to compare the results with those known concerning other open clusters located approximately in the same direction and to extend our knowledge of the Galactic disc. In addition, NGC 1817 and 2251 are in themselves worth a detailed study because no previous DDO and/or Washington photometry has yet been published.

In Section 2 we describe the observational material and the data reduction. Section 3 presents the analysis of the Washington and BV–DDO data, including membership criteria and derivation of reddening, effective temperatures and metallicities. A discussion of the present findings for NGC 1817 and 2251 together with a re-examination of the overall properties of a sample of 30 open clusters located in the Galactic anticentre direction is provided in Section 4. Finally, a brief summary of the main conclusions is presented in Section 5.

2 OBSERVATIONAL MATERIAL

A total of 27 stars in the field of NGC 1817 with $10.0 < V < 13.5$ and $B - V > 1.0$, were originally selected as red giant candidates from the colour–magnitude diagram (CMD) published by HH77 (their fig. 6). 21 of these stars appear to be free from contamination by neighbouring stars and were observed with the C, M, T_1 and T_2 filters of the Washington system (Canterna 1976) using the CTIO 1.0-m telescope in 1993 January. In addition, eight of these stars were also observed with the DDO 51 filter defined by Clark & McClure (1979). This filter was introduced by Geisler (1984) in order to eliminate foreground dwarfs. In NGC 2251, only three stars appear to be probable red giant members according to their positions in the CMD published by H61. These stars are HD 259990 (BD $+8^0$1404) and nos 3 and 6 of the list of photographic observations by H61. Hereafter these three stars will be referred to as 3, 3a and 3b, respectively. These stars were observed at CTIO in the Washington system under the same conditions and with the same equipment as for the NGC 1817 stars. With the aim of obtaining additional information concerning cluster membership, reddening and metallicity, the three stars were also observed in the UBV and DDO systems, using the CTIO 0.6- and 1.0-m telescopes in 1992 January and 1993 January, respectively.

All observations employed a single-channel photometer and pulse-counting electronics. A dry-ice-cooled Hamamatsu R943-02 phototube was used for the CMT_1T_2 measurements, while an EMI 9781A photomultiplier was employed for the UBV and DDO observations. Nightly extinction and transformation coefficients were determined from a large number of observations of Washington, UBV and DDO standard stars taken from the lists of Cousins (1973, 1974), McClure (1976), Harris & Canterna (1979) and Geisler (1990). The average of the rms errors from the transformation to the Washington standard system of the different nights yielded 0.010, 0.007, 0.011 and 0.018 mag for $C - M$, $M - T_1$, $T_1 - T_2$ and T_1, respectively. For the UBV photometry, these values are 0.011, 0.019 and 0.016 for $B - V$, $U - B$ and V, respectively, while for the DDO colours the rms errors are all smaller than 0.011 mag. Tables 2 and 3 present the observed colours and magnitudes of the cluster stars, along with the standard deviations of different observations (in millimagnitudes in parentheses), and the number of nights n_1, n_2 and n_3 on which each star was observed in the Washington, UBV and DDO systems, respectively. Star designations are from HH77 and H61, respectively.

Table 2. Washington photometry of red giant candidates in NGC 1817 and 2251.

Star	$C - M$	$M - T_1$	$T_1 - T_2$	$M - 51$	T_1	n_1	V_r	Notes
NGC 1817								
1008	1.549(6)	1.072(15)	0.715(1)		11.627(15)	2	+29.75	NM
1014	1.088(18)	0.847(9)	0.579(6)	0.061(21)	12.088(23)	3	+67.82	M,SB
1027	1.274(10)	0.892(8)	0.619(6)	0.046(18)	11.567(24)	3	+64.99	M
1038	1.243(18)	0.891(7)	0.608(1)		11.972(14)	2	+64.96	M
1051	1.205(12)	0.874(9)	0.609(19)	0.038(11)	12.186(32)	3	+65.86	M
1061	1.221(5)	0.886(8)	0.601(7)	0.023(9)	11.936(32)	2	+64.79	M
2009	1.240(19)	0.920(9)	0.633(12)		11.846(27)	3	+65.18	M
2038	1.282(9)	0.907(8)	0.625(2)		11.649(9)	2	+64.92	M
2047	1.387(1)	1.035(12)	0.630(8)		10.896(21)	2	−3.08	NM
2059	1.407(20)	0.947(16)	0.640(4)	0.014(9)	11.533(35)	3	+65.52	M
2060	1.237(8)	0.885(15)	0.591(8)	0.023(6)	11.598(31)	3	+63.74	M,SB
2063	1.223(22)	0.875(9)	0.604(14)	0.012(15)	12.370(39)	3	+65.88	M
2104	1.289(13)	0.915(2)	0.607(2)		11.821(32)	2	+64.79	M,SB
2112	1.235(19)	0.898(21)	0.603(6)	0.060(13)	11.706(26)	3	+62.45	M,SB
2124	1.455(3)	1.007(10)	0.645(31)		12.033(44)	2	−9.95	NM
3031	1.257(1)	0.936(19)	0.639(10)		12.013(21)	2	+64.54	M,SB
3066	1.705(32)	1.066(8)	0.684(3)		11.868(17)	2	+8.12	NM
3085	1.038(22)	0.794(9)	0.573(4)		12.003(24)	2		NM
3093	1.341(19)	0.946(11)	0.634(9)		12.181(1)	2		NM
3106	1.276(15)	0.927(9)	0.634(5)		11.750(27)	2	+65.31	M
3114	1.329(10)	0.929(11)	0.639(8)		11.612(24)	3	+65.14	M
NGC 2251								
3	1.462(11)	0.962(21)	0.666(22)		9.852(28)	2	+24.68	M
3a	1.419(4)	0.934(7)	0.637(10)		9.770(28)	2	+24.34	M
3b	1.408(23)	0.954(12)	0.629(19)		10.454(26)	2	+25.13	M

Table 3. UBV and DDO photometry of red giants in NGC 2251.

Star	V	$B - V$	$U - B$	n_2	$C(45 - 48)$	$C(42 - 45)$	$C(41 - 42)$	n_3
3	10.390(12)	1.219(24)	1.005(36)	5	1.278(6)	0.895(12)	0.270(16)	3
3a	10.386(11)	1.206(11)	0.932(19)	2	1.274(9)	0.881(22)	0.250(23)	3
3b	10.997(20)	1.195(24)	0.890(33)	5	1.269(6)	0.850(2)	0.234(12)	3

3 ANALYSIS AND RESULTS

3.1 Membership information

As shown by Geisler (1984), the $M - 51$ index has proved to be quite successful in discriminating dwarf and giant stars. Fig. 1 shows the $(M - 51)_0$ versus $(T_1 - T_2)_0$ diagram for NGC 1817, wherein only the eight stars observed with the DDO filter 51 are included. We have adopted $E(B - V) = 0.23$ for NGC 1817 (see Section 3.2) and the reddening ratios $E(T_1 - T_2) = 0.692E(B - V)$ and $E(M - 51) = 0.03E(B - V)$ given by Geisler et al. (1991). The positions of the eight stars of NGC 1817 in Fig. 1 are compatible with all of them being slightly metal-poor red cluster giants.

However, the best way to confirm the cluster membership status of a given star is from its radial velocity. Friel & Janes (1989) derived radial velocities of some red giant candidates in NGC 1817 from moderate dispersion spectra. In particular, they confirmed that two stars (nos 3085 and 3093) are definitely not cluster members (Table 2). More recently, Mermilliod et al. (2003) obtained high-precision radial velocities for the remaining 19 observed stars, using the photoelectric scanner Coravel (Baranne, Mayor & Poncet 1979). The resulting values are listed in column 8 of Table 2. 14 stars have Coravel radial velocities in the narrow range $62.4 < V_r$

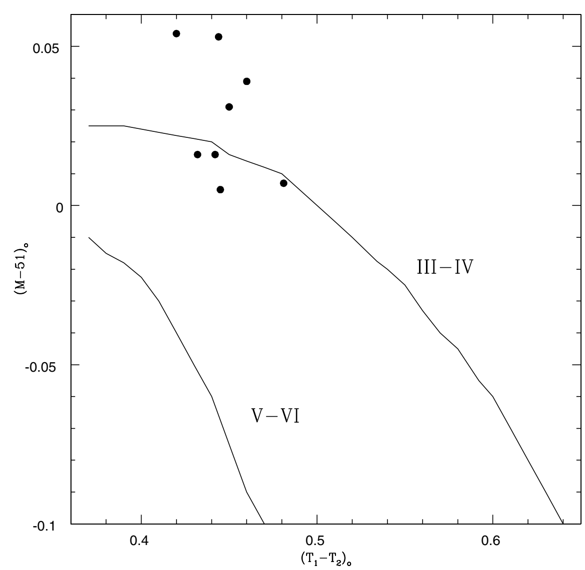

Figure 1. $(M - 51)_0$ versus $(T_1 - T_2)_0$ diagram for eight red giant candidates observed in NGC 1817. Curves are shown for dwarfs and giants of approximately solar metallicity.

Table 4. Red giant membership results in NGC 2251.

Star	$E(B-V)_{\rm DDO}$	σ_E	*LC* Pred.	*MK*(DDO)	Membership (A)	(B)
3	0.19	0.056	II–III	G8II	M	M
3a	0.19	0.045	II–III	G8II	M	M
3b	0.24	0.054	II–III	G5II	M	M

< 65.9 km s^{-1}, including four spectroscopic binaries (SBs) recognized by Mermilliod et al. (2003). All of these stars appear to be unambiguously red giant members of NGC 1817. In addition, the SB star 1014 has a mean radial velocity of 67.82 km s^{-1}, so it is also very likely to be a cluster member.

Glushkova & Rastorguev (1991) measured radial velocities of the three stars here observed in NGC 2251. They found 24.86 ± 0.61, 24.34 ± 0.61 and 25.23 ± 0.87 km s^{-1} for stars 3, 3a and 3b, respectively. The remarkable similarity between these values leaves no doubt about the physical relationship between these three stars and the cluster. In addition, Mermilliod (2005, private communication) obtained very similar Coravel radial velocities and none of these stars exhibits any sign of binarity.

Cluster membership was also examined in NGC 2251 by applying two photometric criteria – denoted A and B – described by Clariá & Lapasset (1983) and Claria (1985), which are based on combined *BV* and DDO data. To apply these criteria, the colour excess for the main-sequence stars and true distance modulus both derived by Loktin et al. (2001) were adopted. The DDO colours were dereddened according to the reddening coefficients given by McClure (1973) and the predicted luminosity class (LC) for each star was determined from the Schmidt-Kaler (1982) calibration assuming $R = A_V/E(B-V) = 3.0$. Columns (2–7) of Table 4 display in succession the colour excess $E(B-V)_{\rm DDO}$ derived from Janes's (1977) iterative method, the standard deviation of the $E(B-V)_{\rm DDO}$ colour excess calculated from equation (2) of Clariá & Lapasset (1983), the *LC* each star would have in order to be a cluster member, the spectral type from the DDO colours using the calibration of Clariá, Piatti & Lapasset (1994b) and the membership results from applying criteria A and B. As shown in Table 4, the three observed stars are found to be cluster members. Therefore, as demonstrated in previous papers (see, e.g., Clariá et al. 2003), criteria A and B lead to reliable membership results for G and K giants provided their *BV* and DDO data are of high quality.

3.2 Reddening

Before any attempt is made to determine the cluster metallicity from Washington photometry, the interstellar reddening must be established as accurately as possible. Regarding NGC 1817, different $E(B-V)$ values are mentioned in the literature. HH77, for example, derived $E(B-V) = 0.28$ from the $B-V$ and $U-B$ colours of the earliest main-sequence stars. To perform this determination, they adopted 0.72 for the reddening ratio $E(U-B)/E(B-V)$. However, it has been well recognized since the work of Schmidt-Kaler (1961) that the degree of reddening experienced by a star is dependent upon the colour of the star. Generally, a red giant exhibits a smaller $E(B-V)$ value than a hotter main-sequence star when obscured by the same dust layer. As shown by several authors (see, e.g., Golay 1974), the $E(U-B)/E(B-V)$ ratio significantly increases when late-type stars are considered. Adopting $E(U-B)/E(B-V) = 0.90$ for the NGC 1817 giants, HH77 derived the smaller reddening value $E(B-V) = 0.23$, which is, however, more representative of the red giant stellar component of NGC 1817. HH77 did not find any evidence of variability in this parameter, so the cluster reddening may be considered uniform.

Cameron (1985) developed a method for calculating simultaneously both the ultraviolet excess and the reddening of an open cluster. Using this procedure and the photometric data of HH77, he derived $E(B-V) = 0.33$ for NGC 1817. On the other hand, using only red giant stars Twarog et al. (1997) derived $E(B-V) = 0.26$, in reasonable agreement with the value previously found by HH77 for the same stars. More recently, Dutra & Bica (2000) derived a far-infrared reddening $E(B-V)_{\rm FIR} = 0.33$ from *DIRBE*/*IRAS* 100-μm dust emission in the cluster field. This value, however, should be interpreted as an upper limit since $E(B-V)_{\rm FIR}$ may include background dust contribution. Even though the published $E(B-V)$ values for NGC 1817 vary from 0.23 up to 0.33 mag, depending on the method and stars used to derive them, we adopted here HH77's reddening as the most robust value for the red cluster giants.

Regarding NGC 2251, the mean value of the individual $E(B-V)_{\rm DDO}$ colour excesses in Table 4 is $\langle E(B-V)_{\rm DDO}\rangle = 0.21 \pm 0.03$, in good agreement with the reddenings published by Lyngå (1987) as well as by Loktin et al. (2001). We have, therefore, adopted this reddening value for NGC 2251 in the subsequent analysis.

3.3 Metallicities

Geisler et al. (1991, hereafter GCM91) have calibrated five Washington metallicity sensitive indices in terms of high-dispersion spectroscopic iron-to-hydrogen ratios and proposed an iterative method to estimate metal abundances of late-type giants. The method allows for mean cluster abundances to be easily obtained after a few iterations, although the accuracy of the resulting metallicity values strictly depends on the quality of the photometric data. Only Washington colour indices with a precision of the order of 0.01–0.02 mag have been used up to now (e.g. Clariá et al. 1999). GCM91 have defined fiducial lines for solar abundance giants in the Washington two-colour diagrams. The first step to derive metallicity from the Washington colours is to correct the observed indices by interstellar reddening using the reddening ratios given by GCM91. Fig. 2 displays the $(C-M)_0/(T_1-T_2)_0$, $(M-T_1)_0/(T_1-T_2)_0$, $(C-T_1)_0/(T_1-T_2)_0$, $(C-M)_0/(M-T_2)_0$ and $(C-T_1)_0/(M-T_2)_0$ two-colour diagrams for the confirmed giant members of NGC 1817. The isoabundance relations range from [Fe/H] = +0.5 (bottom) to −3.0 (top), in steps of 0.5 dex, except for the $(M-T_1)_0/(T_1-T_2)_0$ diagram where the range is from +0.4 to −0.8 in steps of 0.4 dex. According to GCM91, the abundance-sensitive index Δ is the difference between the observed colour and the solar-abundance colour at the observed (T_1-T_2) [or $(M-T_2)$], where all colours refer to unreddened values. GCM91 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], where $\Delta'_1 - \Delta'_5$ refer, respectively, to $\Delta'(C-M)_{T_1-T_2}$, $\Delta'(M-T_1)_{T_1-T_2}$, $\Delta'(C-T_1)_{T_1-T_2}$, $\Delta'(C-M)_{M-T_2}$, and $\Delta'(C-T_1)_{M-T_2}$. These Δ'_i indices can be calculated from the Δ_i indices using GCM91's equation (2). Note, however, that $\Delta'_i = \Delta_i$ for all the observed stars in NGC 1817, because they are all bluer than the relevant limit for which a correction is required. The derived Washington abundance indices for the cluster giants are given in columns 3–7 of Table 5. The resulting mean values and standard deviations of the mean from 15 giant members are: $\langle\Delta'_1\rangle = \langle\Delta'(C-M)_{T_1-T_2}\rangle = -0.14 \pm 0.01$, $\langle\Delta'_2\rangle = \langle\Delta'(M-T_1)_{T_1-T_2}\rangle =$

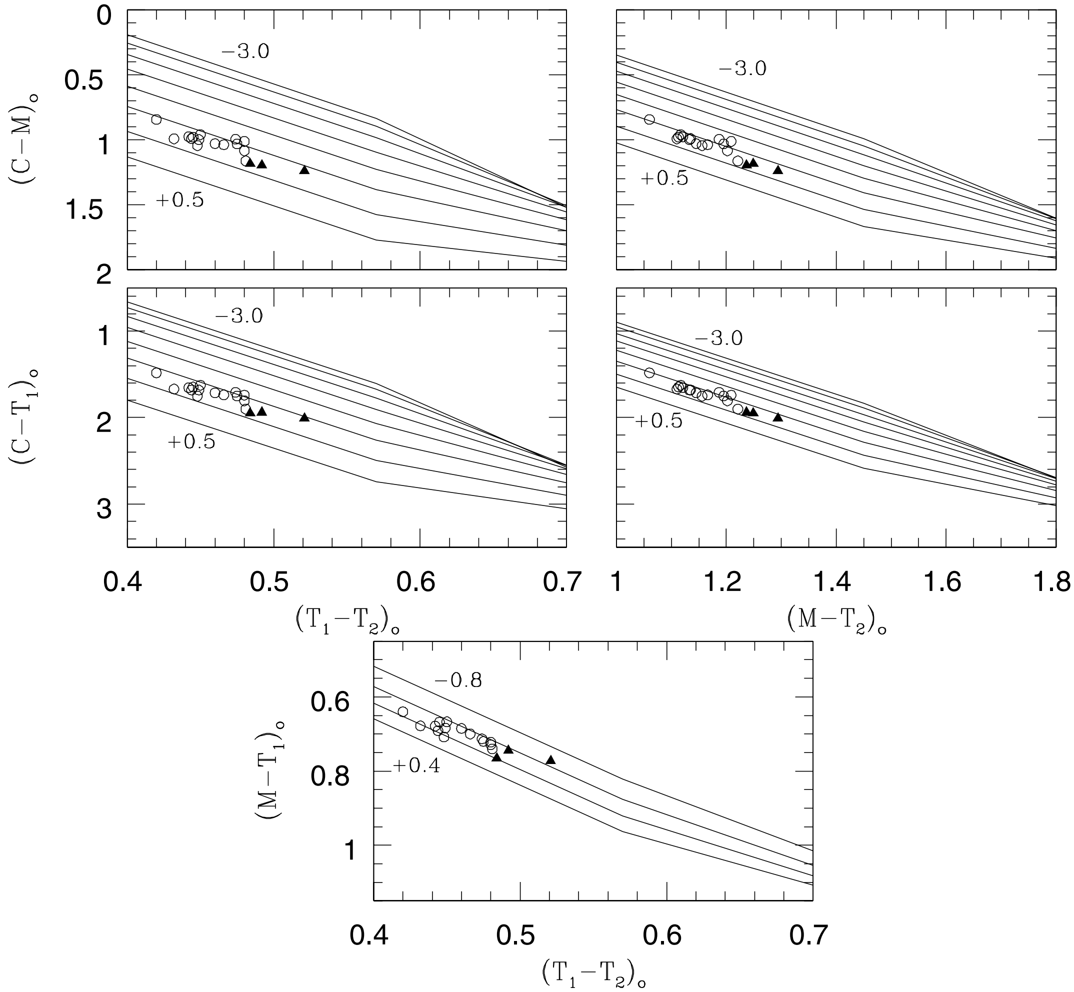

Figure 2. Unreddened Washington colour–colour diagrams for red cluster giants of NGC 1817 (open circles) and 2251 (filled triangles) confirmed from radial velocity data. Isoabundance relations from GCM91 for 0.5 dex intervals from [Fe/H] = +0.5 to −3.0 are shown, except for the $(M - T_1)_0/(T_1 - T_2)_0$ diagram wherein isoabundance relations for 0.4 intervals from +0.4 to −0.8 are given.

Table 5. Effective temperatures and Washington abundance indices.

Star	$T_{\rm eff}$	Δ'_1	Δ'_2	Δ'_3	Δ'_4	Δ'_5
NGC 1817						
1014	5450	−0.17	−0.01	−0.18	−0.14	−0.14
1027	5190	−0.13	−0.04	−0.17	−0.07	−0.09
1038	5275	−0.12	−0.02	−0.14	−0.09	−0.09
1051	5275	−0.16	−0.04	−0.20	−0.10	−0.11
1061	5315	−0.12	−0.01	−0.13	−0.09	−0.09
2009	5095	−0.22	−0.04	−0.25	−0.17	−0.18
2038	5150	−0.15	−0.04	−0.18	−0.09	−0.11
2059	5050	−0.08	−0.02	−0.10	−0.05	−0.06
2060	5375	−0.06	0.00	−0.06	−0.06	−0.06
2063	5290	−0.13	−0.03	−0.15	−0.08	−0.09
2104	5270	−0.07	+0.01	−0.06	−0.07	−0.07
2112	5295	−0.11	−0.01	−0.11	−0.10	−0.10
3031	5055	−0.22	−0.03	−0.25	−0.18	−0.19
3106	5090	−0.19	−0.03	−0.22	−0.14	−0.15
3114	5055	−0.15	−0.04	−0.19	−0.10	−0.11
NGC 2251						
3	4279	−0.15	−0.06	−0.21	−0.08	−0.10
3a	4886	−0.09	−0.04	−0.12	−0.04	−0.05
3b	4930	−0.07	0.00	−0.07	−0.07	−0.07

-0.02 ± 0.01, $\langle \Delta'_3 \rangle = \langle \Delta'(C - T_1)_{T_1-T_2} \rangle = -0.16 \pm 0.02$, $\langle \Delta'_4 \rangle = \langle \Delta'(C-M)_{M-T_2} \rangle = -0.10 \pm 0.01$ and $\langle \Delta'_5 \rangle = \langle \Delta'(C-T_1)_{M-T_2} \rangle = -0.11 \pm 0.01$. These values practically do not change if the five spectroscopic binaries of NGC 1817 (Table 2) are omitted. Finally, five different values of the iron-to-hydrogen ratio were derived from the expression

$$[\mathrm{Fe/H}] = \left[-b_i + \sqrt{b_i^2 - 4a_i(c_i - \Delta'_i)} \right] \Big/ 2a_i, \tag{1}$$

where the constants a_i, b_i and c_i are given in GCM91's table 10. The resulting values and the corresponding standard deviation of the mean are: $[\mathrm{Fe/H}]_1 = -0.36 \pm 0.04$, $[\mathrm{Fe/H}]_2 = -0.19 \pm 0.04$, $[\mathrm{Fe/H}]_3 = -0.33 \pm 0.03$, $[\mathrm{Fe/H}]_4 = -0.39 \pm 0.04$ and $[\mathrm{Fe/H}]_5 = -0.36 \pm 0.04$. Four out of these five values show very good agreement, while just one of them ($[\mathrm{Fe/H}]_2$) turns out to be somewhat larger than the remaining ones. This may be due to the fact that $[\mathrm{Fe/H}]_2$ comes from the $(M - T_1)_0$ index, which collects information from the Fe lines between 4500 and 5500 Å. The four other Washington abundances, however, are derived from the blue spectral features contaminated by CN and CH bands. Even so, the differences found in the [Fe/H] values have a degree of magnitude approximately the same as those found in previous works in which the same technique was used (see, e.g., Clariá et al. 2003). Our tentative conclusion that the cluster giants are not enriched in

Table 6. DDO cyanogen anomalies of red giants in NGC 2251.

Star	$C_s(45-48)$	$C_s(42-45)$	$C_s(41-42)$	ΔCN
3	1.207	0.844	0.240	0.017
3a	1.206	0.837	0.240	−0.003
3b	1.185	0.795	0.218	0.000

elements of the CNO group is based on the scarcely significant difference – in terms of the photometric and calibration errors – between the Washington abundances derived from the iron lines and those obtained from the blue spectral features contaminated by CN and CH. The unweighted mean of the five Washington abundance estimates is $\langle[\mathrm{Fe/H}]_W\rangle = -0.33 \pm 0.08$ (s.d.), which will be adopted in the subsequent analysis.

We have also applied the method recommended by GCM91 to the stars observed in NGC 2251 in the Washington system. Note that, as in the case of NGC 1817, the three stars observed in NGC 2251 (see Fig. 2) are comparatively hot so that their individual Δ'_i indices also coincide with their corresponding Δ_i indices. The resulting mean Δ' values and standard deviations of the mean are: $\langle\Delta'_1\rangle = -0.10 \pm 0.02$, $\langle\Delta'_2\rangle = -0.03 \pm 0.01$, $\langle\Delta'_3\rangle = -0.13 \pm 0.03$, $\langle\Delta'_4\rangle = -0.06 \pm 0.01$ and $\langle\Delta'_5\rangle = -0.07 \pm 0.01$, which in turn imply $[\mathrm{Fe/H}]_1 = -0.25 \pm 0.06$, $[\mathrm{Fe/H}]_2 = -0.30 \pm 0.11$, $[\mathrm{Fe/H}]_3 = -0.27 \pm 0.08$, $[\mathrm{Fe/H}]_4 = -0.20 \pm 0.03$ and $[\mathrm{Fe/H}]_5 = -0.22 \pm 0.04$, if the calibrations of GCM91 are used. The unweighted average of the five abundance estimates is $\langle[\mathrm{Fe/H}]_W\rangle = -0.25 \pm 0.04$.

An independent metallicity determination of the NGC 2251 red giants may be performed from the observed DDO indices. Janes (1975) has shown that the cyanogen anomaly δCN – defined as the excess (positive δCN) or deficiency of the unreddened $C(41-42)$ index in magnitudes over the standard value for a star of the same unreddened $C(45-48)$ and $C(42-45)$ indices – is well correlated with [Fe/H]. However, some inconsistencies in the definition and calculation of δCN pointed out by Piatti, Clariá & Minniti (1993, hereafter PCM93), led them to redefine the cyanogen anomaly – now denoted ΔCN – as the difference between the unreddened $C(41-42)$ index and the standard value of this index corresponding to a star with the same temperature and surface gravity [and not with the same unreddened $C(45-48)$ and $C(42-45)$ indices] as the star in question.

We have corrected the observed DDO indices by interstellar reddening using the colour excess ratios $EC(45-48) = 0.354E(B-V)$, $EC(42-45) = 0.234E(B-V)$ and $EC(41-42) = 0.066E(B-V)$ given by McClure (1973). Then we applied the iterative procedure proposed by PCM93 to derive the cluster metal content. Columns 2-4 of Table 6 list the final standard DDO indices derived after two iterations as explained in PCM93, while column 5 displays the resulting new cyanogen anomalies. The mean cyanogen anomaly is $\langle\Delta\mathrm{CN}\rangle = -0.14$, which implies $[\mathrm{Fe/H}]_{\mathrm{DDO}} = -0.14 \pm 0.05$, if equation (8) of PCM93 is used. We note that if the old cyanogen anomaly δCN instead of ΔCN had been used, the resulting metallicity would have been practically the same. Considering the two independent metallicity determinations, we finally adopted $[\mathrm{Fe/H}] = -0.20 \pm 0.05$ for NGC 2251.

3.4 Effective temperatures

By means of the calibration established by Geisler, Minniti & Clariá (1992b), effective temperatures were determined for the confirmed red giants in NGC 1817 and 2251. Since we are dealing with population I late-type giants, we have assumed $\log g = 1.5$ and interpolated the effective temperatures between grids to the appropriate mean cluster metallicity. Column 2 of Table 5 displays the results. Star 1014, with an effective temperature of 5450 K, is the hottest one among the confirmed cluster giants, which is consistent with its position in the five colour–colour diagrams of Fig. 2. As has been shown in Geisler et al. (1992b), the effective temperatures have an internal error of ∼100 K and should prove useful for future studies. As an illustration, they could be used as input temperatures for model atmosphere analysis of high dispersion spectroscopy. Additionally, they could contribute to the construction of CM diagrams for comparison with theoretical giant branch models.

4 DISCUSSION

NGC 1817 and 2251 have proved to be moderately metal-poor open clusters located in the outer disc towards the Galactic anticentre direction. Their derived abundances are compatible with the existence of a radial metallicity gradient along the Galactic disc (see, e.g., Chen et al. 2003 and references therein). The present metallicity of NGC 1817, determined from confirmed red giants, is in excellent agreement with the value derived by Balaguer-Nuñez et al. (2004) from *uvby*–Hβ photometry of F and G main-sequence stars. Note, however, that if instead of using $E(B-V) = 0.23$ (HH77) we had adopted the reddening value obtained by Twarog et al. (1997) for the cluster giants, i.e. $E(B-V) = 0.26$, the resulting metallicity would have been ∼0.1 dex larger. Friel & Janes (1993, hereafter FJ93), obtained medium-resolution spectra of five red giant candidates in NGC 1817 and derived $[\mathrm{Fe/H}] = -0.39 \pm 0.04$ from spectroscopic indices measuring Fe and Fe-peak element blends, the CN λ4216 band and the Mg *b* and Mg H features. Two of the stars observed by FJ93 (nos 1008 and 2124) are clearly non-members according to Mermilliod et al. (2003). If only the remaining three members are considered, the resulting metallicity is then $[\mathrm{Fe/H}] = -0.38$, in good agreement with the value found in this study. A revised value of $[\mathrm{Fe/H}] = -0.29$ recently obtained for NGC 1817 by Friel et al. (2002) still shows good agreement with the present metallicity determination. Regarding NGC 2251, the present DDO metal content ($[\mathrm{Fe/H}] = -0.14$) is in very good agreement with the preliminary value quoted by PCA. This metallicity was derived from unpublished DDO photometry.

To re-examine the properties of the outer Galactic disc, we searched through the WEBDA Open Cluster data base (see http://obswww.unige.ch/webda/) and in the available literature for objects distributed within a region defined by $155° < l < 205°$, and with known values of their colour excesses, distances, ages and metallicities. In Table 7 we present the final cluster list with the values of the adopted parameters and corresponding references, having averaged the involved quantities when two or more references were used. Column 7 of Table 7 gives the sources from which the reddening, distance and age were taken, while column 11 indicates the sources from which the metallicity was taken. We computed the Galactic coordinates X, Y and Z and the Galactocentric distances R_{GC} for all the clusters from their Galactic coordinates (l, b) and distances from the Sun, assuming the distance of the Sun from the Galactic Centre to be 8.5 kpc. The computed R_{GC} values are displayed in column 9 of Table 7.

The upper left-hand panel of Fig. 3 confirms the fact that the height out of the Galactic plane ($|Z|$) tends to rise as the distance from the Sun (d) increases. In this diagram as well as in the ones that follow, NGC 1817 and 2251 are represented by a filled triangle and square, respectively. The $E(B-V)$ versus d relationship (upper

Table 7. Fundamental parameters of selected anticentre open clusters.

Cluster	l (deg)	b (deg)	d (kpc)	$E(B-V)$ (mag)	Age (Gyr)	Ref.[a]	$\|Z\|$ (kpc)	R_{GC} (kpc)	[Fe/H] (dex)	Ref.[a]
Hyades	180.7	−22.3	0.045	0.01	0.8	2	0.02	8.54	+0.13	2
Melotte 22	166.6	−23.5	0.150	0.03	0.1	2	0.06	8.63	−0.03	2
NGC 1662	187.7	−21.1	0.400	0.34	0.3	8	0.14	8.87	−0.13	8
NGC 2281	174.9	16.9	0.558	0.06	0.4	2,4	0.16	9.03	+0.13	2
NGC 2264	202.9	2.2	0.667	0.05	7.0	22	0.03	9.12	−0.15	22
NGC 2168	186.6	2.2	0.816	0.26	0.1	2	0.03	9.31	−0.21	6
NGC 2099	177.6	3.1	1.360	0.30	0.4	5	0.07	9.86	−0.40	5
NGC 2355	203.4	11.8	2.200	0.12	0.7	2	0.45	10.52	−0.20	14,15
Trumpler 5	202.9	1.1	2.300	0.60	5.0	19	0.04	10.75	−0.30	19
Berkeley 17	175.6	−3.6	2.500	0.58	9.0	1	0.16	10.99	−0.34	1,3
NGC 2420	198.1	19.6	3.085	0.03	1.1	2	1.04	11.35	−0.38	3
Berkeley 12	161.7	−2.0	3.162	0.70	4.0	2	0.11	11.54	+0.07	9
NGC 2194	197.3	−2.3	3.200	0.55	0.4	17	0.13	11.59	−0.27	17
NGC 2259	201.8	2.1	3.311	0.59	0.3	2	0.12	11.64	+0.07	2
NGC 2266	187.8	10.3	3.400	0.10	0.6	18	0.61	11.84	−0.33	18
NGC 2192	173.4	10.7	3.500	0.20	1.1	20	0.65	11.94	−0.31	20
NGC 2158	186.6	1.8	3.600	0.55	2.0	7	0.11	12.08	−0.25	3
NGC 2141	198.0	−5.8	3.800	0.40	2.5	13	0.39	12.16	−0.33	3
NGC 2304	197.2	8.9	3.991	0.10	0.8	2	0.62	12.34	−0.32	9
NGC 1798	160.7	4.9	4.200	0.51	1.4	20	0.36	12.53	−0.47	20
Berkeley 70	166.9	3.6	4.158	0.48	4.0	2	0.26	12.58	−0.32	9
Berkeley 19	176.9	−3.6	4.830	0.40	3.1	2	0.30	13.32	−0.50	2
Berkeley 21	186.8	−2.5	5.000	0.76	2.2	2	0.22	13.48	−0.62	3
Berkeley 18	163.6	5.0	5.800	0.46	4.3	1,21	0.51	14.15	0.00	1
King 8	176.4	3.1	6.403	0.58	0.4	2	0.35	14.89	−0.39	3
Berkeley 22	199.9	−8.1	7.663	0.70	1.1	2	1.08	15.88	−0.32	26
Berkeley 20	203.5	−17.4	9.026	0.82	5.0	16	2.70	16.97	−0.61	3
Berkeley 29	198.0	8.0	13.800	0.12	3.6	10	1.93	21.99	−0.59	10,11,12
NGC 2251	203.6	0.1	1.329	0.21	0.3	4	0.00	9.73	−0.19	4,25
NGC 1817	186.2	−13.1	1.600	0.25	1.1	23,24	0.36	10.06	−0.33	25

[a]References: (1) Carraro et al. (1999), (2) Chen, Hou & Wang (2003), (3) Friel et al. (2002), (4) Loktin et al. (2001), (5) Nilaksi & Sagar (2002), (6) Barrado Y. Navascués, Deliyannis & Stauffer (2001), (7) Carraro, Girardi & Marigo (2002), (8) Clariá, Piatti & Osborn (1996), (9) Ann et al. (2002), (10) Tosi et al. (2004), (11) Bragaglia, Held & Tosi (2005), (12) Carraro et al. (2004), (13) Carraro et al. (2001), (14) Ann et al. (1999), (15) Soubiran, Odenkirchen & Le Campion (2000), (16) Durgapal, Pandey & Mohan (2001), (17) Piatti, Clariá & Ahumada (2003), (18) Kaluzny & Mazur (1991), (19) Piatti, Clariá & Ahumada (2004), (20) Park & Lee (1999), (21) Kaluzny (1997), (22) Dias et al. (2002), (23) Harris & Harris (1977), (24) Twarog et al. (1997), (25) this paper, (26) Villanova et al. (2005).

right-hand panel) indicates a simple result which can ordinarily be expected, i.e. that the further the cluster is located along the same line of sight, the higher the interstellar reddening. Note that NGC 1817 and 2251 have colour excesses compatible with the general tendency in the considered direction, while the very distant cluster Berkeley 29 does not have as high a reddening as would be expected.

The lower left-hand panel of Fig. 3 shows how the absolute distances away from the Galactic plane vary as a function of cluster ages. Even though the $|Z|$ values do not seem to exhibit any tendency to decrease or increase with age, it is seen that the clusters younger than ∼0.5 Gyr located in the direction being considered tend to be located practically in the Galactic plane, while those which are older and are located in the same direction display a greater dispersion in $|Z|$. It would be quite reasonable to assume that the latter might have moved through the Galactic disc several times (Carraro & Chiosi 1994; Piatti et al. 1995), being currently observed at different Z values. These objects were probably formed at $|Z|$ values higher than those corresponding to the younger clusters, considering the fact that if they had been formed close to the Galactic plane, they would have done so with initial perpendicular velocities too high for them to be located at high $|Z|$ values at present. The second alternative seems quite unlikely to happen for objects formed close to the Galactic plane.

As can be seen in the lower right-hand panel of Fig. 3, the selected clusters do not show any trend between their metal abundances and ages, a result confirmed by several authors who considered clusters in other directions (see, e.g., Friel & Janes 1993; Friel et al. 2002). The cluster metallicities cover a wide range, from values as deficient in heavy elements as [Fe/H] ~ -0.6 dex to metal-rich ones of $\sim +0.15$ dex, the dispersion in the [Fe/H] values being mainly caused by the dependence of cluster metallicities on their Galactocentric distances (R_{GC}).

Fig. 4 illustrates the behaviour of the cluster metallicities with respect to R_{GC} in the anticentre direction. Filled circles represent the average of [Fe/H] values within R_{GC} intervals of 1.0 kpc, weighted by the number of clusters in each interval. In order to design this diagram all the clusters in Table 7 were taken into account, except for Berkeley 18, due to the fact that its metallicity is highly incompatible with its position. It is indeed possible that the solar metallicity derived by Carraro et al. (1999) for Berkeley 18 from the slope of the red giant branch in the K versus $J-K$ diagram, has been strongly overestimated due to the poor definition of the RGB in this diagram. When only one cluster has been considered in a certain interval in R_{GC}, its name is indicated in Fig. 4. If the cluster Berkeley 29, situated at ∼22 kpc from the Galactic Centre (Tosi et al. 2004) and presumably associated with the Monoceros stream (Carraro et al.

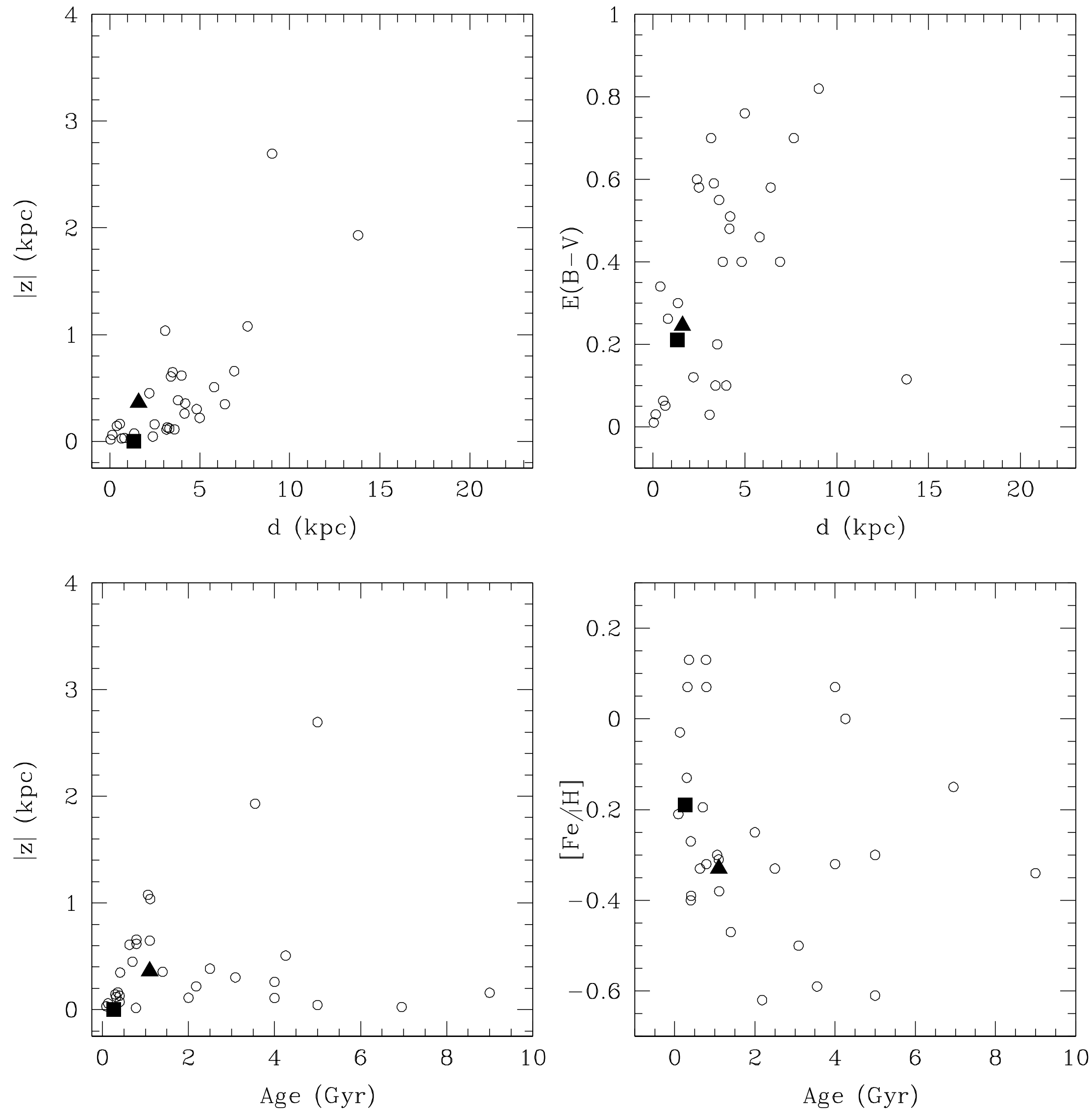

Figure 3. Relationship between the distance from the Sun, the height out of the Galactic plane, the reddening, the age and metallicity of open clusters with known fundamental parameters (open circles) located in the anticentre direction. NGC 1817 (triangle) and NGC 2251 (square) are shown. See Section 4 for details.

2004) is not considered, then we estimate a formal radial abundance gradient of -0.052 dex kpc^{-1} (full line) within the first 16 or 17 kpc from the Galactic Centre. However, if only the clusters within the first 14 kpc are considered, then this gradient turns out to be -0.093 dex kpc^{-1} (dashed line). Beyond this distance, the gradient becomes uncertain mainly because of the lack of objects at great distances from the Galactic Centre. Although this radial gradient shows good agreement with that determined in other studies using clusters of a wide range of ages (see, e.g., Hou, Chang & Chen 2002 and references therein) and there is no evidence of a sharp discontinuity at 10 kpc of Galactocentric distance, as claimed by Twarog et al. (1997), we would like to make clear that the results which surge from the interpretation of Fig. 4 should be very carefully considered, due to the fact that the used data do not have a homogeneous origin. Besides, in some cases we have averaged different metallicity values for the same cluster (e.g. NGC 2355).

Fig. 5 was obtained by means of a similar procedure as in Fig. 4. In it, filled circles represent mean [Fe/H] values within $|Z|$ intervals of 0.1 kpc. To build this diagram, the data were previously corrected for the $R_{\rm GC}$ dependence on metallicity. Although no gradient perpendicular to the Galactic plane is seen in this figure, the same words of caution as for Fig. 4 should hold good for this one.

What happens if instead of considering the open clusters located towards the Galactic anticentre direction, we include all the clusters with known [Fe/H] values in the WEBDA Open Cluster data base or in the recent literature? In this case, the abundance gradient defined by 134 open clusters is shown in Fig. 6, wherein filled circles now represent the average of [Fe/H] values in $R_{\rm GC}$ intervals of 0.5 kpc. When only one cluster has been considered in a certain interval in $R_{\rm GC}$, its name is indicated in the figure itself. According to Fig. 6, there exists a radial abundance gradient within the first 14 kpc of Galactocentric distance, the value of which is -0.094 dex kpc^{-1}, no other gradient being clearly observed beyond this distance. For the few open clusters beyond 14 kpc, it is clear that this gradient does not continue but appears to approximately level off. However, the number of clusters is very small. Note that the conclusion on the flattening of the gradient was previously reached by Carraro et al. (2004) and Yong, Carney & Teixera de Almeida (2005).

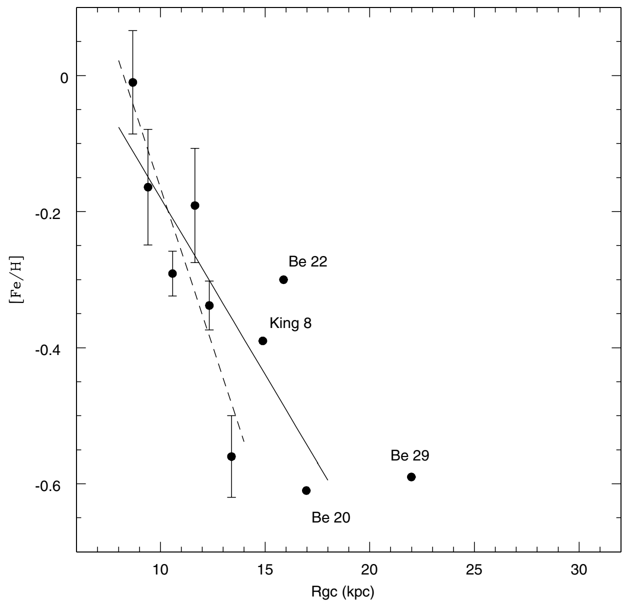

Figure 4. Relationship between the metallicity and the Galactocentric distance of the open clusters of Table 7. Filled circles and bars denote the mean abundance and the standard deviations, respectively, for clusters within $R_{\rm GC}$ intervals of 1.0 kpc. When only one cluster is considered in a certain interval in $R_{\rm GC}$, its name is indicated. The full line is the unweighted least-squares fitting of the clusters of Table 7, except for Berkeley 18 and 29. The resulting gradient is -0.052 dex kpc^{-1}. If only the clusters within the first 14 kpc are considered, this gradient turns out to be -0.093 dex kpc^{-1} (dashed line).

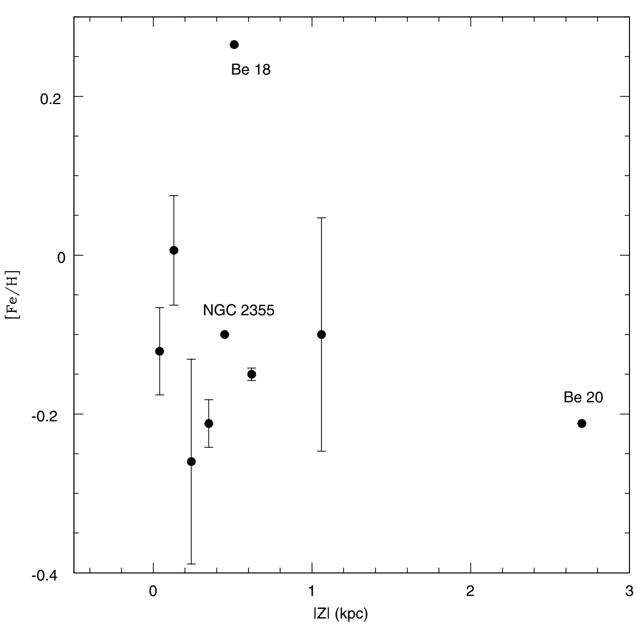

Figure 5. Relationship between metallicity and absolute distance away from the Galactic plane for clusters of Table 7. Filled circles and bars denote the mean abundance and standard deviations, respectively, for clusters within $|Z|$ intervals of 0.1 kpc. When only one cluster is considered in a certain interval in $|Z|$, its name is indicated.

5 CONCLUSIONS

Washington photoelectric photometry is presented for 21 and three red giant candidates in the open clusters NGC 1817 and 2251, respectively, both located towards the Galactic anticentre direction.

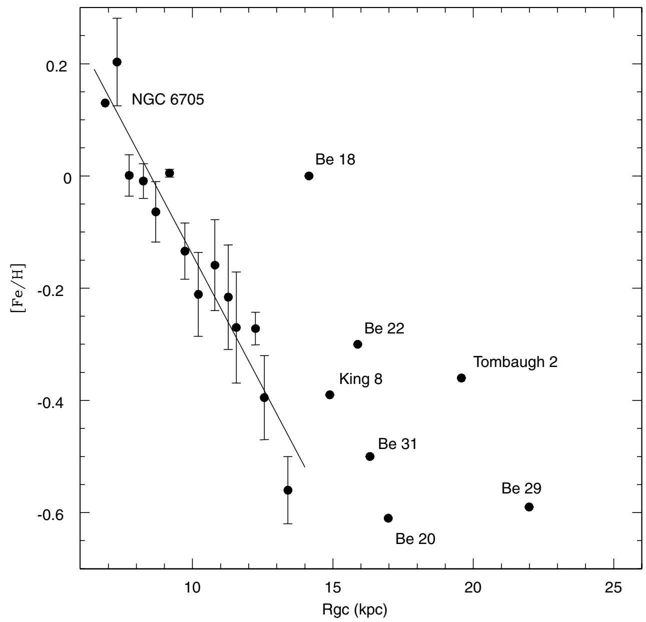

Figure 6. The radial abundance gradient across the Galactic disc defined by 134 open clusters with distances and metallicities known up to date. Filled circles and bars now denote the mean abundance and standard deviations, respectively, for clusters within $R_{\rm GC}$ intervals of 0.5 kpc. When only one cluster is considered in a certain interval in $R_{\rm GC}$, its name is indicated. The full line is the unweighted least-squares fitting to the clusters with $R_{\rm GC} <$ 14 kpc. The resulting gradient for this new sample is -0.094 dex kpc^{-1}.

These data yield an effective temperature and metal abundance for each star. In addition to the CMT_1T_2 data, *UBV* and DDO photoelectric photometry was obtained for the three stars in NGC 2251. The three of them as well as 15 of the stars observed in NGC 1817 are all unambiguously cluster members according to their radial velocities measured by Mermilliod et al. (2003) and Glushkova & Rastorguev (1991). The primary results from this study are summarized as follows.

(i) The three stars observed in NGC 2251 are found to have a high probability of being cluster members according to two photometric criteria based on combined *BV* and DDO data. This fact demonstrates that when the photometric data are of high quality, the application of these criteria leads to reliable results.

(ii) Effective temperatures have been determined with an internal error of ~100 K for the cluster giants from the unreddened $T_1 - T_2$ index and overall abundances [Fe/H] are derived from five independent Washington abundance indicators. The mean cluster abundances are [Fe/H] $= -0.33 \pm 0.08$ and -0.25 ± 0.04 for NGC 1817 and 2251, respectively. An independent metallicity determination was also performed for NGC 2251 from DDO data yielding [Fe/H] $= -0.14 \pm 0.05$. Therefore, both clusters turned out to be moderately metal-poor.

(iii) A set of 30 anticentre open clusters with known distances, ages and metallicities are used to re-examine the overall properties of the outer Galactic disc in this direction. Although the cluster data have in general a non-homogeneous origin, we derive a formal radial metal abundance of -0.093 dex kpc^{-1} for this cluster sample, within a $R_{\rm GC}$ range of ~14 kpc and no apparent discontinuity in the metallicity distribution is observed. This sample of clusters shows no correlation between age and metallicity. If all open clusters with distances and metallicities known to date are considered, i.e. 134 in all, the value of the radial gradient is practically the same as that derived for the anticentre clusters.

ACKNOWLEDGMENTS

We are gratefully indebted to the CTIO staff for their hospitality and support during our observing runs. We wish to thank J.-C. Mermilliod for providing a wealth of unpublished radial velocity membership information concerning stars in NGC 2251. We also thank the anonymous referee for his valuable comments and suggestions. This work was partially supported by the Argentinian institutions CONICET, Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT) and Agencia Córdoba Ciencia. Partial support from the Asociación Argentina de Astronomía is also gratefully acknowledged by one of us (MCP). DG gratefully acknowledges support from the chilean Centro de Astrofísica FONDAP no 15010003. This work is based on observations made at Cerro Tololo Inter-American Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

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