First identification and absolute magnitudes of the red clump stars in the Solar neighbourhood for WISE

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Abstract

We present the first determination of absolute magnitudes for the red clump (RC) stars with the Wide-field Infrared Survey Explorer (WISE). We used recently reduced parallaxes taken from the Hipparcos catalogue and identified 3889 RC stars with the WISE photometry in the Solar neighbourhood. Mode values estimated from the distributions of absolute magnitudes and a colour of the RC stars in WISE photometry are $M_{W1} = -1.635 \pm 0.026$, $M_{W3} = -1.606 \pm 0.024$ and $(W1 - W3)_0 = -0.028 \pm 0.001$ mag. These values are consistent with those obtained from the transformation formulae using 2MASS data. Distances of the RC stars estimated by using their $M_{W1}$ and $M_{W3}$ absolute magnitudes are in agreement with the ones calculated by the spectrophotometric method, as well. These WISE absolute magnitudes can be used in astrophysical researches where distance plays an important role.

Key words: 97.10.Vm Distances, parallaxes, 97.20.Li Giant and subgiant stars, 98.35.Pr Solar neighbourhood

1 Introduction

The RC stars are core-helium-burning stars on the horizontal branch of the Hertzsprung–Russell diagram. They lie on the red counterpart of the horizontal branch in the colour-magnitude diagrams of the globular clusters (Cannon, * Corresponding author. Fax: +90 212 440 03 70
Email address: esmayaz@istanbul.edu.tr (E. Yaz Gökce).
One of the most important features of the RC stars is their very limited luminosity distribution in all photometric systems which makes them standard candles for estimating astronomical distances in Galactic and extra-galactic scales. Thus, a mean absolute magnitude obtained for the RC stars in any photometric system may be very useful in studies where distance is a crucial parameter.

Using Hipparcos astrometric and photometric data (ESA, 1997), Keenan & Barnbaum (1999) found the spectral types (G8III-K2III) of the RC stars in the Solar neighbourhood and estimated that their absolute magnitudes are $0.7 \leq M_V \leq 1.0$ mag. Alves (2000), who combined the near-infrared photometry (NIR) and Hipparcos parallax data (ESA, 1997), obtained that the mean absolute magnitude of the RC stars is $M_K = -1.61 \pm 0.03$ mag in the $K_s$-band. With the newly reduced Hipparcos parallaxes (van Leeuwen, 2007), Groenewegen (2008) estimated a mean $K_s$-band absolute magnitude of $M_K = -1.54 \pm 0.04$ mag for the RC stars with a negligible dependence on the metallicity. By re-observing the RC stars in the sample of Alves (2000), Laney, Joner & Pietrzyński (2012) obtained a mean absolute magnitude of $M_K_s = -1.613 \pm 0.015$ mag for these stars, which is a very consistent value with the mean in Alves (2000). In one of the most recent studies, Bilir et al. (2013a) calibrated the $M_K$, $M_V$, $M_J$ and $M_g$ absolute magnitudes of the RC stars in terms of the colours in the Johnson–Cousins, Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006) and the Sloan Digital Sky Survey (SDSS, York et al., 2000) photometric systems.

**WISE** is the recent generation infrared (IR) space telescope with much higher sensitivity than previous IR survey missions (Wright et al., 2010). It began surveying the sky on 2010, January 14 and completed its full coverage of the sky on 2010, July 17. The all sky data were released on 2012, March 14. WISE surveyed the entire sky in four mid–infrared (MIR) bands, i.e. 3.4, 4.6, 12 and 22 μm. These bands are denoted as W1, W2, W3 and W4 with the angular resolutions 6.1, 6.4, 6.5 and 12 arcsec, respectively. **WISE** has achieved $5\sigma$ point source sensitivities better than 0.08, 0.11, 1 and 6 mJy at the W1, W2, W3 and W4 bands, respectively. These sensitivities correspond to the Vega magnitudes of 16.5, 15.5, 11.2 and 7.9 mag. Thus, **WISE** will go one magnitude deeper than the 2MASS $K_s$-band data in W1 for sources with spectra close to that of an A0 star and even deeper for moderately red sources like K stars or galaxies with old stellar populations. The passband profiles for the 2MASS (Cohen, Wheaton & Megeath, 2003) and **WISE** (Wright et al., 2010) photometric systems are shown in Fig. 1. **WISE** is the ideal photometric system for investigating RC stars. It is almost hundred times more sensitive than other infrared surveys, e.g. **IRAS** (InfraRed Astronomical Satellite, Neugebauer et al., 1984), **COBE** (COsmic Background Explorer, Smoot et al., 1992) and **AKARI** (Murakami, 2004).
The mean absolute magnitudes of the RC stars can be affected by Galactic population differences. A weak dependence of the $I$-band absolute magnitude of the RC stars in the Solar neighbourhood on $[Fe/H]$ was found by Udalski (2000). He suggested an absolute magnitude correction of 0.07 mag in the $I$-band for Large Magellanic Cloud. Girardi & Salaris (2001) and Salaris & Girardi (2002) predicted mean absolute magnitudes in $V$, $I$ and $K$ bands for the RC stars for a large range of ages and metallicities from the models of Girardi et al. (2000). According to their models, the absolute magnitudes of the RC stars in $I$-band depends both on metallicity and age. Metallicity dependence of $V$-band absolute magnitudes for the RC stars was recently studied by Bilir et al. (2013b) using a sample of globular and open clusters. They presented an absolute magnitude calibration including the $B-V$ colour and $[Fe/H]$ metallicity of the RC stars in the clusters with a wide range of metallicities. As mentioned above, Groenewegen (2008) suggested that dependence of the mean $K_s$-band absolute magnitude of the RC stars on metallicity is negligible. Although there are neither theoretical nor observational studies for the metallicity dependence of the *WISE* photometric bands on age and/or metallicity, it may be estimated that this dependence, if present, must not be important.

As *WISE* can go at least one magnitude deeper than the 2MASS for the RC stars, a mean absolute magnitude of these stars in any *WISE* photometric band may be very useful. Thus, their mean magnitudes and locations in the colour spaces should be estimated using newly released *WISE* data (Cutri et al., 2012). In this study, we aim to estimate mean absolute magnitudes for the RC stars with MIR photometry, i.e. $W1$ and $W3$. In section 2 we present the data. Identification of the RC stars in *WISE* is given in Section 3. Section 4 is devoted to testing the absolute magnitude estimation, and finally, we give conclusions in Section 5.

2 The data

As the aim of this study is to estimate MIR absolute magnitudes of the RC stars using their precise trigonometric parallaxes, the RC stars in the Solar neighbourhood should be selected. Thus, the main sample in this study was constructed using the newly reduced *Hipparcos* catalogue (van Leeuwen, 2007). Stars with the relative parallax errors $0 < \sigma_\pi/\pi \leq 0.15$ were selected from the *Hipparcos* catalogue which allows us to study a stellar sample with precise distances in the Solar neighbourhood. In order to obtain 2MASS and *WISE* magnitudes of the stars selected from the *Hipparcos* catalogue, we matched the selected sample with the available 2MASS Point Source Catalog (Cutri et al., 2003) and *WISE* All-Sky Data Release (Cutri et al., 2012) according to the equatorial coordinates. The number of stars matched in the both photometric
system is 46,214 which are from different luminosity classes and spectral types.

The observed trigonometric parallaxes are systematically biased, called Lutz-Kelker bias (Lutz & Kelker, 1973), and this should be corrected for the stars with $0 < \sigma_\pi/\pi \leq 0.175$. Thus, we corrected the observed Hipparcos parallaxes of the stars in our sample using the method in Smith (1987) who described the Lutz-Kelker correction (LK) analytically, as follows

$$\pi_0 = \pi \left( \frac{1}{2} + \frac{1}{2} \sqrt{1 - 16(\sigma_\pi/\pi)^2} \right),$$  \hspace{1cm} (1)

where $\pi$ and $\pi_0$ are the observed and corrected parallaxes, respectively, and $\sigma_\pi$ denotes the observed parallax error.

Although we study the stars in the Solar neighbourhood, the reddening should be taken into account. Thus, we used the dust maps taken from Schlegel, Finkbeiner & Davis (1998) and evaluated an $E_\infty(B-V)$ colour excess for each star. We then reduced them using the procedure described by Bahcall & Soneira (1980). Details of the procedure can be found in Bilir et al. (2013a). Distributions of the reduced colour excesses of the stars in our sample (46,214 stars) according to the Galactic latitude are shown in Fig. 2. The median value of the reduced colour excesses for all the Galactic latitude intervals is $\sim 0.03$ mag.

3 Identification of the RC stars in WISE

Bilir et al. (2012) showed that the RC stars can be effectively detectable in W1, W2 and W3 bands of the WISE photometry while dwarfs can be found using W1 and W2 (Bilir et al., 2011). We preferred W1 and W3 bands in order to identify the RC stars in WISE. For de–reddening the magnitudes $W_1$ and $W_3$, we adopted the equations in Bilir et al. (2011) derived by means of a spline function fitted to the data of Cardelli, Clayton & Mathis (1989) which cover a range of $0.002 \leq \lambda \leq 250 \ \mu$m:

$$\begin{align*}
(W1)_0 &= W1 - 0.158 \times E(B-V), \\
(W3)_0 &= W3 - 0.087 \times E(B-V).
\end{align*}$$  \hspace{1cm} (2)

Absolute magnitudes were calculated by setting the Hipparcos parallaxes, apparent magnitudes and total absorptions in the Pogson’s equation. We constructed the $M_{W1}-(W1-W3)_0$ colour-magnitude diagram for the 46,214 sample stars obtained from the Hipparcos data as explained in Sect. 2. The $M_{W1}-(W1-W3)_0$ colour-magnitude diagram of these stars is shown in Fig. 3.
The RC stars can be prominently detectable by an eye inspection in a region defined by a rectangle constrained with $-2.35 \leq M_{W1} \leq -1.00$ and $-0.10 < (W1 - W3)_0 < +0.05$ mag. The central position of this adopted region is roughly $(M_{W1}, (W1 - W3)_0) = (-1.64, -0.03)$ mag and there are 3889 stars in it.

Median $E(B-V)$ colour excess for these most probable RC stars is 0.031 mag. Distribution of the relative parallax errors of the stars is shown in Fig. 4 with a median value of 0.1. WISE photometric errors of the RC stars are shown in Fig. 5. Photometric errors for the stars brighter than 4 mag are roughly between 0.1-0.2 mag in the $W1$ filter, while they are smaller for fainter stars. Errors for the $W3$ filter are almost the same for all stars in the sample. Median errors for the $W1$ and $W3$ filters are 0.081 and 0.015 mag, respectively. Median colour error for the RC stars is $(W1 - W3)_{err} = 0.082$ mag.

In order to test the dependence of the mean absolute magnitudes in WISE-bands on the relative parallax errors, we created three sub-samples of the RC stars according to the relative parallax errors of $\sigma_{\pi}/\pi \leq 0.05$, $\sigma_{\pi}/\pi \leq 0.10$ and $\sigma_{\pi}/\pi \leq 0.15$. Distributions of the $M_{W1}$ and $M_{W3}$ absolute magnitudes and $(W1 - W3)_0$ colour for the RC stars in these sub-samples are shown in Fig. 6. Gaussian fits applied to the distributions are also shown. Modes of the absolute magnitudes and a colour in WISE obtained by fitting the Gaussian functions to the corresponding histograms in Fig. 6 are listed in Table 1. As can be seen from Table 1, the LK-corrected mean absolute magnitudes and the colour are decreasing with increasing relative parallax errors. Although the parallax errors are very small for the stars in the second column of Table 1, the number of stars with $\sigma_{\pi}/\pi \leq 0.05$ is about ten times smaller than the ones with $\sigma_{\pi}/\pi \leq 0.15$. While the number of stars increases about ten times, the mean absolute magnitudes and colour decrease about 0.06 and 0.007 mag, respectively. This small change indicates the reliability of the sample in this study. The mean absolute magnitudes and colors for the sub-samples in the last two columns of Table 1 are in agreement. Although the LK-correction for the stars with $\sigma_{\pi}/\pi \geq 0.10$ is larger, this agreement demonstrates that there are no crucial LK-correction effects on the mean values obtained for the sub-samples in the last two columns of Table 1. Moreover, the number of stars with $\sigma_{\pi}/\pi \leq 0.15$ is about two times larger than the ones with $\sigma_{\pi}/\pi \leq 0.10$. With these reasons, we adopted the mean values obtained for the stars with $\sigma_{\pi}/\pi \leq 0.15$ in this study.
Table 1
Mode values of the Gaussian fits applied to the absolute magnitude and colour distributions in WISE for three different relative parallax error limits. $N$ represents the number of stars.

|        | $\sigma_\pi/\pi \leq 0.05$ | $\sigma_\pi/\pi \leq 0.10$ | $\sigma_\pi/\pi \leq 0.15$ |
|--------|----------------------------|----------------------------|----------------------------|
| $M_W1$ | $-1.576 \pm 0.024$         | $-1.612 \pm 0.022$         | $-1.635 \pm 0.026$         |
| $M_W3$ | $-1.552 \pm 0.020$         | $-1.585 \pm 0.019$         | $-1.606 \pm 0.024$         |
| $(W1 - W3)_0$ | $-0.021 \pm 0.002$ | $-0.026 \pm 0.001$ | $-0.028 \pm 0.001$ |
| $N$    | 397                        | 1969                       | 3889                       |

4 Testing the WISE absolute magnitudes and colour of the RC stars

4.1 Absolute magnitudes from transformation equations

Absolute magnitudes and colour of the RC stars estimated in the previous section for WISE can be tested using known transformation equations that use magnitudes and colours of the 2MASS photometric system. In order to use the transformation equations, we should identify the RC stars in a colour-magnitude diagram of the 2MASS photometric system. By the procedure explained in Sect. 2 for the WISE data, we de-reddened the 2MASS photometric data of 46,214 stars selected from the Hipparcos catalogue. The 2MASS colours and magnitudes of the stars were de-reddened using the reduced colour excesses and the following equations from Fiorucci & Munari (2003) and Bilir et al. (2008) for the 2MASS photometric system,

\[
J_o = J - 0.887 \times E(B - V),
\]

\[
(J - H)_o = (J - H) - 0.322 \times E(B - V),
\]

\[
(H - K_s)_o = (H - K_s) - 0.183 \times E(B - V),
\]

\[
(J - K_s)_o = (J - K_s) - 0.505 \times E(B - V).
\] (3)

We used empirical colour–magnitude diagrams to determine the locations of the RC stars. Firstly, we plotted the $M_{K_s}$ absolute magnitudes versus $(J - K_s)_0$ colours of 46,214 stars in Fig. 7 and identified the RC stars with two constraints, i.e. $-2.25 \leq M_{K_s} \leq -1.00$ and $0.50 \leq (J - K_s)_0 \leq 0.75$ mag, by an eye inspection. With this procedure, we identified the most probable 2937 RC stars in our sample. Median colour excess for these stars is 0.026 mag which is in agreement with the median value calculated for the whole sample including 46,214 stars. Distribution of the relative parallax errors of the 2937 RC stars is shown in Fig. 8. The median value of the relative parallax errors is 0.097.

2MASS photometric errors of these most probable RC stars are shown in Fig.
Table 2
Modes of the absolute magnitudes, colours and internal errors in 2MASS obtained by fitting the Gaussian functions to the corresponding histograms in Fig. 10.

| Mode (mag)      | Value         |
|----------------|---------------|
| \(M_J\)        | -0.970 ± 0.016|
| \(M_H\)        | -1.462 ± 0.014|
| \(M_{Ks}\)     | -1.595 ± 0.025|
| \((J - H)_0\)   | 0.485 ± 0.002 |
| \((H - Ks)_0\)  | 0.130 ± 0.002 |
| \((J - Ks)_0\)  | 0.612 ± 0.003 |

This table presents two different error populations in the \(J\), \(H\) and \(K_s\) magnitude measurements. These populations originate from the saturation of bright stars with \(J \lesssim 5\) mag, about 32 per cent of the sample. This analysis shows that signal-to-noise ratio is greater than 20 (\(J_{err} \lesssim 0.1\) mag) for most of the stars in the sample. In this case, median magnitude errors for the 2937 RC stars are \(J_{err} = 0.027\), \(H_{err} = 0.042\) and \(K_{serr} = 0.021\) mag. Two different populations are also seen in the distribution of NIR colours. Median colour errors for the sample are \((J - H)_{err} = 0.050\), \((H - Ks)_{err} = 0.047\) and \((J - Ks)_{err} = 0.034\) mag. Distributions of the \(M_J\), \(M_H\) and \(M_{Ks}\) absolute magnitudes and the \((J - H)_0\), \((H - Ks)_0\) and \((J - Ks)_0\) colours of the 2937 RC stars are shown in Fig. 10. Gaussian fits applied to the distributions are also shown in the same figure. Modes of the absolute magnitudes and colours in 2MASS obtained by fitting the Gaussian functions to the corresponding histograms in Fig. 10 are listed in Table 2. Internal errors for the modes of the absolute magnitude and colour distributions are \(M_{Jerr} = 0.016\), \(M_{Herr} = 0.014\), \(M_{Kserr} = 0.025\), \((J - H)_{err} = 0.002\), \((H - Ks)_{err} = 0.002\) and \((J - Ks)_{err} = 0.003\) mag.

The \(K_s\) absolute magnitude in Table 2 is smaller than the value given by Groenewegen (2008) \((M_{Ks} = -1.54 ± 0.04\) mag) while it is greater than the values in Alves (2000) \((M_{Ks} = -1.61 ± 0.03\) mag) and Laney et al. (2012) \((M_{Ks} = -1.613 ± 0.015\) mag). Laney et al. (2012) observed 226 RC stars in the Solar neighbourhood in near-infrared \(JHK\)-bands and calculated mean absolute magnitudes of the RC stars using Hipparcos parallaxes. The mean absolute magnitudes given by Laney et al. (2012) are \(M_J = -0.984 ± 0.014\), \(M_H = -1.490 ± 0.015\) and \(M_{Ks} = -1.613 ± 0.015\) mag. Differences between the mode values in this study (Table 2) and the ones in Laney et al. (2012) are not larger than 0.030 mag. Using these comparisons, we conclude that the mean absolute magnitudes and colours of the RC stars in our study are in good agreement with the ones in the previous studies, although the saturated stars mentioned above are included in the calculations.

We tested the adopted absolute magnitudes and colours of the RC stars es-
Table 3
Modes of distributions for the absolute magnitudes and a colour in \textit{WISE} for the RC stars with $\sigma_{\pi}/\pi \leq 0.15$ (see Table 1). The evaluated values from the transformation equations (TEs; Bilir et al. 2012) are also given. Differences between two sets of the data are in the last column.

| Mode (mag) | Value from TEs (mag) | Difference (mag) |
|------------|----------------------|------------------|
| $M_{W1}$   | $-1.635 \pm 0.026$   | $0.000$          |
| $M_{W3}$   | $-1.606 \pm 0.024$   | $+0.070$         |
| $(W1 - W3)_0$ | $-0.028 \pm 0.001$   | $-0.069$         |

Estimated with the \textit{WISE} data using equations evaluated by Bilir et al. (2012) which transform magnitudes and colours from the 2MASS photometric system to the \textit{WISE} photometric system and vice versa. Thus, the $M_{W1}$, $M_{W3}$ absolute magnitudes and $(W1 - W3)_0$ colour were evaluated using these transformation equations and compared them with the corresponding ones estimated in this study. As the metallicities of the RC stars in the sample are not known and metallicity dependence of \textit{WISE} magnitudes and colours of these stars must be very weak, we preferred the metal free transformation equations as follows (Bilir et al., 2012):

\begin{align*}
(J - W1)_0 &= 1.102(55)(J - H)_0 + 0.737(72)(H - K_s)_0 + 0.035(31), \\
(J - W3)_0 &= 1.029(64)(J - H)_0 + 0.780(84)(H - K_s)_0 + 0.106(36). \quad (4)
\end{align*}

Here the numbers in parenthesis are the errors of coefficients for the last two digits. By setting the 2MASS magnitudes and colours in Table 2 in the transformation equations, we obtained the semi-empirical \textit{WISE} $M_{W1}$, $M_{W3}$ absolute magnitudes and $(W1 - W3)_0$ colour and listed them in Table 3. In this table, the adopted absolute magnitudes and a colour in \textit{WISE} (Table 1) and the evaluated ones from the transformation equations are compared.

Table 3 demonstrates that the \textit{WISE} absolute magnitudes and colour estimated for the RC stars in this study are in very good agreement with the semi-empirical \textit{WISE} $M_{W1}$, $M_{W3}$ absolute magnitudes and $(W1 - W3)_0$ colour within the error limits. While $W1$ is the same as evaluated from the transformation equations, the original $W3$ magnitude deviates from the evaluated one within the error limits. Difference between the estimated and evaluated $(W1 - W3)_0$ colours originates from the deviation of $W3$ magnitude, as expected.

4.2 \textit{Comparison with distances estimated from stellar parameters}

Second test was done using the comparison of the distances estimated from \textit{WISE} photometry and spectrophotometric parallaxes. Saguner et al. (2011)
derived atmospheric parameters of 245 faint and high Galactic latitude RC stars from high signal-to-noise middle resolution spectra and calculated their spectrophotometric distances. We removed 23 of 245 stars from the sample as their distance errors are too high, decreasing the number of stars to 222. These RC stars with \(200 \lesssim d \lesssim 500\) pc give us the chance to compare their distances estimated by two different, photometric and spectrophotometric, methods.

We obtained the \textit{WISE} magnitudes of the stars from the \textit{WISE} All-Sky Data Release \cite{Cutri12} according to the equatorial coordinates in \cite{Saguner11}. The \textit{WISE} magnitudes and colour of these 222 stars were de-reddened using the colour excesses in \cite{Saguner11} and Eq. 2. in this study. Distances of the RC stars were evaluated by Pogson’s equation using the absolute magnitudes in Table 1. The distances calculated using the adopted absolute magnitudes \(M_{W1} = -1.635 \pm 0.026\) and \(M_{W3} = -1.606 \pm 0.024\) mag of the RC stars with \(\sigma_\pi/\pi \leq 0.15\) are compared with the ones in \cite{Saguner11} in Fig. 11a and c, respectively. Residuals from 1-1 line are also shown in Fig. 11b and d. These figures demonstrate that there is good agreement between the distances calculated using the both methods. The mean of the differences between two sets of distances and the corresponding standard deviations are \(<\Delta d> = -9.2\) pc and \(\sigma = 30.8\) pc for Fig 11a and \(<\Delta d> = -9.6\) pc and \(\sigma = 30.7\) pc for Fig 11c. There are 153 stars in both panels within the \(\pm 1\sigma\) limits, 69 per cent of the sample.

5 Conclusions

In this study, we identified the RC stars with the \textit{WISE} photometry for the first time. We also identified them with the 2MASS photometry, in order to compare their \textit{WISE} absolute magnitudes in this study with the ones evaluated from the transformation equations \cite{Bilir12}. Another comparison was made between the distances obtained using the \textit{WISE} absolute magnitudes and those taken from \cite{Saguner11} who used a spectrophotometric method.

Conclusions of this study can be summarized as follows,

- The RC stars occupy a very small region in the \textit{WISE} colour-magnitude diagram of the stars in the Solar neighbourhood, as expected from the general properties of these stars in other photometric systems.
- The adopted \textit{WISE} absolute magnitudes and colour of the RC stars are \(M_{W1} = -1.635 \pm 0.026, M_{W3} = -1.606 \pm 0.024\) and \((W1-W3)_0 = -0.028 \pm 0.001\) mag.
- As for the effect of LK-corrected parallaxes on the results, it is found that selecting different limits for the relative parallax errors, provided that it is
higher than 0.10, does not considerably affect the mean absolute magnitudes and the colour of the RC stars.

- The 2MASS absolute magnitudes and colours of the RC stars are $M_J = -0.970 \pm 0.016$, $M_H = -1.462 \pm 0.014$, $M_{K_s} = -1.595 \pm 0.025$, $(J-H)_0 = 0.485 \pm 0.002$, $(H-K_s)_0 = 0.130 \pm 0.002$ and $(J-K_s)_0 = 0.612 \pm 0.003$ mag.
- The WISE absolute magnitudes and colour of the RC stars are in good agreement with the semi-empirical ones evaluated from the transformation equations.
- From the comparisons of the distances estimated using the WISE absolute magnitudes and the ones calculated using a spectrophotometric method, we conclude that agreement of two sets of distances confirms the confidence of the absolute magnitudes in question.

As stated above, WISE photometry goes one magnitude deeper than the 2MASS photometry for sources with spectra close to that of an A0 star, and even deeper for moderately red sources like K stars or galaxies with old stellar populations. Hence, we suggest that the absolute magnitudes estimated in this study can be used in the distance calculations for new sets of the RC stars at relatively larger distances. For example, these values can be used to estimate the Galactic model parameters, in order to test any degeneracy between different parameters of the Galactic components.

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Fig. 1. Relative responses of the 2MASS (a) and WISE filters (b).
Fig. 2. Distributions of the reduced colour excesses of the 46,214 stars in our sample according to the Galactic latitude ($b$).
Fig. 3. The $M_{W1}$ absolute magnitudes versus $(W1 - W3)_0$ colours for 46,214 stars with the relative parallax errors $\sigma_\pi/\pi \leq 0.15$ selected from the Hipparcos catalogue. Stars in the rectangle are adopted as the RC stars.
Fig. 4. Number (lower panel) and cumulative (upper panel) distributions of the relative parallax errors for the 3889 RC stars selected from WISE photometry. Dashed lines represent the median value.
Fig. 5. Photometric errors of the 3889 RC stars selected from the WISE data.
Fig. 6. Histograms of $M_{W1}$ and $M_{W3}$ absolute magnitudes and $(W1 - W3)_0$ colour for the RC stars with relative parallax errors $\sigma_\pi/\pi \leq 0.05$ (a-c), $\sigma_\pi/\pi \leq 0.10$ (d-f) and $\sigma_\pi/\pi \leq 0.15$ (g-i). Gaussian functions fitted to the distributions are shown with dashed lines.
Fig. 7. The $M_{K_s}$ absolute magnitudes versus $(J - K_s)_0$ colours for 46,214 stars with the relative parallax errors $\sigma_\pi/\pi \leq 0.15$ selected from the Hipparcos catalogue. Stars in the rectangle are adopted as the RC stars.
Fig. 8. Number (lower panel) and cumulative (upper panel) distributions of the relative parallax errors for the 2937 RC stars in the 2MASS photometry. Dashed lines represent the median value.
Fig. 9. Photometric errors of the 2MASS observations for the 2937 RC stars selected from the $M_{K_s} - (J - K_s)$ colour-magnitude diagram.
Fig. 10. Distributions of the $M_J$, $M_H$ and $M_K_s$ absolute magnitudes (a-c) and $(J - H)_0$, $(H - K_s)_0$ and $(J - K_s)_0$ colours (d-f) for the 2937 RC stars in our sample. Gaussian fits to the distributions are also shown.

Fig. 11. Comparison of the distances for the 222 RC stars estimated in Saguner et al. (2011) and in this study using the adopted $M_{W1}$ (a) and $M_{W3}$ (c). Distributions of their differences relative to the distances estimated in our study (b and d). Solid lines represent the 1-1 values, dashed lines $\pm 1\sigma$ limits.