SDSS absolute magnitudes for thin-disc stars based on trigonometric parallaxes

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ABSTRACT
We present a new luminosity–colour relation based on trigonometric parallaxes for thin-disc main-sequence stars in Sloan Digital Sky Survey (SDSS) photometry. We matched stars from the newly reduced Hipparcos catalogue with the ones taken from Two-Micron All-Sky Survey (2MASS) All-Sky Catalogue of Point Sources, and applied a series of constraints, i.e. relative parallax errors (σπ/π ≤ 0.05), metallicity (−0.30 ≤ [M/H] ≤ 0.20 dex), age (0 ≤ t ≤ 10 Gyr) and surface gravity (log g > 4), and obtained a sample of thin-disc main-sequence stars. Then, we used our previous transformation equations (Bilir et al. 2008a) between SDSS and 2MASS photometries and calibrated the Mg absolute magnitudes to the (g − r)0 and (r − i)0 colours. The transformation formulae between 2MASS and SDSS photometries along with the absolute magnitude calibration provide space densities for bright stars which saturate the SDSS magnitudes.

Key words: stars: distances – Galaxy: disc – solar neighbourhood.

1 INTRODUCTION
Among several large sky surveys, two have been used most widely in recent years. The first, Sloan Digital Sky Survey (SDSS; York et al. 2000), is the largest photometric and spectroscopic survey in optical wavelengths. The second, Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), has imaged the sky in infrared. The SDSS obtains images almost simultaneously in five broadband filters (u, g, r, i and z) centred at 3540, 4760, 6280, 7690 and 9250 Å, respectively (cf. Fukugita et al. 1996). The photometric pipeline detects the objects, then matches the data from various filters and measures instrumental fluxes, positions and shape parameters. The shape parameters allow the classification of objects as ‘point source’ or ‘extended’. The limiting magnitudes of the passbands are 22, 22.2, 22.2, 21.3 and 20.5 for u, g, r, i and z, respectively. The data are saturated at about 14 mag in g, r and i, and about 12 mag in u and z (cf. Chonis & Gaskell 2008).

2MASS provides the most complete data base of near-infrared (NIR) galactic point sources. During the development of this survey, two highly automated 1.3-m telescopes were used: one at Mt. Hopkins, Arizona, to observe the northern sky, and the other at Cerro Tololo Observatory, Chile, to survey the southern half. Observations cover 99.998 per cent (Skrutskie et al. 2006) of the sky with simultaneous detections in J (1.25 μm), H (1.65 μm) and Ks (2.17 μm) bands up to limiting magnitudes of 15.8, 15.1 and 14.3, respectively. The passband profiles for ugriz and JHKs photometric systems are given in Fig. 1 (Bilir et al. 2008a).

Saturation of the ugriz data at bright magnitudes is a disadvantage for galactic surveys. Actually, space densities cannot be evaluated for distances less than ~0.5 kpc due to this saturation. The number of distance intervals without space densities is even larger for bright absolute magnitude intervals. On the other hand, 2MASS is a shallow survey, i.e. it contains relatively bright point sources, which can be used to fill up the gap of SDSS photometry for short distances. Our aim is to use the transformations between 2MASS and SDSS given in our previous paper (Bilir et al. 2008a) and to calibrate the Mg absolute magnitude using (g − r)0 and (r − i)0 colours based on Hipparcos trigonometric parallaxes. Thus, two sets of data will be used in estimating galactic model parameters: the first set is the JHKs data of relatively nearby stars in a given field of the Galaxy. The second one consists of SDSS data of stars occupying further distances in the same field. For the first set, 2MASS data need to be transformed into SDSS data before applying procedures used in estimating absolute magnitude, whereas for the second set of data (the SDSS data) the procedures can be applied directly.

In Section 2, the data and the determination of the sensitive sample are presented. The procedure and absolute magnitude calibration are given in Section 3, and the results are discussed in Section 4. Finally, a conclusion is given in Section 5.

2 THE DATA
We matched stars from the newly reduced Hipparcos catalogue (van Leeuwen 2007) with the ones from 2MASS All-Sky Catalogue of

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Point Sources (Cutri et al. 2003), and applied a series of constraints in order to obtain a sample of thin-disc main-sequence stars. To produce the sample, the first constraint we applied was to choose the 11,644 stars from the newly reduced Hipparcos catalogue (van Leeuwen 2007) with relative parallax errors $\sigma_\pi/\pi \leq 0.05$. Then, we omitted the stars without 2MASS data. Afterwards, to eliminate reddening, 2MASS magnitudes were de-reddened using the procedure given by Bilir et al. (2008a), even though the program stars are relatively close and the NIR reddening correction is very small. The second restriction was to limit the absolute magnitude between $0 < M_J < 6$, which corresponds to the spectral type range A0–M0. The estimation of the absolute magnitude range can be seen from the 2MASS colour–magnitude diagram (Fig. 2). Finally, we adopted the procedure used in our previous paper (Bilir et al. 2008b) to exclude evolved, thick-disc and halo stars from the sample. The mentioned procedure requires the following limitations for metallicity, age and surface gravity taken from Padova isochrones (Marigo et al. 2008): $-0.30 \leq [\text{M/H}] \leq 0.20$ dex, $0 \leq t \leq 10$ Gyr and $\log g > 4$, respectively. Thus, to establish the luminosity–colour relation, we produced a thin-disc sample of 4449 main-sequence stars with accurate trigonometric parallaxes and 2MASS data. The typical NIR colour and absolute magnitude errors of our sample are $\pm 0.04$ and $\pm 0.14$ mag, respectively. Lutz & Kelker (1973) stated that there is a systematic error in computed distances, which only depends on the $\sigma_\pi/\pi$ ratio. Jerzykiewicz (2001) showed that the error is negligible if $\sigma_\pi/\pi \leq 0.10$, which is the case in this study as $\sigma_\pi/\pi \leq 0.05$.

3 THE PROCEDURE AND ABSOLUTE MAGNITUDE CALIBRATION

We adopted the metallicity sensitive equations (13), (18) and (19) from Bilir et al. (2008a) for the calibration of $M_g$ absolute magnitudes for our star sample. These equations are as follows:

\begin{align}
(g - J)_0 &= 1.361(\pm 0.016)(g - r)_0 + 1.724(\pm 0.019)(r - i)_0 + 0.521(\pm 0.009) ,
\end{align}

\begin{align}
(g - r)_0 &= 1.991(\pm 0.040)(J - H)_0 + 1.348(\pm 0.066)(H - K_s)_0 - 0.247(\pm 0.019) ,
\end{align}

\begin{align}
(r - i)_0 &= 1.000(\pm 0.036)(J - H)_0 + 1.004(\pm 0.064)(H - K_s)_0 - 0.220(\pm 0.017) .
\end{align}

We transformed $(J - H)_0$ and $(H - K_s)_0$ colours of the stars in our sample into $(g - r)_0$ and $(r - i)_0$ colours using equations (2) and (3). Then, we used these colours and the $J_0$ magnitudes in equation (1) and obtained the $g_0$ magnitudes for the star sample. Finally, combining the $g_0$ magnitudes and Hipparcos parallaxes of stars, we obtained accurate $M_g$ absolute magnitudes.

Now, we have two sets of SDSS data, i.e. $M_g$ absolute magnitudes and $(g - r)_0$ and $(r - i)_0$ colours for 4449 thin-disc main-sequence stars. We can adopt a procedure similar to the one used in our recent works (Bilir, Karaali & Tunçel 2005; Bilir et al. 2008b) and calibrate...
the $M_g$ absolute magnitude to SDSS colours $(g-r)_0$ and $(r-i)_0$ as follows:

$$M_g = a_1(g-r)_0^2 + b_1(r-i)_0^2 + c_1(g-r)_0(r-i)_0 + d_1(g-r)_0 + e_1(r-i)_0 + f_1.$$  \hspace{1cm} (4)

We applied the covariance matrices of the solutions (1)–(3) and obtained the individual estimation errors depending on the actual coefficients. The errors given in the parentheses in equations (1)–(3) correspond to the dispersion of the observations. If we assume a total noise of approximately 0.1 associated with these calibrations, the complement error can be attributed to cosmic noise.

The numerical values of the coefficients in equation (4) and their errors, the corresponding standard deviation and the squared correlation coefficient are given in Table 1. One can deduce that the error in absolute magnitude $M_g$ is of the order of 0.19 (the standard deviation). This is true when the colours in equation (4) are free of errors. However, this is not the case. The colours are associated with the errors given for equations (1)–(3). Hence, one expects an additional error originating from the colours. We added an additional error evaluated by means of equation (4). For simplicity, we called absolute magnitudes evaluated using this procedure $M'_g$. As expected, there is a mean offset of 0.12 mag from the Hipparcos absolute magnitudes. The standard deviation of $\Delta M'_g = (M'_g)_{\text{Hip}} - (M'_g)$ is 0.19. Hence, the total and maximum error for the absolute magnitude evaluated by equation (4) is $\sqrt{2} \times 0.19 = 0.27$ mag.

**Table 1.** Coefficients and their standard errors for equation (4). $R^2$ and $s$ denote the squared correlation coefficient and the standard deviation, respectively.

| $a_1$     | $b_1$       | $c_1$       | $d_1$       | $e_1$       | $f_1$       | $R^2$ | $s$  |
|-----------|-------------|-------------|-------------|-------------|-------------|-------|-----|
| $-0.719$  | $1.953$     | $-0.474$    | $10.697$    | $-9.350$    | $1.668$     | $0.99$ | $0.19$ |

3.1 Testing the procedure

We tested our procedure by comparing the $M_g$ absolute magnitudes calculated by means of equation (4) with the ones evaluated via combining $g_0$ apparent magnitudes and trigonometric parallaxes adopted from the newly reduced Hipparcos catalogue (van Leeuwen 2007). Fig. 3 shows that there is a one-to-one correspondence between two sets of $M_g$ absolute magnitudes. Also, the mean and the standard deviations of differences in-between original absolute magnitudes and calculated absolute magnitudes are rather small, i.e. $\langle \Delta M_g \rangle \approx 0.00$ and $s = 0.19$ mag.

Most of the sample stars were obtained by applying a series of constraints to the newly reduced Hipparcos catalogue. These stars lie within 2σ (upper panel in Fig. 3). However, the $\Delta M_g = (M'_g)_{\text{Hip}} - (M'_g)$ residuals give the impression of a small, but systematic drift. That is, the calculated absolute magnitudes are a bit larger than the expected ones for faint absolute magnitudes. Keeping in mind that the data sample was reduced from 11 644 (original sample) to 4449, one can try to explain this drift with applied constraints. We should add that our aim in this work is to obtain absolute magnitudes for a pure thin-disc population, so applying the constraints was needed. Hence, the results of the applied constraints are unavoidable.
Table 2. Comparison of the absolute magnitudes calculated in our work with the absolute magnitudes of Covey et al. (2007). Data in Columns (1–4) were taken from Covey et al. (2007). \((M_g)_c\) is calculated using equation (4) and the data in Columns (3 and 4). \(M_g\) is the absolute magnitude evaluated using Bilir et al.’s (2008a) procedure and the data in Columns (2–4). \(\Delta M_g\) is the difference between \(M_g\) and \((M_g)_c\).

| Spectral type | \(M_g\) | \((g - r)_0\) | \((r - i)_0\) | \((M_g)_c\) | \(\Delta M_g\) |
|---------------|--------|-------------|-------------|-------------|-------------|
| A0V           | 0.430  | −0.250      | −0.180      | 0.300       | 0.674       |
| A2V           | 1.170  | −0.230      | −0.170      | 1.085       | 0.797       |
| A3V           | 1.250  | −0.160      | −0.150      | 1.295       | 1.373       |
| A5V           | 1.380  | −0.100      | −0.110      | 1.575       | 1.638       |
| A7V           | 1.730  | −0.020      | −0.080      | 2.086       | 2.214       |
| F0V           | 2.430  | 0.100       | 0.010       | 3.104       | 2.637       |
| F2V           | 2.630  | 0.190       | 0.030       | 3.461       | 3.393       |
| F5V           | 2.620  | 0.260       | 0.030       | 3.547       | 4.118       |
| F6V           | 2.900  | 0.280       | 0.080       | 3.940       | 3.861       |
| F8V           | 2.980  | 0.360       | 0.100       | 4.163       | 4.493       |
| G0V           | 3.180  | 0.380       | 0.140       | 4.460       | 4.333       |
| G5V           | 3.540  | 0.490       | 0.160       | 5.004       | 5.254       |
| K2V           | 4.500  | 0.780       | 0.240       | 6.496       | 7.354       |
| K3V           | 4.940  | 0.850       | 0.320       | 7.170       | 7.320       |
| K4V           | 5.210  | 1.000       | 0.380       | 7.747       | 8.195       |
| K5V           | 5.450  | 1.180       | 0.400       | 8.267       | 9.638       |
| M0V           | 5.720  | 1.310       | 0.640       | 9.127       | 8.866       |

3.2 Comparison of absolute magnitudes using different data sets

We compared the \(M_g\) absolute magnitudes determined in this work with the ones appearing in the literature. Comparison with the data of Covey et al. (2007) and Sloan Extension for Galactic Understanding and Exploration (SEGUE) data of SDSS Data Release 6 (DR6) by means of Allende Prieto et al.’s (2006) method could be carried out after some reductions and/or constraints, whereas a direct comparison could be made with Karaali, Bilir & Tuncel (2005), Bilir et al. (2005), Jurić et al. (2008) and Just & Jahreiss (2008).

3.2.1 Comparison with the data of Covey et al. (2007)

Covey et al. (2007) used the synthetic library of Pickles (1998) and evaluated the \(M_g\) absolute magnitudes and, \((g - r)_0\) and \((r - i)_0\) colours for 18 main-sequence stars of different spectral types (Table 2). Using these values in the following equation (equation 5), modified from equation (1), we obtained the corresponding \(M_g\) absolute magnitudes. Then, we compared these values with \((M_g)_c\) absolute magnitudes, which were calculated using equation (4):

\[
M_g - M_J = 1.361(\pm 0.016)(g - r)_0 + 1.724(\pm 0.019)(r - i)_0 + 0.521(\pm 0.009).
\]

There is an agreement between the two sets of absolute magnitudes (Table 2 and Fig. 4) confirming our new procedure for absolute magnitude determination. The small drift in the vertical direction in Fig. 4 for the faint absolute magnitudes originates from the application of two different procedures. Although all the data, i.e. \(M_g\), \((g - r)_0\) and \((r - i)_0\), were taken from Covey et al. (2007), the \((M_g)_c\) absolute magnitudes (on the Y-axis) were evaluated only using \((g - r)_0\) and \((r - i)_0\) colours and equation (4), whereas \(M_g\) absolute magnitudes (on the X-axis) were evaluated by substituting these colours and \(M_g\) absolute magnitudes in equation (5).

3.2.2 Comparison with SDSS DR6

The second data set we compared ours to is the SEGUE data of SDSS DR6. Spectra for over 250 000 stars in the galactic disc and spheroid for all common spectral types exist in SEGUE.\(^1\) These spectra were processed with a pipeline called the ‘Spectro Parameter Pipeline’ which computes standard stellar atmospheric parameters.

\(^1\) http://cas.sdss.org/segue/dr6/en/tools/search/sql.asp
such as [Fe/H], log $g$ and $T_{\text{eff}}$, for each star by a variety of methods. We used the parameters evaluated by Allende Prieto et al.'s (2006) model-atmosphere analysis method and applied the following constraints in order to obtain a thin-disc sample: $4 \leq \log g \leq 4.5$ and $-0.3 \leq [\text{M/H}] \leq +0.2$ dex. The $M_g$ absolute magnitudes of 2289 stars, which satisfied our constraints, were evaluated by combining their $g_0$ apparent magnitudes and distances. The comparison of these absolute magnitudes with the ones determined using equation (4), $(M_g)_c$, is shown in Fig. 5. There is an agreement between the two sets of absolute magnitudes. However, the dispersion is larger than the ones in Figs 3 and 4. Also, there are clearly visible systematic effects shown in the distributions, in particular at $(M_g)_c = 6$. These effects probably originate from a series of constraints applied to the data, i.e. (1) we used the atmospheric parameters evaluated using Allende Prieto et al.'s (2006) method, (2) we selected stars with $4 \leq \log g \leq 4.5$ and (3) we limited the metallicities with $-0.3 \leq [\text{M/H}] \leq +0.2$ dex in order to obtain a pure thin-disc population. It seems that all these limitations caused the systematic effects mentioned above.

3.2.3 Comparison with data appearing in the literature

Karaali et al. (2005) used observations obtained in $u'g'r'$ filters at Isaac Newton Telescope (INT) at La Palma in Spain. The filters were designed to reproduce the SDSS system. The data were complemented by Landolt (1992) $UBV$ standard star photometry and were used to calculate transformations between the INT SDSS $u'g'r'$ filter-detector combination and the standard Johnson–Cousins photometry. Karaali et al. (2005) presented transformation equations depending on two colours for the first time. The $M_g$ absolute magnitudes evaluated by these equations agree with the $(M_g)_c$ absolute magnitudes calculated using equation (4) in this work (Fig. 6). The best fit in Fig. 6 is between the colour–absolute-magnitude diagrams obtained in our work and in the work of Karaali et al. (2005). Actually, the open circle symbols used for the data of Karaali et al. (2005) and the locus of the grey circles representing the data in this work overlap.

The transformations between SDSS and $UBVRI$ photometries in our previous work (Bilir et al. 2005) provide $M_g$ absolute magnitudes for late-type dwarfs. We compared the $(M_g)_c$ absolute magnitudes determined using equation (4) and the ones obtained using the procedure in Bilir et al. (2005) to note any possible deviation. Fig. 6 shows that the agreement is limited with colours $(g - r)_0 < 1.2$ mag.

Just & Jahreiss (2008) applied the transformation equations of Chonis & Gaskell (2008) to the 786 star sample in the solar neighbourhood $(r \leq 25$ pc) and obtained a mean $M_g/(g - r)_0$ main sequence in 0.05 mag bins. The nearby stars represent the thin-disc population completely. Hence, we expect an agreement between the $M_g$ absolute magnitudes evaluated in our work and in Just & Jahreiss (2008). Fig. 6 shows that this is the case.

The only deviation is noted between our $M_g$ absolute magnitudes and those of Jurić et al. (2008) (Fig. 6). However, their $M_g/(g - r)_0$ colour–magnitude diagram is a combination of apparent colour–magnitude diagrams and that may be the reason of the deviation mentioned (see Discussion).

3.3 Alternative procedure

We applied an alternative procedure to our sample of 4449 thin-disc main-sequence stars to evaluate the $M_g$ absolute magnitudes, explained as follows. First, we transformed their $(J - H)_0$ and $(H - K_s)_0$ colours into $(g - r)_0$ and $(r - i)_0$ colours using equations...
Gilmore & Tout (1991) found that for the extreme value, i.e. $f = 1$, a single mass function provides the best representation of a single luminosity function.

In our previous work (Bilir et al. 2008b), we adopted a simple but reasonable procedure and revealed the binarism effect for $M_M$ and $M_M$ absolute magnitudes. The scatter in absolute magnitude as a function of binary fraction $f$ was found to be $\Delta M_M = 0.266 \times f + 0.014$. In this work, the calibration of $M_M$ absolute magnitudes to $(g - r)_0$ and $(r - i)_0$ colours is carried out using the 2MASS data. Hence, we can adopt the same calibration for the scatter in $M_M$, i.e.

$$\Delta M_M = 0.266 \times f + 0.014.$$  

(6)

4 DISCUSSION

We matched stars taken from the newly reduced *Hipparcos* catalogue (van Leeuwen 2007) with the ones taken from 2MASS All-Sky Catalogue of Point Sources (Cutri et al. 2003), and applied a series of constraints in order to obtain a sample of thin-disc main-sequence stars. These constraints reduced the original sample of 11644 stars with relative parallax errors $\sigma_\pi/\pi \leq 0.05$ to 4449. Then, we used the 2MASS data in the transformation equations presented in our previous work (Bilir et al. 2008a) and calibrated the $M_M$ absolute magnitudes to the SDSS colours, i.e. $(g - r)_0$ and $(r - i)_0$.

The advantage of this procedure is that it uses a specific sample of nearby stars with small parallax errors. The constraints, i.e. $-0.30 \leq [M/H] \leq 0.20$ dex, $0 \leq t \leq 10$ Gyr and $\log g > 4$, exclude any contamination of evolved thin- and thick-disc stars and halo stars. Thus, we obtained a colour–magnitude diagram which provides accurate $M_M$ absolute magnitudes for the thin-disc main-sequence stars. The calibration can be used directly for faint stars, whereas for bright stars with saturated SDSS magnitudes one needs to transform the 2MASS data into SDSS data via our previous transformation formulæ (Bilir et al. 2008a).

We compared the $M_M/(g - r)_0$ colour–magnitude diagram obtained in this study with six others appearing in the literature. The best fit is between our diagram and that of Karaali et al. (2005) which indicates that there are no systematic deviations between the in $u'g'r'$ filters at INT and the original SDSS filters.

Since Just & Jahreiss (2008) used a sample of 786 stars in the solar neighbourhood, which have a much higher probability of consisting of pure thin-disc main-sequence stars, their results are precise. The precision of Just & Jahreiss’ (2008) results along with the agreement level between our data and theirs confirms our calibration.

The $M_M$ absolute magnitudes evaluated from the synthetic data of Covey et al. (2007) also agree with our $M_M$ absolute magnitudes. The same agreement holds for the $M_M$ absolute magnitudes of SEGUE data of SDSS DR6 by means of Allende Prieto et al.‘s (2006) method, however, with larger dispersion.

$M_M/(g - r)_0$ colour–magnitude diagram of Jurić et al. (2008) deviates from our colour–magnitude diagram and from those cited above. These authors compared the $M_M/(g - r)_0$ colour–magnitude diagrams appearing in the literature and used two colour–magnitude diagrams, one for bright stars and one for faint stars in their extensive work. We preferred the one for bright stars in this comparison due to our sample of stars being bright. However, we could not avoid the deviation mentioned.

Finally, we should note that the $M_M/(g - r)_0$ colour–magnitude diagram presented in this work agrees with the previous one (Bilir

3.4 Binarism effect

A high fraction of stars are in fact binary systems, and being a binary system makes stars appear brighter and redder than they normally are. Different fractional values (defined as $f$) can be found in the literature. As it was quoted in our previous work (Bilir et al. 2008b and the references therein), the range of $f$ is $0.4 \leq f < 1$. Kroupa,
et al. 2005) for stars with $(g - r)_0 < 1.2$ mag, but there is a deviation for red stars which increases slightly with $(g - r)_0$ colour.

5 CONCLUSION

We calibrated the $M_g$ absolute magnitudes to the $(g - r)_0$ and $(r - i)_0$ colours by using the newly reduced Hipparcos catalogue and 2MASS data for thin-disc main-sequence stars with bright apparent magnitude which can be used in evaluating space densities for nearby stars. Thus, any possible degeneration due to extrapolation of density functions to zero distance should be avoided. This will lead to more accurate galactic model parameter estimation.

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