THE ARAUCARIA PROJECT. INFRARED TIP OF THE RED GIANT BRANCH DISTANCES TO THE CARINA AND FORNAX DWARF SPHEROIDAL GALAXIES*

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ABSTRACT

We present distance determinations for two Local Group dwarf spheroidal galaxies, Carina and Fornax, based on the near-infrared magnitudes of the tip of the red giant branch (TRGB). For Carina we derive true distance moduli of 20.09 and 20.13 mag in the J and K bands, respectively, while for Fornax the same distance modulus of 20.84 mag was derived in both filters. The statistical errors of these determinations are of the order of 0.03–0.04 mag, whereas the systematic uncertainties on the distances are 0.12 mag in the J band and 0.14 mag in the K band. The distances obtained from the near-infrared TRGB method in this paper agree very well with those obtained for these two galaxies from optical calibrations of the TRGB method, their horizontal branches, RR Lyrae variables, and the near-infrared magnitudes of their red clumps.

Key words: distance scale – galaxies: distances and redshifts – galaxies: individual (Carina, Fornax)

1. INTRODUCTION

The main goal of the Araucaria project is to improve the calibration of the cosmic distance scale from accurate observations of the various primary stellar distance indicators in nearby galaxies (e.g., Gieren et al. 2005b). In the course of our project we are observing Cepheids, RR Lyrae stars, red clump stars, blue supergiants, eclipsing binaries, and the tip of the red giant branch (TRGB) brightness in both optical and infrared (IR) domains. Since with IR photometry one can minimize the influence of interstellar reddening on the derived distances, and in many cases also the population dependence of the standard candles, this part of our project is particularly important for precise distance determinations to our target galaxies, and therefore for a more accurate calibration of the extragalactic distance scale. In our previous papers we already demonstrated that red clump stars (Pietrzyński & Gieren 2002; Pietrzyński et al. 2003), Cepheids (e.g., Pietrzyński et al. 2006; Gieren et al. 2005a, 2006, 2008a, 2008b; Soszyński et al. 2006), and RR Lyrae stars (Pietrzyński et al. 2008; Szweczyk et al. 2008) in the IR domain are very accurate tools for distance determination to nearby galaxies. In this paper, we extend our near-infrared distance work to the TRGB method in the J and K bands, starting with the two dwarf spheroidals Carina and Fornax. The success of the TRGB method as a tool for distance measurement began in 1993 when Lee et al. (1993) convincingly showed that the optical I-band magnitude of the TRGB does not depend on metallicity and age in environments with metallicity lower than about −0.7 dex. Subsequently, very detailed studies of a possible population dependence of the I-band TRGB magnitude (e.g., Kennicutt et al. 1998; Ferrarrese et al. 2000; Udalski 2000) confirmed the finding of Lee et al. and converted the I-band TRGB method into a widely used standard candle. Due to its simplicity and the relatively large absolute brightness of stars at the TRGB in the I band (about −4 mag), over the past decade this method has been applied to most of the nearby galaxies (e.g., Ferrarrese et al. 2000; Karachentsev et al. 2003). However, a very important problem with this technique was the potentially strong influence of reddening on the distances obtained from the optical data, especially for galaxies located at low Galactic latitudes.

Very recently important progress has been achieved by Ivanov & Borissova (2002) and Valenti et al. (2004), who provided an accurate calibration of the J, H, and K band absolute magnitudes of the TRGB. Because of the fact that the TRGB magnitude in the IR domain is much brighter than in the optical (Mk < −6 mag), it is very insensitive to reddening (which in the near-IR domain is an order of magnitude smaller than in the optical), and that the infrared calibration is valid over a very broad range of metallicities (−2.2 < [Fe/H] < −0.4 dex) these works opened the possibility to use the infrared TRGB magnitude to measure accurate distances to galaxies located out to several Mpc. The technique has been already applied to derive distances to several nearby galaxies (e.g., Cioni et al. 2000 (Magellanic Clouds); Rejkuba 2004 (NGC 5128)).

This paper is organized as follows. In the next section, we describe the observations, and the reduction and calibration methods we used. Then we present the distance determination to the Fornax and Carina Local Group galaxies, followed by a discussion of the errors associated with our results and a comparison with the distances previously derived for these galaxies from other techniques. Finally, we present a summary and final remarks.

2. OBSERVATIONS, DATA REDUCTION, AND CALIBRATION

The near-infrared data presented in this paper were collected as a part of the Araucaria project, with the ESO NTT telescope on La Silla equipped with the SofI infrared camera (Moorwood et al. 1998). The Large Field Mode, with a field of view of 4.9 × 4.9 arcmin, and a scale of 0.288 arcsec pixel−1 was used. During one night nine and four SofI fields were observed.
in Carina and Fornax, respectively (see Table 1 and Figures 1 and 2). These galaxies were already the subject of earlier deep IR imaging performed by our group with the ESO VLT (Pietrzyński et al. 2003). However, those observations were optimized for studying the relatively faint red clump stars, and the stars having brightnesses similar to the TRGB magnitude were saturated in these images, or fell into the nonlinear regime of the ISAAC camera. Therefore, in order to measure accurately the TRGB magnitude in both filters, we averaged over 20 (Carina) and 10 (Fornax) consecutive 1.5 s integrations (DITs) at any given pointing before moving the telescope to a randomly selected different position within a $20 \times 20$ arcsec square. Twelve dithering positions were sufficient to extract the sky and obtain photometry deep enough to measure accurately the TRGB magnitude in both filters.

The reductions were performed in a similar manner to those described in Pietrzyński & Gieren (2002). The sky was subtracted from the images with a two-step process implying masking of the stars with the _IRAF_ package. Then, the individual images for each field and filter were flat-fielded and stacked into a final composite image. The point-spread function (PSF) photometry was carried out with the DAOPHOT and ALLSTAR programs. About 10–20 relatively bright and isolated stars were selected visually, and the first PSF model was derived from them. Then, following Pietrzyński et al. (2002), we iteratively improved the PSF model by subtracting all stars from their neighborhood and re-calculating the PSF model. After three such iterations no further improvement was noted, and the corresponding PSF model was adopted as the final one.

Since the observations were performed under nonphotometric conditions we decided to transform our data onto the standard system using the Two Micron All Sky Survey (2MASS) data. Typically about 30 stars from the 2MASS Point-Source Catalog (Wachter et al. 2003) were found in a given SofI field. The scatter (rms) of the calculated zero-point offsets was always smaller than 0.01 mag. Several of the observed fields overlap with the regions observed by Pietrzyński et al. (2003). Therefore, it was possible to check the zero point of our photometry transformed onto the 2MASS system with the carefully calibrated deep photometry obtained by these authors. In each case, the difference in the corresponding zero points was found to be smaller than 0.02 mag. We therefore conclude that the zero-point uncertainty of our photometry does not exceed 0.02 mag.

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**Table 1**

Coordinates of the NTT/SofI Fields Observed in the Carina and Fornax Dwarf Spheroidal Galaxies

| Field Name | R.A. 2000 | Decl. 2000 |
|------------|-----------|------------|
| CarI       | 06°42'05" | -50°53'24"
| CarII      | 06°42'05" | -50°53'24"
| CarIII     | 06°42'05" | -50°53'24"
| CarIV      | 06°41'36" | -50°53'24"
| CarV       | 06°41'36" | -50°53'24"
| CarVI      | 06°41'08" | -50°53'16"
| CarVII     | 06°41'08" | -50°57'58"
| CarVIII    | 06°41'08" | -50°52'24"
| CarIX      | 06°41'36" | -50°57'58"
| ForI       | 02°40'18" | -34°25'02" |
| ForII      | 02°39'56" | -34°26'04" |
| ForIII     | 02°39'34" | -34°24'05" |
| ForIV      | 02°39'20" | -34°28'26" |

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**Figure 1.** Nine $5 \times 5$ arcmin NTT/SofI fields observed in the Carina dSph galaxy, marked on the $20 \times 20$ arcmin DSS image of this galaxy (large squares). The location of the five $2.5 \times 2.5$ arcmin VLT/ISAAC fields observed previously by Pietrzyński et al. (2003) are shown with small squares. North is up and east is to the left.

**Figure 2.** Four $5 \times 5$ arcmin NTT/SofI fields observed in the Fornax dSph galaxy, marked on the $20 \times 20$ arcmin DSS image of this galaxy (large squares). The location of the two $2.5 \times 2.5$ arcmin VLT/ISAAC fields observed previously by Pietrzyński et al. (2003) are shown with small squares. North is up and east is to the left.
3. DISTANCE DETERMINATION

From the $K, J - K$ color–magnitude diagrams for Carina and Fornax obtained from our data (Figure 3), the stars on the RGB were selected and their respective luminosity functions were calculated using a bin size of 0.08 mag, which represents a reasonable compromise between the number of stars in a magnitude bin, and the magnitude resolution we can achieve. In each galaxy the location of the TRGB is well marked (see Figure 4) and does not depend on either bin size or the starting point of the histogram.

In order to obtain TRGB magnitudes in a more objective way we computed the Gaussian-smoothed luminosity functions and use the Sobel edge-detection filter, following the procedure described in detail by Sakai et al. (1996). The resulting luminosity functions and the outputs of the edge-detection filter for the $J$ and $K$ bands and both galaxies are presented in Figures 5 and 6. As can be seen, the location of the highest peak in the edge-detection filter output, which we interpreted as the TRGB magnitude, is very well defined in both filters, in each galaxy. The automatically detected TRGB locations agree very well with those obtained from the visual inspection of the binned luminosity functions. The presence of asymptotic giant branch (AGB) stars adds additional noise in the procedure of the TRGB analysis, and if the intermediate-age population is very large in a given galaxy the TRGB detection may in principle be difficult. This effect was studied in detail by Makarov et al. (2006), and Barker et al. (2004), who concluded that the TRGB detection is quite insensitive to the AGB contamination. As can be seen in Figures 5 and 6, the locations of the most significant peaks in the Sobel filter outputs, and therefore the corresponding $J$- or $K$-band magnitudes of the TRGB, could be unambiguously identified in both galaxies.

![Figure 3](image-url)

**Figure 3.** $K, J - K$ color–magnitude diagrams for the Carina (left panel) and Fornax (right panel) dwarf spheroidal galaxies obtained from our data.

| Galaxy  | TRGB ($K$) (mag) | TRGB ($J$) (mag) | [Fe/H] (dex) | $E(B - V)$ (mag) |
|---------|------------------|------------------|-------------|------------------|
| Carina  | 14.17            | 15.00            | −1.7        | 0.06             |
| Fornax  | 14.45            | 15.51            | −1.0        | 0.03             |

We note that our $K$-band TRGB magnitude of $14.45 \pm 0.04$ mag differs by some $3\sigma$ from the results obtained by Gullieuszik et al. (2007; $14.59 \pm 0.03$). This difference is most probably caused by the different technique of TRGB detection employed by these authors (i.e., the Maximum Likelihood Algorithm (MLA) of Makarov et al. 2006). Rizzi et al. (2006), applying both Sobel filter and MLA techniques to the same Hubble Space Telescope (HST) data set of NGC 300, obtained results which in some cases were different by 0.08 mag.

In Table 2, we report the $J$- and $K$-band magnitudes of the TRGB in the Carina and Fornax dSph Galaxies, Together with Information About Metallicity and Reddening.
clusters covering the wide metallicity range from $-2.12$ to $-0.49$ dex was used (Equations (1) and (2)). It was demonstrated by these authors that these calibrations agree very well with the predictions from theoretical models:

$$M_{J}^{\text{TRGB}} = -5.67 - 0.31 \times [\text{Fe/H}],$$

$$M_{K}^{\text{TRGB}} = -6.98 - 0.58 \times [\text{Fe/H}].$$

Adopting the metallicities and reddenings listed in Table 2, and our measured TRGB magnitudes, the following true distance moduli were calculated from these calibration equations:

Carina: $20.09 \pm 0.03$ (J band), $20.13 \pm 0.04$ (K band),
Fornax: $20.84 \pm 0.03$ (J band), $20.84 \pm 0.04$ (K band).

For both galaxies, the respective distances from the J and K bands agree within the statistical uncertainties of the TRGB magnitudes.

4. DISCUSSION

With the assumed uncertainty of the photometric J- and K-band zero points of 0.02 mag, an estimated error associated with the extinction determinations of 0.02 mag, and an assumed uncertainty in the adopted metallicities of 0.2 dex we calculate the total systematic uncertainties of our distance moduli determinations for Carina and Fornax to be of 0.12 mag and 0.14 for the J- and K-band filters, respectively, for both galaxies. The dominant part in the systematic uncertainties of the current infrared TRGB distances to Carina and Fornax comes from the assumed uncertainties on the appropriate metallicities of the red giant branch tip stars. Their effect on the distance has been estimated from the metallicity coefficients in Equations (1) and (2). It should be noted here that we did not take into account any contribution from possible systematic errors in the coefficients themselves in the calibration of Valenti et al. (2004). As our final distance results, we adopt a true distance modulus of $(20.11 \pm 0.13)$ mag for the Carina dSph galaxy, and $(20.84 \pm 0.15)$ mag for the Fornax dSph galaxy.

Results of previous distance determinations to the Fornax and Carina galaxies from different methods reported in the literature are given in Table 3. Pietrzyński et al. (2003) obtained from deep K-band imaging of red clump stars true distance moduli of $20.165 \pm 0.015$ mag and $20.858 \pm 0.013$ mag for Carina and Fornax, respectively. Similar results were obtained for the Carina distance from an analysis of its RR Lyrae stars ($20.10 \pm 0.12$ mag; Dall’Ora et al. 2003), from its optical TRGB and horizontal branch (HB) luminosities ($20.05 \pm 0.06$ mag and $20.12 \pm 0.08$ mag; Smecker-Hane et al. 1994), and from dwarf Cepheids ($20.06 \pm 0.12$ mag; Mateo et al. 1998). A shorter distance to Carina of 19.94 mag was calculated by Udalski (2000) from J-band photometry of red clump stars and the TRGB, and from V-band photometry of RR Lyrae stars. However, Udalski’s distance estimation for Carina was tied to a short assumed Large Magellanic Cloud (LMC) distance of
Figure 5. J- and K-band Gaussian-smoothed luminosity functions of the RGB in the Carina dSph (top) and the corresponding outputs of the edge-detection filter (bottom).

Table 3
Distance Determinations for the Carina and Fornax dSph Galaxies Obtained with Different Stellar Indicators, in the Optical and Near-Infrared Domain

| Galaxy | Method          | Band | Distance Modulus (mag) | Error (mag) | Reference                  |
|--------|-----------------|------|------------------------|-------------|----------------------------|
| Carina | Red clump       | K    | 20.165                 | 0.015       | Pietrzyński et al. (2003)  |
| Carina | RR Lyrae        | V    | 20.10                  | 0.12        | Dall’Ora et al. (2003)     |
| Carina | TRGB            | I    | 20.05                  | 0.06        | Smecker-Hane et al. (1994) |
| Carina | HB              | I    | 20.12                  | 0.08        | Smecker-Hane et al. (1994) |
| Carina | DC              | V    | 20.06                  | 0.12        | Mateo et al. (1998)        |
| Fornax | TRGB            | I    | 20.76                  | 0.20        | Buonanno et al. (1999)     |
| Fornax | HB              | I    | 20.70                  | 0.12        | Rizzi et al. (2007)        |
| Fornax | RR Lyrae        | V    | 20.72                  | 0.10        | Greco et al. (2005)        |
| Fornax | Red clump       | I    | 20.66                  | ...         | Bersier (2000)             |
| Fornax | TRGB            | I    | 20.65                  | 0.11        | Bersier (2000)             |
| Fornax | TRGB            | K    | 20.75                  | 0.19        | Gullieuszik et al. (2007)  |
| Fornax | Red clump       | K    | 20.858                 | 0.013       | Pietrzyński et al. (2003)  |

18.24 mag, which is probably an underestimation of the true LMC distance modulus (e.g., Schaefer 2008; Fouqué et al. 2007). Correcting the LMC distance to a more likely value near 18.5 would bring Udalski’s result for the Carina distance in close agreement with the present work, and the other results cited above.

Regarding the Fornax dSph galaxy, optical photometry of the TRGB and horizontal branch (HB) has yielded the following distance moduli: 20.76 ± 0.02 (Buonanno et al. 1999), 20.70 ± 0.12 (Saviane et al. 2000), 20.65 ± 0.11 (Bersier 2000), and 20.71 ± 0.07 (Rizzi et al. 2007). Greco et al. (2005) measured \( m - M \) = 20.72 ± 0.10 for this galaxy from RR Lyrae stars. A slightly shorter distance modulus (20.66 mag) was obtained by Bersier from I-band photometry of red clump stars. Recently, Gullieuszik et al. (2007) derived the distance modulus for Fornax from near-infrared photometry of the TRGB (20.75 ± 0.19) and red clump stars (20.74 ± 0.11) applying population corrections derived from models. Our current distance result for
Fornax is at the upper limit of the distribution of these earlier measurements, but within its uncertainty clearly consistent with these. It is likely that the quality of the distance determinations to galaxies from their TRGB in the optical $I$ band and in the near-IR $JK$ bands is quite similar as to the correction of the effect of the varying metallicities of different red giant populations; however, a decisive advantage of the infrared TRGB method is its basic insensitivity to reddening corrections. While this has no strong consequences in the case of the Carina and Fornax dwarf galaxies due to their low foreground reddenings, and (assumed) negligible internal reddenings, things might be very different when highly reddened galaxies are under study.

5. SUMMARY AND CONCLUSIONS

From near-infrared photometry of the Carina and Fornax dSph galaxies we have derived the distances to these galaxies using the calibration of the TRGB absolute magnitudes in the $J$ and $K$ bands given by Valenti et al. (2004). We have obtained the following results:

$$20.09 \pm 0.03 \pm 0.12 \text{ mag (Carina, } J \text{ band)},$$
$$20.14 \pm 0.04 \pm 0.14 \text{ mag (Carina, } K \text{ band),}$$
$$20.84 \pm 0.03 \pm 0.12 \text{ mag (Fornax, } J \text{ band)},$$
$$20.84 \pm 0.04 \pm 0.14 \text{ mag (Fornax, } K \text{ band).}$$

Our distance determinations are in very good agreement with the results obtained from deep infrared imaging of red clump stars, and an analysis of the optical photometry of the TRGB and HB, and RR Lyrae stars in these galaxies. Our results show that the $K$- and $J$-band magnitudes of the TRGB in sufficiently metal-poor galaxies are promising tools for distance determinations. However, in order to further check and potentially improve this technique it should be applied to measure distances to other galaxies showing a broad range of environments. A comparison of such results with the distances measured from other distance indicators from both optical and near-infrared photometric data should shed more light on the population dependence of the stellar distance indicators, and also on the problems related to the interstellar extinction corrections. Currently, our group is involved in near-infrared imaging of several other nearby galaxies which will enable such comparative studies.

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