The Araucaria Project. The Distance to the Sculptor Group Galaxy NGC 7793 from Near-infrared Photometry of Cepheid Variables

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Abstract

Following the earlier discovery of classical Cepheid variables in the Sculptor Group spiral galaxy NGC 7793 from an optical wide-field imaging survey, we have performed deep near-infrared J- and K-band follow-up photometry of a subsample of these Cepheids to derive the distance to this galaxy with a higher accuracy than what was possible from optical photometry alone, by minimizing the effects of reddening and metallicity on the distance result. Combining our new near-infrared period–luminosity relations with previous optical photometry, we obtain a true distance modulus to NGC 7793 of $(27.66 \pm 0.04)$ mag (statistical) $\pm 0.07$ mag (systematic), i.e., a distance of $(3.40 \pm 0.17)$ Mpc. We also determine the mean reddening affecting the Cepheids to be $E(B - V) = (0.08 \pm 0.02)$ mag, demonstrating that there is significant dust extinction intrinsic to the galaxy in addition to the small foreground extinction. A comparison of the new, improved Cepheid distance to earlier distance determinations of NGC 7793 from the Tully–Fisher and TRGB methods is in agreement within the reported uncertainties of these previous measurements.

Key words: distance scale – galaxies: distances and redshifts – galaxies: individual (NGC 7793) – infrared: stars – stars: variables: Cepheids

1. Introduction

The Araucaria Project is an international project focusing on precise calibration of the cosmic distance scale, using a variety of stellar distance indicators (Gieren et al. 2005a). The calibration of the first rungs of the distance ladder still resembles the most critical problem in the determination of the Hubble constant (e.g., Freedman et al. 2001; Riess et al. 2016). Like nearby galaxies in the Local Group, the Sculptor Group provides a number of perfect environments for improving stellar methods of distance measurement and determining their dependence on metallicity. Important results have been achieved by our project recently. For instance, we measured the distance to the Magellanic Clouds with an unprecedented accuracy using eclipsing binaries, 2% in the case of the LMC (Pietrzyński et al. 2013) and 3% in the case of the SMC (Graczyk et al. 2014). With these results, the Magellanic Clouds, and in particular the LMC, are now firm anchors for the extragalactic distance scale. Our project has also shown that combined optical and near-infrared photometry of classical Cepheid variables provides an excellent way to measure the distances to nearby spiral or irregular galaxies with a typical precision of 3% (e.g., NGC 300, Gieren et al. 2005b; NGC 55, Gieren et al. 2008a; NGC 247, Gieren et al. 2009; IC 1613, Pietrzyński et al. 2006; NGC 3109, Soszyński et al. 2006; WLM, Gieren et al. 2008b; and M 33, Gieren et al. 2013).

In a previous study, we reported on the discovery of a sample of classical Cepheids in the Sculptor Group spiral galaxy NGC 7793 and derived a first Cepheid distance to this galaxy based on these objects of $27.68 \pm 0.05$ mag (statistical) $\pm 0.08$ mag (systematic; Pietrzyński et al. 2010, hereafter Paper I). The obvious drawback of this distance determination from optical $(V, I)$ data was its relatively high sensitivity to dust extinction, including the dust extinction produced in the galaxy itself, which must have affected the Cepheids’ luminosities. In addition, evidence has been mounting in recent years that the effect of metallicity on Cepheid absolute magnitudes is smaller in near-infrared than in optical bands, making a distance measurement from near-infrared photometry very desirable. We therefore obtained near-infrared follow-up photometry of the Cepheids, as reported in Section 2 of this paper. Obtaining an accurate distance to NGC 7793 from Cepheids is of high importance, as we can then compare this measurement to the previous distance determinations to NGC 7793 from the TRGB and Tully–Fisher methods to determine their accuracy. Moreover, the Type IIP supernova SN 2008bk has been observed in the galaxy, and an improved Cepheid distance will lead to a more accurate determination of its absolute peak magnitude. Also, the previous Cepheid distance measurement from optical data indicated that NGC 7793 might be the most distant spiral galaxy in the Sculptor Group, arguing for a significant extension of the Group in the line of sight, a conclusion that we wanted to confirm with an improved Cepheid distance from infrared data.

2. Observations, Data Reduction, and Calibration

We collected our J- and K-band data under photometric conditions using the High Acuity Wide field K-band Imager (HAWK-I) installed on the 8.2 m ESO Very Large Telescope at Paranal as a part of a program 087.D-0425(B). The field of view of HAWK-I is $7.5 \times 7.5$ arcmin and the pixel scale is 0.106 arcsec pix$^{-1}$. The detector of HAWK-I consists of four
chips with a 15 arcsec cross-shaped gap between them. We observed one field during two photometric nights on 2011 September 5 and September 18. The location of this field is shown in Figure 1. It was chosen as such to cover as many of the previously known Cepheids as possible (13 out of 17). The periods of the Cepheids and a preliminary distance from the optical data were published in Paper I.

From the 13 Cepheids in NGC 7793 located in our HAWK-I field, we were able to identify 11 objects. One Cepheid fell into a gap between the different chips of the HAWK-I imager, and another Cepheid, located closer to the center of the galaxy than any other of the variables, could not be clearly identified because the field in that region was too crowded in the near-infrared.

The HAWK-I observations in the $J$- and $K$-bands were performed using a dithering technique with a jitter radius of 30–40 arcsec in order to subtract the sky. For each band, 30 exposures were taken resulting in 30 minutes of total net exposure. To avoid saturation, each exposure performed in the $J$ ($K$) filter consisted of six (four) sub-integrations of 10 s (15 s) each.

In order to reduce our data, we used the dedicated ESO HAWK-I pipeline implemented in Esorex software and corresponding optional Gasgano graphic interface. It includes all necessary procedures such as basic reduction, sky subtraction, correction for distortion of the detector, and stacking into the final images. We performed point-spread function (PSF) photometry of our images using DAOPHOT and ALLSTAR.
as described in Pietrzyński et al. (2002) after dividing each multi-extension fit into four ordinary fits, corresponding to each chip of the detector. We carefully selected about 7–20 isolated stars to calculate the PSF models on each chip. The calibration of the photometry onto the standard system was based on the observations of 14 standard stars from the United Kingdom Infrared Telescope (UKIRT) list (Hawarden et al. 2001) observed on two photometric nights. All of them were observed along with the target fields in NGC 7793 at different air masses and under photometric conditions. We obtained the absolute photometric zero points with an accuracy close to 0.03 mag in both filters. This is demonstrated in Figure 2, which shows the histograms of the measured magnitude differences for constant stars in our fields between the two nights.

In addition, we analyzed IR images of NGC 7793 that we obtained with the ISAAC near-infrared camera on the ESO VLT as part of ESO proposal 171.D-0004 (A). These observations were obtained under photometric conditions but the integration times for both J- and K-bands were too short to obtain accurate photometry of the Cepheids in this galaxy. However, they are very well suited for checking the zero points of our HAWK-I photometry. In order to do that, we reduced the ISAAC data in the same manner as reported in our previous papers (e.g., Gieren et al. 2005b). The calibration to the UKIRT system was based on seven standard stars. The photometric zero points were determined with an accuracy better than 0.03 mag for both J- and K-filters.

The observed ISAAC field overlaps with all HAWK-I chips. We cross-matched common stars in both photometric lists and calculated the mean difference between ISAAC and HAWKI photometry. In all cases, the differences in the zero points in both J- and K-filters, and for all HAWK-I chips, were smaller than 0.03 mag, a result which strongly reinforces both calibrations.

3. Results

3.1. Near-infrared Photometry and Mean Magnitudes of the Cepheids

In the resulting near-infrared photometric catalog, we were able to identify, as stated above, 11 Cepheids previously discovered by Pietrzyński et al. (2010). These variables span a period range from 26 to 62 days. Figure 3 shows their location in the K versus J − K color–magnitude diagram obtained from our data. As one can appreciate, the Cepheids fall into the expected region of the HRD and do fill the instability strip rather homogeneously, showing that no significant selection bias affects our period–luminosity (PL) relations. It is also worth noting that the faintest Cepheid in our sample is still about 3 mag brighter than the faintest stars measured in the field. Therefore, we do not expect that our near-infrared PL relations are significantly affected by a Malmquist bias.

In order to calculate the Cepheid mean magnitudes, we simply took the average of the two observations per Cepheid obtained in this study (except the object cep012, which has only one measurement in J and K each, which we adopted as its respective mean magnitudes). Table 1 presents the detailed journal of individual observations of our 11 Cepheids. As can be seen, the four Cepheids with short periods (26–28 days) and two observations are brighter on September 18 than on September 5. It should be noted that for these variables, the phase progression between the first and second observing night was just about half a pulsation cycle, which can lead to a large
difference in their magnitudes on these nights—a fact we have confirmed by simulations. This shows that even with a reasonably large sample of Cepheids, it is important to obtain more than one observation in order to determine accurate mean magnitudes for the individual variables.

In principle, one could follow the procedures described by Soszyński et al. (2005) and Inno et al. (2015), which allow one to calculate the mean magnitude of a Cepheid in near-infrared bands from a single random-phase NIR magnitude measurement if accurate optical light curves and period of the Cepheid are available. The method however relies critically on well-known phase shifts between the optical and near-infrared observations. In our case, the time interval between our previous optical data sets and the current near-infrared follow-up observations of the Cepheids is too large (6–8 years) to apply this technique, so we decided to adopt the average of the two measured magnitudes to estimate the mean magnitudes.

3.2. Near-infrared PL Relations and Distance Determination

Figure 4 presents the Cepheid PL relations for the J- and K-band in NGC 7793 obtained from the data in Table 1. The scatter of the Cepheid magnitudes around the mean relations is 0.13 mag and 0.16 mag for J- and K-bands, respectively, and there is no obvious outlier that would hint at a possible misidentification or any other problem with the measurements for our Cepheids.

Fitting least-squares lines with two free parameters to the data, we obtained slope values of the PL relations of $-3.47 \pm 0.30$ and $-3.17 \pm 0.38$ for J and K respectively. Within their large uncertainties, these values are in agreement with the corresponding slopes of the near-infrared Cepheid PL relations in the LMC obtained by Persson et al. (2004; e.g., $-3.153$ in J and $-3.261$ in K). We adopt the very accurate Persson’s slopes in our analysis as we have done in our previous papers in the Araucaria Project, and we fit the PL relations for NGC 7793 once more, now only with one free parameter—the zero point. This yields the following PL relations for NGC 7793:

$$J = -3.153 \log P + (25.534 \pm 0.042) \text{mag} \quad (1)$$

$$K = -3.261 \log P + (25.214 \pm 0.051) \text{mag}. \quad (2)$$

In order to calculate the distance moduli of NGC 7793 relative to the LMC, we had to determine the shifts between the Cepheid PL relations in NGC 7793 and in the LMC in the J- and K-bands. To do this, we converted our magnitudes from the UKIRT to the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) system on which the zero points of Persson et al. (2004) were calibrated. According to Hawarden et al. (2001) there are only small and constant zero-point differences between the UKIRT and NICMOS systems: 0.034 mag and 0.015 mag for J and K, respectively.

To obtain the absolute distance moduli to NGC 7793, we adopted the very accurate (2%) LMC distance modulus of 18.493 mag measured by Pietrzyński et al. (2013), which is in excellent agreement with the value of 18.50 we had adopted in our previous Araucaria work. Thanks to this very accurate distance measurement to the LMC, we are also able to improve the NGC 7793 distance moduli from the V- and I-bands given originally in Paper I. Table 2 shows the resulting distance moduli of NGC 7793 obtained in the different photometric bands, together with their respective uncertainties.

Following our previous work (e.g., Gieren et al. 2005b; Pietrzyński et al. 2006), we used all measured, reddened distance moduli in the optical and near-infrared bands to determine the true distance modulus of NGC 7793. Adopting the Schlegel et al. (1998) reddening law, we fit a straight line to the relation $(m - M)_0 = (m - M)_h - A_V = (m - M)_h - E(B - V)R_V$. The least-squares fit shown in Figure 5 yields the true distance modulus of NGC 7793 and the total reddening affecting its Cepheids, which results in the following:

$$(m - M)_0 = 27.66 \pm 0.04 \quad (3)$$

corresponding to distance to NGC 7793 of $d = 3.40$ Mpc.

$$E(B - V) = 0.08 \pm 0.02 \quad (4)$$

The last line in Table 2 shows the true distance moduli calculated for each of the four bands, adopting the Schlegel et al. (1998) reddening law together with the reddening determined from the slope in Figure 5. The agreement between the different values is excellent, supporting the accuracy of both the values for the reddened distance moduli and the value of the total reddening affecting the NGC 7793 Cepheids of our sample.

4. Discussion and Conclusions

There are several factors contributing to the systematic uncertainty of the distance determination to NGC 7793 derived in this paper. These include the accuracy of the zero point of the photometry, the accuracy of the distance to the LMC, which we have adopted as the fiducial galaxy to which the Cepheid PL relation in NGC 7793 is tied, the uncertainty related to a metallicity correction due to a possible metallicity dependence of the Cepheid PL relation in tandem with a possible systematic metallicity difference between the sample of Cepheids in NGC
Pietrzyński et al. (2011) showed by zero points accuracy to around 0.03 mag. Regarding the uncertainty of our photometric calibration and the resulting systematic uncertainty on our current distance measurement is 2.2%, or 0.05 mag. While the effect of crowding and blending in our images. In an earlier study of our project, we made an exhaustive test of how blending affects the distance to another spiral member of the Sculptor Group, NGC 300, and concluded that its distance modulus was affected by less than 0.04 mag (Bresolin et al. 2005). While NGC 7793 is more distant than NGC 300, the HAWK-I imager used in the present study has a higher resolution (seeing for our HAWK-I data is about 0.5 arcsec) than the ISAAC near-infrared camera we used in the NGC 300 NIR work (Gieren et al. 2005b), leading to the expectation that the blending effect on the current NGC 7793 Cepheids should be of a similar size as the one we measured in NGC 300, given also the fact that both NGC 300 and NGC 7793 have very similar inclinations (nearly face-on) with respect to the line of sight. We adopt 0.04 mag as a contribution of the effect of crowding and blending to the systematic uncertainty of our current distance determination to NGC 7793. The total systematic uncertainty on our current distance measurement of NGC 7793 is therefore estimated to be about 0.07 mag, or 3%.

Table 1
Journal of J- and K-band Individual Observations of NGC 7793 Cepheids

| ID    | P (days) | HJD-2450000 (J observations) | J (mag) | σ_J (mag) | HJD-2450000 (K observations) | K (mag) | σ_K (mag) |
|-------|----------|-------------------------------|---------|-----------|-------------------------------|---------|-----------|
| cep002| 62.120   | 5809.68                       | 19.758  | 0.014     | 5809.65                       | 19.292  | 0.032     |
| cep003| 57.600   | 5809.68                       | 19.979  | 0.012     | 5809.65                       | 19.497  | 0.023     |
| cep006| 48.008   | 5809.68                       | 20.415  | 0.022     | 5809.65                       | 19.996  | 0.050     |
| cep007| 47.783   | 5809.68                       | 19.995  | 0.022     | 5809.65                       | 19.898  | 0.039     |
| cep008| 39.741   | 5809.68                       | 20.462  | 0.017     | 5809.65                       | 19.738  | 0.023     |
| cep009| 39.683   | 5809.68                       | 20.190  | 0.033     | 5809.65                       | 19.633  | 0.049     |
| cep010| 31.255   | 5809.68                       | 20.556  | 0.037     | 5809.65                       | 19.834  | 0.055     |
| cep011| 28.011   | 5809.68                       | 20.573  | 0.021     | 5809.65                       | 20.256  | 0.036     |
| cep012| 27.601   | 5809.68                       | 20.834  | 0.031     | 5809.65                       | 20.341  | 0.065     |
| cep013| 26.364   | 5809.68                       | 20.700  | 0.030     | 5809.65                       | 20.508  | 0.078     |
| cep014| 26.216   | 5809.68                       | 21.062  | 0.026     | 5809.65                       | 20.483  | 0.058     |
| cep015| 26.364   | 5809.68                       | 21.413  | 0.023     | 5809.65                       | 20.931  | 0.063     |

Note. Names of objects and periods (accurate to $10^{-3} \times P$) were adopted from Pietrzyński et al. (2010).

Figure 4. The near-infrared period–luminosity relations in the J- and K-bands as defined by the Cepheids in NGC 7793. The mean magnitudes of each variable were obtained by averaging two random-phase observations. The respective slopes on these diagrams were adopted from the LMC Cepheids (Persson et al. 2004).

The near-infrared period–luminosity relations in the J- and K-bands as defined by the Cepheids in NGC 7793. The mean magnitudes of each variable were obtained by averaging two random-phase observations. The respective slopes on these diagrams were adopted from the LMC Cepheids (Persson et al. 2004).

Magellanic Clouds (whose Cepheid populations exhibit a metallicity difference of about 0.4 dex (Luck et al. 1998)) derived from the near-geometrical, metallicity-independent eclipsing binary method (Pietrzyński et al. 2013; Graczyk et al. 2014) and the distance difference between SMC and LMC as determined from the magnitude offsets of the observed Cepheid K-band PL relations in the two galaxies: the two determinations agree to within 1% (Wielgorski et al. 2017). We also note that the metallicities of the young stellar populations in NGC 7793 and the LMC seem to agree to within 0.1 dex (Van Dyk et al. 2012 and Stanghellini et al. 2015), minimizing a metallicity correction to our distance result even if the metallicity effect in the J- and K-bands were much larger than expected according to the studies cited above.

Another factor that might affect the Cepheid magnitudes is the effect of crowding and blending in our images. In an earlier study of our project, we made an exhaustive test of how blending affects the distance to another spiral member of the Sculptor Group, NGC 300, and concluded that its distance modulus was affected by less than 0.04 mag (Bresolin et al. 2005). While NGC 7793 is more distant than NGC 300, the HAWK-I imager used in the present study has a higher resolution (seeing for our HAWK-I data is about 0.5 arcsec) than the ISAAC near-infrared camera we used in the NGC 300 NIR work (Gieren et al. 2005b), leading to the expectation that the blending effect on the current NGC 7793 Cepheids should be of a similar size as the one we measured in NGC 300, given also the fact that both NGC 300 and NGC 7793 have very similar inclinations (nearly face-on) with respect to the line of sight. We adopt 0.04 mag as a contribution of the effect of crowding and blending to the systematic uncertainty of our current distance determination to NGC 7793. The total systematic uncertainty on our current distance measurement of NGC 7793 is therefore estimated to be about 0.07 mag, or 3%.
Apart from using Cepheids in this work, and previously in Paper I for a distance determination to NGC 7793, the distance to NGC 7793 has also been determined by applying the TRGB method (Karachentsev et al. 2003; Jacobs et al. 2009) and the Tully–Fisher method (Tully et al. 2009). Jacobs et al. derived a distance of 27.79 ± 0.08 mag. This result is consistent with ours within a precision of 2σ. Another TRGB distance modulus of (27.96 ± 0.24 mag) was obtained by Karachentsev et al. (2003). Within its relatively large uncertainty, it also agrees with our measurement. The Tully–Fisher determination of the distance to NGC 7793, which yields a distance modulus of 28.06 ± 0.35 mag (Tully et al. 2009), is consistent with our current Cepheid determination but has a much larger uncertainty.

Our measurement confirms the large difference between the distances to the Sculptor Group galaxies NGC 300—(m − M)0 = 26.37 ± 0.04 ± 0.03 mag or d = 1.88 ± 0.06 Mpc (Gieren et al. 2005b), NGC 55—(m − M)0 = 26.43 ± 0.037 mag or d = 1.88 ± 0.03 Mpc (Gieren et al. 2008a), and NGC 7793, confirming the elongated structure of the Sculptor Group in the line of sight. It might even be possible that NGC 7793 does not belong to the Group, but a discussion of this possibility is beyond the scope of this study.

As the principal result of this study, we confirm and significantly improve the accuracy of the distance determination to NGC 7793 obtained in Paper I. Extending our wavelength baseline to 2.2 μm, we confirm that there is significant intrinsic reddening in NGC 7793 that dominates the total reddening affecting the Cepheids in the galaxy. This effect will need to be taken into account when calculating any other photometric distance determination to this galaxy. The current distance measurement to NGC 7793 from optical and near-infrared photometry of Cepheid variables is estimated to be accurate to about 5%.

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![Graph showing apparent distance moduli of NGC 7793 as derived in different photometric bands, plotted against the ratio of total to selective extinction as adopted from the Schlegel et al. (1998) reddening law.](image)

**Figure 5.** Apparent distance moduli of NGC 7793 as derived in different photometric bands, plotted against the ratio of total to selective extinction as adopted from the Schlegel et al. (1998) reddening law. The intersection and slope of the best-fitting line give the true distance modulus and reddening, respectively. The extremely small scatter of the reddened distance moduli in the different bands around the best-fitting line is spurious.
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