

THE ARAUCARIA PROJECT: THE DISTANCE TO THE SCULPTOR GROUP GALAXY NGC 247 FROM CEPHEID VARIABLES DISCOVERED IN A WIDE-FIELD IMAGING SURVEY*

ALEJANDRO GARCÍA-VARELA¹, GRZEGORZ PIETRZYŃSKI^{1,2}, WOLFGANG GIEREN¹, ANDRZEJ UDALSKI², IGOR SOSZYŃSKI^{1,2}, ALISTAIR WALKER³, FABIO BRESOLIN⁴, ROLF-PETER KUDRITZKI⁴, OLAF SZEWCZYK^{1,2}, MICHAŁ SZYMAŃSKI², MARCIN KUBIAK², AND ŁUKASZ WYRZYKOWSKI^{2,5}

¹ Universidad de Concepción, Departamento de Física, Astronomy Group, Casilla 160-C, Concepción, Chile; agarcia@astro-udec.cl, wgieren@astro-udec.cl, soszynsk@astrouw.edu.pl, szewczyk@astro-udec.cl, msz@astrouw.edu.pl, mk@astrouw.edu.pl, and wyrzykow@astrouw.edu.pl

² Warsaw University Observatory, Aleje Ujazdowskie 4, PL-00-478, Warsaw, Poland; pietrzyn@astrouw.edu.pl, udalski@astrouw.edu.pl

³ Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile; awalker@ctio.noao.edu

⁴ Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822, USA; bresolin@ifa.hawaii.edu, kud@ifa.hawaii.edu

⁵ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

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ABSTRACT

We report on the discovery of a Cepheid population in the Sculptor Group spiral galaxy NGC 247 for the first time. On the basis of wide-field images collected in photometric surveys in V and I bands that were conducted with three different telescopes and cameras, 23 Cepheid variables were discovered with periods ranging from 17 to 131 days. We have constructed the period–luminosity relations from these data and obtained distance moduli to NGC 247 of 28.20 ± 0.05 mag (internal error) in V , 28.04 ± 0.06 mag in I , and 27.80 ± 0.09 mag in the reddening-independent Wesenheit index. From our optical data we have determined the total mean reddening of the Cepheids in NGC 247 to be $E(B - V) = 0.13$ mag, which brings the true distance modulus determinations from the V and I bands into excellent agreement with the distance determination in the Wesenheit index. The best estimate for the true distance modulus of NGC 247 from our optical Cepheid photometry is 27.80 ± 0.09 (internal error) ± 0.09 mag (systematic error), which is in excellent agreement with other recent distance determinations for NGC 247 from the tip of the red giant branch method and from the Tully–Fisher relation. The distance for NGC 247 places this galaxy at twice the distance of two other Sculptor Group galaxies, NGC 300 and NGC 55, yielding supporting evidence for the filament-like structure of this group of galaxies. The reported distance value is tied to an assumed Large Magellanic Cloud distance modulus of 18.50 mag.

Key words: Cepheids – galaxies: distances and redshifts – galaxies: individual (NGC 247) – galaxies: stellar content – techniques: photometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

In order to improve the extragalactic distance scale using stellar standard candles that are observable in nearby galaxies, the Araucaria Project⁶ (Gieren et al. 2005c) has been investigating the most promising stellar distance indicators: Cepheid variables, RR Lyræ stars, red clump stars, blue supergiants, and the tip of the red giant branch (TRGB). The main goal of our project is to obtain an accurate calibration—better than 5%—of these primary distance indicators as a function of the environmental properties of the host galaxy: metallicity, age, and star-formation history. To achieve this goal, the Araucaria Project studies galaxies of different morphological types, ages, and metallicities in the Local Group and in the more distant Sculptor Group, which contains a number of spiral galaxies easily accessible from the southern hemisphere.

One of the Araucaria target galaxies is the spiral galaxy NGC 247 (Figure 1), a member of the Sculptor Group (Jerjen et al. 1998; Karachentsev 2005). This spiral, classified as SAB(s)d in the NASA/IPAC Extragalactic Database, is located in the constellation of Cetus near the South Galactic Pole and

is far from the Galactic Plane, as indicated by its galactic coordinates $\ell = 113^\circ 95'$, $b = -83^\circ 56'$. In this paper, we give a brief overview of the previous studies of NGC 247 that have measured the most important properties of this galaxy.

The first authors to conduct a photoelectric study of bright stars in NGC 247 in the U , B , V , R , and I bands were Alcaino & Liller (1984), who provided a fundamental reference for the subsequent photometric calibration of resolved stellar populations of this galaxy. From Schmidt plates, Carignan (1985) studied the surface brightness of NGC 247 and computed a distance modulus of 27.01 mag for the galaxy. Carignan was also able to establish that NGC 247 has an inclination of $75^\circ 4'$, indicating the difficulty involved in the study of its stellar populations due to the problems of crowding and blending accentuated by this high inclination.

Through a study of the properties of the neutral hydrogen and the mass distribution using Very Large Array (VLA)⁷ data, Carignan & Puche (1990) established that the H I disk of NGC 247 is relatively limited in extension. Based on the distance of 2.52 Mpc (Carignan 1985), these authors determined the total mass in H I to be $(8.0 \pm 0.3) \times 10^8 M_\odot$, which corresponds to a mass–luminosity ratio of $M_{H I}/L_B = 0.34$.

* Based on observations obtained with the 1.3 m telescope at the Las Campanas Observatory, the 2.2 m ESO/MPI telescope at the European Southern Observatory for Large Programme 171.D-0004, and the 4.0 m Blanco telescope at the Cerro Tololo Inter-American Observatory. This work is part of the PhD thesis of A.G.V.

⁶ <http://ezzelino.ifa.hawaii.edu/~bresolin/Araucaria/index.html>

⁷ The VLA is operated by the National Radio Astronomy Observatory, which is a facility of The National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

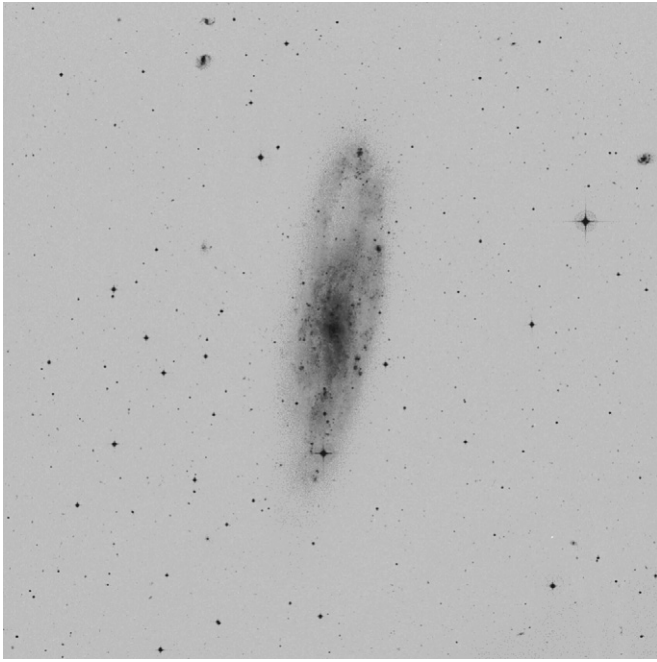


Figure 1. DSS map of the observed region centered on the galaxy NGC 247. The FOV is 35×35 arcmin.

Strässlé et al. (1999) made a study in the X-ray energy range between 0.25 and 2 keV using *ROSAT* data. They found that the mass of the hot gas of NGC 247, which emits mainly in the band of 0.25 keV, is $0.7 \times 10^8 M_{\odot}$. Taking the model for dwarf galaxies of Burlak (1996), which integrates three components of the galaxy, stellar disk, gaseous disk, and dark halo, these authors found that the total mass of NGC 247 is $7.5 \times 10^{10} M_{\odot}$ —a value consistent with their measurements of the rotation curve for this galaxy. Based on these data, Strässlé et al. found a mass–luminosity ratio of $M/L_x = 28.4$, which is in agreement with determinations of the same ratio for other Sculptor galaxies.

Using the MOSAIC II camera at the 4.0 m Blanco telescope at Cerro Tololo, Olsen et al. (2004) conducted a modern study of globular clusters in the Sculptor galaxies. These authors were able to detect a very small population of three globular clusters in NGC 247.

Karachentsev et al. (2006) were the first to measure the distance to NGC 247 from the Tully–Fisher method and obtained a value of 27.87 ± 0.21 mag, which is in significant disagreement with the earlier, shorter distance obtained by Carignan (1985). In their infrared study of the central regions of nearby galaxies, Davidge & Courteau (2002) had adopted a distance modulus of 27.3 mag for NGC 247. The most recent study reporting a measurement of the distance of NGC 247 from a stellar population was performed by Davidge (2006). Based on the *I*-band magnitude of the TRGB, he obtained a distance modulus of 27.9 ± 0.1 mag, which implies a distance of 3.80 ± 0.18 Mpc, making this galaxy one of the most distant targets of the Araucaria Project. Taking into account the inclination of the NGC 247 disk, Davidge stressed that variable internal extinction is expected since the galaxy inclination favors the possibility that the line of sight passes through dust clouds more than once. Freedman et al. (1988) and Catanzarite et al. (1994) were the first to mention the discovery of a number of Cepheid variables in NGC 247. They reported that 12 Cepheids had been found from optical surveys in *B*, *V*, *R*, and *I* bands conducted at Cerro Tololo Inter-American Observatory (CTIO) and Las Campanas Observatory (LCO). Unfortunately, neither a

Table 1
Camera Properties

| Telescope | FOV | SF ($''\text{pixel}^{-1}$) |
|-----------|------------------|---------------------------------|
| 1.3 m | $35' \times 35'$ | 0.26 |
| 2.2 m | $34' \times 33'$ | 0.24 |
| 4.0 m | $36' \times 36'$ | 0.27 |

Table 2
Summary of Observations

| Telescope | t_{exp} (s) | Time Baseline (yr) | Seeing (arcsec) | Band |
|-----------|-------------------------|-----------------------|--------------------|---------------------|
| 1.3 m | 900 | 1.3 | 0.8–1.4 | <i>V</i> , <i>I</i> |
| 2.2 m | 700 | 2.3 | 0.7–1.5 | <i>V</i> |
| 4.0 m | 300,720 | 2.2 | 1.0–1.7 | <i>V</i> |
| 4.0 m | 300,360 | 2.2 | 1.0–1.7 | <i>I</i> |

catalog nor photometric data for these Cepheids were ever published.

This paper is the first study which reports the discovery of a sizeable Cepheid population in NGC 247 in a verifiable catalog. The paper is structured as follows: details of the observations, data reductions, and calibrations are described in Section 2. Section 3 presents the catalog of the photometric properties of the 23 Cepheid variables in NGC 247 that we have discovered. The determination of the distance of NGC 247 from the observed period–luminosity relations in the *V* and *I* bands, as well as in the reddening-independent Wesenheit index, is the subject of Section 4. We discuss our results in Section 5 and summarize our conclusions in Section 6.

2. OBSERVATIONS, REDUCTIONS, AND CALIBRATIONS

NGC 247 was observed with the 1.3 m Warsaw telescope at LCO, the 2.2 m MPG/ESO telescope at La Silla Observatory, and the 4.0 m Blanco telescope at CTIO. Each telescope was equipped with a mosaic $8k \times 8k$ detector with a field of view (FOV) and a scale factor (SF) as indicated in Table 1. For more instrumental details on these cameras, the reader is referred to the camera Web sites.⁸

The observations of NGC 247 with the 1.3 m Warsaw telescope were conducted in the service mode. The collection of data began on 2003 August 5 and ended on 2004 December 18. We obtained 40 epochs in the *V* band and 38 epochs in the *I* band. With the 2.2 m telescope at La Silla, service mode observations in the *V* band were obtained for 19 epochs between 2003 June 23 and 2005 November 6. With the CTIO 4.0 m telescope, we obtained data in the *V* and *I* bands during nine epochs. These observations were conducted in the visitor mode between 2002 October 30 and 2005 January 17. Table 2 summarizes the information about the observations for each telescope.

For all images, the debiasing and flat-fielding reductions were done with the IRAF⁹ package. Then, point-spread function photometry was obtained for all of the stars in the same way as that described by Pietrzyński et al. (2002b). Independently,

⁸ <http://ogle.astrouw.edu.pl/ogle/index.html>,
<http://www.la.silla.eso.org/lasilla/sciops/2p2/E2p2M/WFI/>, and
<http://www.ctio.noao.edu/mosaic/>

⁹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 3
Photometric Calibration for the 1.3 m Warsaw Telescope Data

| Chip 2 | Chip 3 |
|--------------------------------|--------------------------------|
| $V = v - 0.032(V - I) - 2.339$ | $V = v - 0.030(V - I) - 1.898$ |
| $I = i + 0.031(V - I) - 2.572$ | $I = i + 0.037(V - I) - 2.283$ |
| $V - I = 0.939(v - i) + 0.226$ | $V - I = 0.936(v - i) + 0.365$ |

Table 4
Photometry Comparison

| ID | $V_{A\&L}$ | V |
|----|------------|--------|
| J | 12.58 | 12.585 |
| M | 13.47 | 13.490 |
| N | 14.25 | 14.287 |
| O | 13.83 | 13.841 |

data taken with the 1.3 m Warsaw telescope were reduced with the OGLE-III pipeline based on the image subtraction technique (Udalski 2003; Woźniak 2000).

In order to perform an accurate calibration of our instrumental photometry obtained with the 1.3 m Warsaw telescope onto the standard system, this galaxy was observed on an excellent photometric night, 2006 January 26, in the V and I bands, along with 25 Landolt standard stars that were monitored at very different air masses and covered a wide range of colors ($-0.14 < V - I < 1.43$). Because the transformation equations for each chip can have different zero points, the standard star sample was observed on each chip individually. The transformation equations that were obtained for each chip on which the galaxy was recorded (chips 2 and 3) are given in Table 3. Lower case letters v and i refer to the aperture instrumental magnitudes, standardized to 1 s exposure time. Capital letters refer to the magnitudes calibrated onto the standard system. The computed color coefficients are consistent with those that were derived to calibrate our earlier mosaic data from the same telescope and camera for NGC 6822 (Pietrzyński et al. 2004), NGC 3109 (Pietrzyński et al. 2006a), NGC 55 (Pietrzyński et al. 2006b), and WLM (Pietrzyński et al. 2007)—all these galaxies being targets of the Araucaria Project.

To correct the possible small variation of the photometric zero points in V and I over the mosaic, we used the maps established by Pietrzyński et al. (2004). Comparison with studies in the other Araucaria papers revealed that these maps allow us to correct the zero-point variations across the mosaic field in such a way that the residuals do not exceed 0.02–0.03 mag.

In order to perform an external check of our photometry, we compared it to the photoelectric measurements obtained by Alcaïno & Liller (1984), who established a sequence of secondary standards in the field of NGC 247. In our database, four stars were found to be common to this sequence. The remaining stars were either saturated or located outside of our FOV. In Table 4, the first column gives the identification of the stars according to the Alcaïno & Liller system. The second column is the V magnitude measured by Alcaïno & Liller. The third column reports the V magnitude obtained in this work. The comparison of our V -band photometry for these objects with that of Alcaïno & Liller demonstrates that the zero points of the two data sets agree within 0.02 mag.

In order to calibrate the instrumental photometry obtained with the 2.2 m and 4.0 m telescopes, linear offsets were applied to the photometric zero points of the data since the magnitudes did not show any dependence on the color terms. We developed an internal test to estimate the accuracy of the zero-point

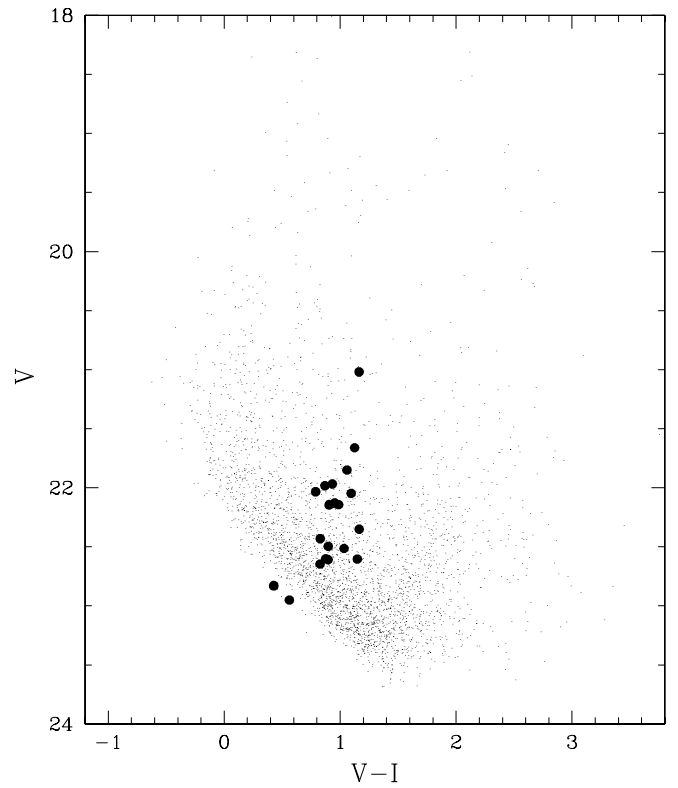


Figure 2. V , $V - I$ CMD for stars in NGC 247 observed with the 1.3 m Warsaw telescope. The detected Cepheid candidates are marked with the filled circles. With the exception of the two faintest variables which are very blue for their periods, the Cepheids populate the expected region in this diagram, supporting their correct identification as Cepheid variables.

photometry of the final data set that was obtained by joining data of the three telescopes. Computing the mean magnitudes of bright stars observed with each telescope, and comparing the values with those obtained by combining data of the three telescopes, we were able to establish that the accuracies of the V and I zero points of the photometry are 0.02 mag and 0.01 mag, respectively. This is borne out in the Cepheid light curves obtained from the combined data sets, where evidence for systematic offsets between the data sets from the different cameras is not observed in any of the cases (see Figure 2).

3. THE CEPHEID CATALOG

The photometric database was made with the 2.2 m and 4.0 m telescopes data. This database was constructed using the DAOMASTER and DAOMATCH programs (Stetson 1994). A search for variable stars with periods between 0.2 and 150 days was conducted using the analysis of variance algorithm (Schwarzenberg-Czerny 1989) and FNPEAKS software (Z. Kolaczowski 2003, private communication). In order to distinguish Cepheids from other types of variable stars, we adopted the same criteria used by Pietrzyński et al. (2002a). All light curves showing the typical shape of Cepheid variables were approximated by Fourier series of order less than 5 and 4 for photometric time series in the V and I bands, respectively. We rejected all candidates whose amplitudes in the V band were smaller than 0.4 mag, which is approximately the lower limit amplitude for normal classical Cepheids. For the variable stars passing our selection criteria, mean V and I magnitudes were derived by integrating their light curves, which had been previously converted onto an intensity scale, and converting the

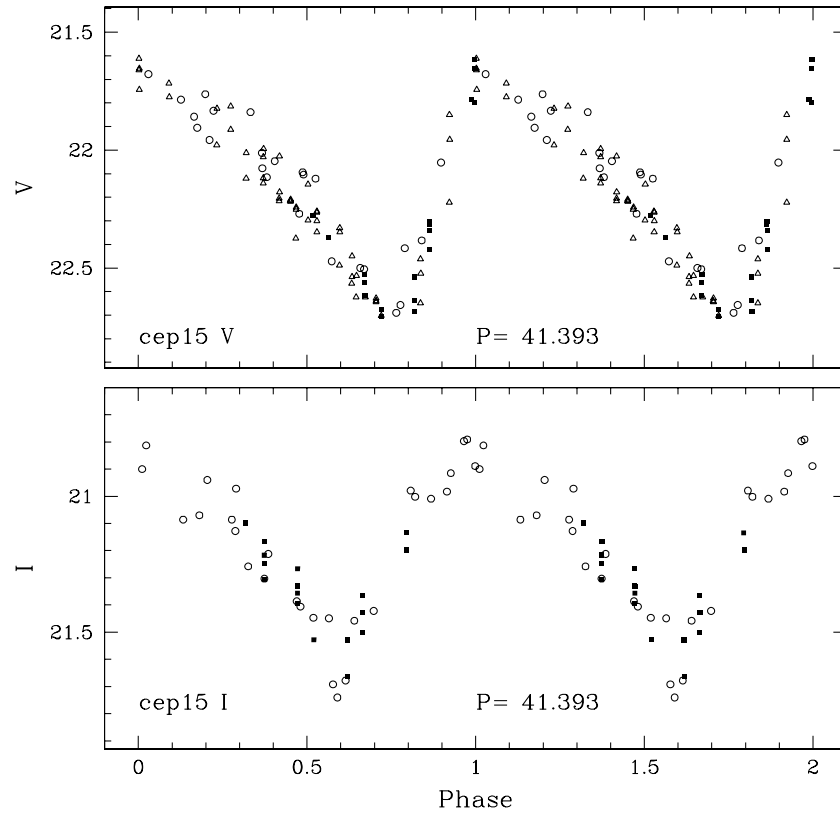


Figure 3. Phased V- and I-band light curves for one of the Cepheids (cep15) discovered in NGC 247. The open circles, triangles, and filled squares correspond to the data obtained with the Warsaw 1.3 m, ESO 2.2 m, and CTI 4 m telescopes, respectively. The good agreement of the different data sets is demonstrated.

Table 5
Catalog of Cepheid Variables in NGC 247

| ID | R.A. (J2000) | Decl. (J2000) | P (days) | $T_0 - 2,450,000$ (days) | $\langle V \rangle$ (mag) | $\langle I \rangle$ (mag) | $\langle W_1 \rangle$ (mag) |
|--------|-----------------|------------------|---------------|-----------------------------|------------------------------|------------------------------|--------------------------------|
| cep001 | 0:47:29.60 | -20:45:28.3 | 15.949 | 2807.3298 | 23.372 | | |
| cep002 | 0:46:51.06 | -20:33:18.4 | 17.837 | 2805.8816 | 23.357 | | |
| cep003 | 0:46:59.67 | -20:39:30.0 | 17.966 | 2576.1692 | 22.951 | 22.389 | 21.518 |
| cep004 | 0:47:06.69 | -20:37:10.2 | 18.424 | 2821.5388 | 22.830 | 22.402 | 21.739 |
| cep005 | 0:47:07.59 | -20:37:51.4 | 27.821 | 2586.0627 | 22.431 | 21.603 | 20.320 |
| cep006 | 0:47:11.60 | -20:44:08.2 | 29.585 | 2799.9832 | 22.601 | 21.726 | 20.370 |
| cep007 | 0:47:03.39 | -20:44:47.7 | 29.977 | 2582.8054 | 22.604 | 21.456 | 19.677 |
| cep008 | 0:47:03.46 | -20:47:58.5 | 30.978 | 2559.6931 | 22.609 | 21.713 | 20.324 |
| cep009 | 0:47:09.93 | -20:39:28.6 | 32.114 | 2587.5518 | 22.496 | 21.599 | 20.209 |
| cep010 | 0:47:00.54 | -20:37:09.7 | 33.023 | 2811.5498 | 22.646 | 21.819 | 20.537 |
| cep011 | 0:47:10.11 | -20:48:45.1 | 33.172 | 2558.3767 | 22.514 | 21.481 | 19.880 |
| cep012 | 0:47:17.14 | -20:44:18.8 | 35.809 | 2580.2461 | 22.145 | 21.239 | 19.835 |
| cep013 | 0:47:09.62 | -20:51:38.2 | 36.192 | 2803.8462 | 22.415 | | |
| cep014 | 0:46:56.65 | -20:41:34.7 | 39.747 | 2569.9172 | 22.129 | 21.177 | 19.701 |
| cep015 | 0:46:58.44 | -20:44:02.9 | 41.393 | 2579.1355 | 22.143 | 21.156 | 19.626 |
| cep016 | 0:47:10.52 | -20:47:21.3 | 44.481 | 2566.2730 | 22.351 | 21.186 | 19.380 |
| cep017 | 0:47:03.82 | -20:41:04.0 | 48.663 | 2583.7842 | 21.968 | 21.035 | 19.589 |
| cep018 | 0:47:04.28 | -20:47:42.2 | 63.505 | 2581.4636 | 22.047 | 20.952 | 19.255 |
| cep019 | 0:47:10.19 | -20:42:11.7 | 64.889 | 2597.1514 | 22.034 | 21.245 | 20.022 |
| cep020 | 0:47:10.64 | -20:40:11.0 | 65.862 | 2589.5732 | 21.983 | 21.114 | 19.767 |
| cep021 | 0:47:04.85 | -20:44:22.6 | 69.969 | 2595.1423 | 21.661 | 20.536 | 18.792 |
| cep022 | 0:47:09.29 | -20:51:11.9 | 73.300 | 2564.7302 | 21.850 | 20.791 | 19.150 |
| cep023 | 0:47:08.91 | -20:43:21.4 | 131.259 | 2563.3052 | 21.019 | 19.855 | 19.855 |

results back to the magnitude scale. The quality and phase-coverage of the light curves allowed us to obtain a statistical accuracy of the derived mean magnitudes in the V band of typically 0.01 mag for the brightest variables, increasing to 0.03 mag for the faintest Cepheids in our sample. Our Cepheid

catalog consists of 23 members. Table 5 presents their identifications, equatorial coordinates, periods, V and I mean magnitudes, and their Wesenheit index magnitudes (defined as $W_1 = I - 1.55(\langle V \rangle - \langle I \rangle)$; see Udalski et al. 1999). Other variables in NGC 247 that were discovered in

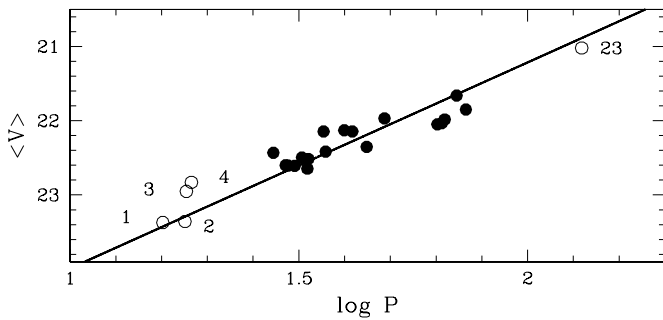


Figure 4. V-band period–luminosity relation defined by the Cepheid variables in NGC 247. The open circles denote stars not used for the distance determination.

our search for photometric variability and not classified as Cepheids will be studied in a forthcoming paper. In Figure 3, we show the V and I light curves of a typical Cepheid that we discovered in NGC 247, cep015, with a period of 41.4 days, as obtained from the combined data sets. It can be seen that the different data sets match each other very well indeed, and that the light variations of this Cepheid (and the others) in our catalog in the V and I bands are very well determined.

It is not surprising that we detected a relatively small number of Cepheids from our images in NGC 247, given both the distance to this galaxy and the fact that most of the frames were obtained on small telescopes (there were only nine epochs obtained on the Blanco 4 m telescope), which restrict the detection to the bright, long-period Cepheid population in this galaxy. On the other hand, this is the population most useful for the distance determination, which is the primary purpose of our project; a sample of 23 Cepheids with a period baseline of more than 100 days is very well suited for an accurate distance determination.

In Figure 2, we show the locations of the NGC 247 Cepheids in the V , $V - I$ color–magnitude diagram (CMD), where they delineate the expected Cepheid instability strip (Chiosi et al. 1992; Simon & Young 1997). Three stars in Table 5 are missing in this plot because we could not measure their I -band light curves (objects cep001, cep002, and cep013). While the 18 brightest Cepheids in our sample delineate the instability strip very well (supporting their correct identification as Cepheid variables), the two faintest Cepheids in our sample appear too blue for their periods and seem to be placed beyond the blue edge of the Cepheid instability strip. While this is likely to be attributed to the relatively low accuracy of the photometric data for these two stars, it could also mean that these objects are not Cepheids, but we consider this very unlikely from an inspection of their light curves. In any case, as discussed in the following section of this paper, these two variables are excluded from our distance determination for NGC 247.

In Table 6, we report our individual V - and I -band observations of the discovered Cepheids. The full Table 6 is available in the online version of this paper.

4. PERIOD–LUMINOSITY RELATIONS AND DISTANCE DETERMINATION

In Figures 4–6, we show the period–luminosity (PL) relations in the V , I , and Wesenheit bands (the latter defined in the usual way) resulting from the data from Table 5. For the distance determination from these diagrams, we adopt the 18 Cepheids in the period range from 27.8 to 73.3 days. The variables with smaller periods in Table 5 were excluded from the distance analysis because they might be affected by a

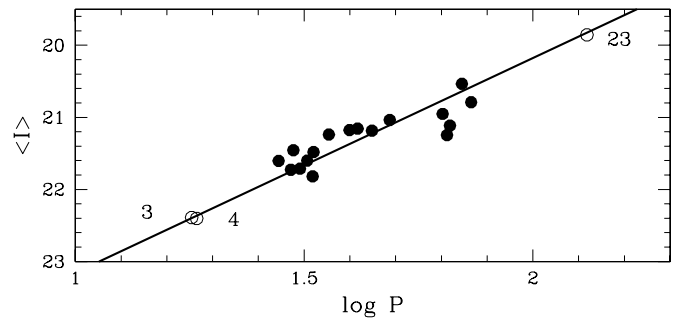


Figure 5. Same as Figure 4, for the I band.

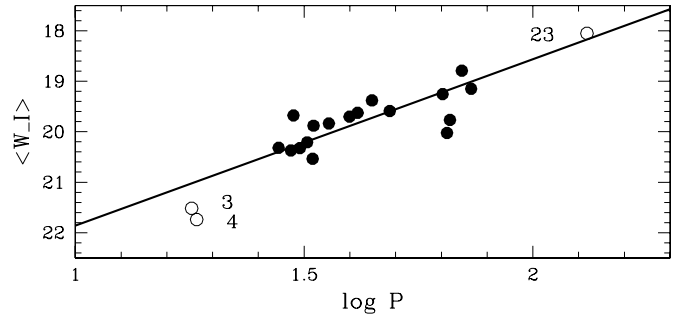


Figure 6. Same as Figure 4, for the reddening-independent ($V - I$) Wesenheit magnitudes.

Table 6
Individual V and I Observations

| Object | Filter | HJD–2,450,000 | mag | σ_{mag} |
|--------|--------|---------------|--------|-----------------------|
| cep001 | V | 2814.91283 | 23.616 | 0.119 |
| cep001 | V | 2931.81538 | 23.508 | 0.128 |
| cep001 | V | 2931.82500 | 23.644 | 0.158 |
| cep001 | V | 2934.62648 | 22.706 | 0.038 |
| cep001 | V | 2937.78340 | 22.939 | 0.112 |
| cep001 | V | 2966.63869 | 22.640 | 0.056 |
| cep001 | V | 2966.65743 | 22.721 | 0.077 |
| cep001 | V | 2968.58759 | 23.074 | 0.095 |
| cep001 | V | 2968.59719 | 23.021 | 0.074 |
| cep001 | V | 2968.60686 | 23.086 | 0.073 |
| cep001 | V | 2968.62680 | 22.936 | 0.067 |
| cep001 | V | 2968.63630 | 23.052 | 0.063 |
| cep001 | V | 2970.65025 | 23.190 | 0.085 |
| cep001 | V | 2970.65964 | 23.140 | 0.076 |
| cep001 | V | 2970.66902 | 23.229 | 0.096 |
| cep001 | V | 3270.88984 | 22.811 | 0.090 |
| cep001 | V | 3295.68266 | 23.965 | 0.119 |
| cep001 | V | 3295.69197 | 23.927 | 0.136 |
| cep001 | V | 3327.61168 | 23.930 | 0.244 |
| cep001 | V | 3376.55724 | 23.822 | 0.130 |
| cep001 | V | 3639.79773 | 23.201 | 0.082 |
| cep001 | V | 3639.80704 | 23.283 | 0.096 |
| cep001 | V | 3651.77611 | 22.852 | 0.061 |
| cep001 | V | 3651.78545 | 22.851 | 0.065 |
| cep001 | V | 3651.79484 | 22.807 | 0.059 |
| cep001 | V | 3681.73375 | 23.472 | 0.117 |
| cep001 | V | 3681.75232 | 23.540 | 0.135 |

Notes. The printed edition contains only the measurements in the V band for the Cepheid variable cep001.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Malmquist bias, given that their mean magnitudes are relatively close to the cutoff in our photometry (see Figure 2). We also exclude the one very long-period variable at 131.3 days because such very luminous Cepheids might not obey the linear PL relation defined by the shorter-period (less than 100 days) variables (e.g., Freedman et al. 1992; Gieren et al. 2004). Such an effect is also predicted from theoretical models (Bono et al. 2002). Although the 131.3 day Cepheid in NGC 247 seems to perfectly fit the linear extension of the PL relation in both V and I , it carries a strong weight in the solution and we prefer not to use it in the distance calculation.

As in the previous papers in this series, we adopt the slopes of the Cepheid PL relations as given by the OGLE-II project for the Cepheids in the Large Magellanic Cloud (LMC; Udalski 2000). These slopes are extremely well determined, with 1σ errors of 0.021, 0.014, and 0.008 in the V , I , and the reddening-free Wesenheit bands, respectively. Least-squares fits to the observed PL relations in NGC 247 from our data yield slopes of -2.571 ± 0.261 in V , -2.685 ± 0.214 in I , and -3.497 ± 0.421 in W_1 , which are all consistent with the OGLE LMC slopes within about 1σ . This supports our adopted procedure to use the well-measured LMC Cepheid PL relation slopes for the distance determination of NGC 247.

Fitting the LMC Cepheid PL relation slopes to our data of the 18 adopted Cepheids (indicated as filled circles in Figures 4–6) yields the following equations:

$$V = -2.775 \log P + (26.766 \pm 0.048) \sigma = 0.199,$$

$$I = -2.977 \log P + (26.131 \pm 0.056) \sigma = 0.229,$$

$$W_1 = -3.300 \log P + (25.163 \pm 0.086) \sigma = 0.355.$$

If we fit the data of *all* Cepheids in Table 5 (23 stars) with the same slopes, the zero points in the above PL relations change to 26.735, 26.134, and 25.219 in V , I , and the Wesenheit index, respectively. This shows that our distance result for NGC 247 changes by less than 3% if we replace our adopted sample of 18 Cepheids by the full sample of Cepheids that we detected and measured in NGC 247, in any filter. If we take into account the small errors on the adopted LMC PL relation slopes in our calculation, the effect on the zero points of the NGC 247 PL relations is less than 0.01 mag in each band, and therefore insignificant.

Adopting, as in our previous papers, a value of 18.50 for the true distance modulus of the LMC, a value of 0.02 mag for the foreground reddening toward NGC 247 (Schlegel et al. 1998), and the reddening law of Schlegel et al. ($A_V = 3.24E(B - V)$, $A_I = 1.96E(B - V)$), we obtain the following absorption-corrected distance moduli for NGC 247 in the three different bands:

$$(m - M)_0(V) = 28.135 \pm 0.048,$$

$$(m - M)_0(I) = 27.998 \pm 0.056,$$

$$(m - M)_0(W_1) = 27.795 \pm 0.086.$$

These values suggest that, in addition to the foreground reddening toward our target galaxy, there is substantial intrinsic reddening in NGC 247 affecting the Cepheid magnitudes in V and I . We will determine this intrinsic component of the total reddening affecting the NGC 247 Cepheids with high accuracy

in a future study that will provide near-infrared photometry for the Cepheids and combine it with the present optical VI data, as we did in previous papers of the Araucaria Project (e.g., Gieren et al. 2005a). From the distance moduli derived in the V and I bands, our current best estimate for the *total* mean reddening of the NGC 247 Cepheids, including that produced in the galaxy itself, is $E(B - V) = 0.13$ mag. With this value of the total reddening, the true distance moduli in the V and I bands are in very good agreement with the value derived from the W_1 . As our present best determination of the true distance modulus of NGC 247, we adopt the value 27.80 ± 0.09 mag (random error) derived from the reddening-free Wesenheit magnitude. The corresponding distance of NGC 247 is 3.63 ± 0.15 Mpc, placing the galaxy at about twice the distance of the other two Sculptor Group galaxies for which our project has previously provided accurate Cepheid distances: NGC 300 (Gieren et al. 2004, 2005a) and NGC 55 (Pietrzyński et al. 2007; Gieren et al. 2008a). We will discuss our distance determination for NGC 247 and estimate its total uncertainty, including systematic errors, in the following section.

5. DISCUSSION

The current distance determination to NGC 247 is the first one based on Cepheid variables discovered in our present wide-field imaging survey. It is affected to some extent by the well-known sources of systematic error that are inherent in such studies, which have been discussed in some detail in our previous wide-field Cepheid surveys of Araucaria galaxies mentioned in the introduction. These systematic error sources include the zero point of our photometry, possible problems with the Cepheid sample itself (overtone pulsators, Malmquist bias, filling of the instability strip), blending of the Cepheids with objects not resolved in the images, possible metallicity effects on the PL relation, reddening, and the adopted distance of the LMC to which the NGC 247 distance is tied. We will, in turn, discuss these factors and estimate their influence on our current distance determination.

As discussed in Section 2, we have been very careful to determine the photometric zero points of the different sets of photometric data used in this study with the highest possible accuracy. Our tests and discussion in Section 2 lead us to believe that the photometric zero points of the common data sets in V and I are determined to an accuracy better than ± 0.03 mag in both bands. This is in agreement with our previous experience; data sets obtained with the same instruments and reduced and calibrated in the same way always led to photometric zero points whose accuracy was better than 2%.

While the Cepheid sample used in this study of about 20 stars is relatively small as compared with our previous surveys of other (and nearer) Araucaria galaxies, it is still large enough to expect that an inhomogeneous filling of the instability strip is not a significant problem in the present case of NGC 247. Indeed, the dispersion of the positions of the Cepheids in Figure 3 seems to indicate that the distribution of the Cepheids in the instability strip is approximately random. This is supported by the fact that the effect of the sample size or the adopted cutoff period on the distance solution is only $\sim 2\%$ in all bands, as discussed in the previous section. This same result also suggests that there is no significant Malmquist bias affecting our distance result, in agreement with the fact that even the faintest Cepheids in our sample are still about 1 mag brighter than the faintest stars in NGC 247 that were detected and measured from our images. Also, we can clearly assume that our adopted Cepheid sample

has only fundamental-mode pulsators, given that many studies have shown that overtone Cepheids are restricted to periods smaller than about 6 days (e.g., Udalski et al. 1999; Gieren et al. 1993).

Blending of the Cepheids in NGC 247 that were used for the distance determination is potentially a more serious problem. In extrapolation of our result of the effect of blending on the Cepheid-based distance of NGC 300 (Bresolin et al. 2005), which was found to be less than 2%, we would expect a slightly larger effect for NGC 247 due to its larger distance and larger inclination as compared to NGC 300; both tend to increase the probability of significant blending with unresolved and relatively bright nearby stars. On the other hand, the relative effect of blending decreases with the period of the Cepheids; longer-period Cepheids are more luminous, and therefore the relative effect of a given unresolved companion star on its observed flux tends to be less important. Since all Cepheids in our sample that were used for the distance determination have periods longer than 27 days—the mean period is about 50 days—our NGC 247 sample should be less affected in this regard than the sample in NGC 300, for which the mean period is considerably shorter (about 30 days; Gieren et al. 2004). From these considerations, we expect that any residual systematic effect on the NGC 247 distance due to blending of the Cepheids should not exceed 4%, or 0.08 mag in the distance modulus. It should be noted that the sign of this error is to *underestimate* the true distance of the galaxy by such an amount.

The effect of metallicity on the PL relations in different bands has been discussed in some detail in the previous papers of this series. Here, we just note that for any of the Araucaria target galaxies we have studied so far, the observed slopes of the Cepheid PL relations in the *VIJK* bands were consistent with the respective slopes found in the LMC by the OGLE-II project in *VI* bands and by Persson et al. (2004) in the near-infrared bands. NGC 247 is no exception, as evident from Figures 4–6, although the slope is less well-determined in this case due to the relatively small Cepheid sample we were able to detect. The recent work of Gieren et al. (2005b) and Fouqué et al. (2007) on Galactic and LMC Cepheid distances measured from the infrared surface brightness technique (Fouqué & Gieren 1997) has confirmed that the slope of the Cepheid PL relation does not change significantly with metallicity, even for a solar abundance sample of Cepheid variables. The effect of a possible nonlinearity of the PL relation at a period of 10 days, discussed by Ngeow et al. (2008), does not affect the determination of distances of galaxies in any significant way. The question of the effect of metallicity on the zero point of the PL relation is less clear at the present time; it is one of the main goals to determine this effect by comparison of the Cepheid distances of our target galaxies with those derived from other methods. However, the effect of metallicity on the PL-relation zero points in *VIJK* is certainly not dramatic and likely less than $\sim 3\%$ (e.g., Storm et al. 2004; Sakai et al. 2004; Macri et al. 2006). The generally very good agreement of our Cepheid distances with those derived from the TRGB method (e.g., Rizzi et al. 2006, 2007) for common galaxies seems to support the idea that the effect of metallicity on the PL zero point is small. For NGC 247, the agreement of the TRGB distance of 27.9 ± 0.1 mag of Davidge (2006) with our present value of 27.80 mag is clearly excellent. Although we do not have any detailed information on the metallicity of the young stellar population in NGC 247, it is likely more metal rich than that of the less

massive Local Group irregular galaxies WLM, NGC 3109, and IC 1613, for which the metallicity of young stars is about -1.0 dex (Bresolin et al. 2006, 2007; Evans et al. 2007). This suggests that Cepheid and TRGB distances do agree well over a range of metallicities, and not only for very metal-poor galaxies. A detailed quantitative discussion of this issue will be given in a forthcoming paper of the Araucaria Project.

Any residual systematic effect of reddening on our present distance result adopted from the Wesenheit PL relation should be small. In our previous Cepheid studies, we have usually found that the distance of a galaxy derived from the W_1 -magnitude PL relation agreed with that derived from our combined optical-near-infrared technique to within 2% (Gieren et al. 2005a, 2006, 2008a; Pietrzyński et al. 2006c; Soszyński et al. 2006). This is, in principle, expected due to the reddening-free nature of the Wesenheit magnitudes. However, the Wesenheit-band PL relations for more distant galaxies tend to show an increasing dispersion that is on the order of (or even surpasses) that observed in *V* and/or *I*. This is likely due to the combined effect of photometric errors and blending with unresolved nearby stars that affect the Wesenheit magnitudes by increasing amounts. In our recent study of the WLM galaxy (Gieren et al. 2008b), we find a distance from near-infrared data that is 0.09 mag shorter than that which we had previously obtained from the Wesenheit index. In the case of NGC 247, there might be an effect of similar order. Future planned infrared photometry of the Cepheids in NGC 247 will allow us to investigate this question and provide a more accurate distance determination to the galaxy. We estimate that the remaining systematic effect due to reddening on the present distance modulus determination for NGC 247 should not be larger than 4%. Our planned infrared work on the NGC 247 Cepheids will definitively prove or disprove the validity of our current estimation of the effect of reddening on the distance of NGC 247.

Finally, there is the problem of the adopted LMC distance, which has been most recently discussed by Schaefer (2008). We do not wish to add to the discussion here, but we just mention that some recent results for the distance modulus of the LMC using local open clusters (An et al. 2007), revised *Hipparcos* Cepheid parallaxes (van Leeuwen et al. 2007), and the infrared surface brightness technique (Fouqué et al. 2007) have yielded a somewhat shorter LMC distance, with values close to 18.40 mag. Since all galaxy distance moduli reported in previous papers of the Araucaria Project have been tied to the same assumed LMC distance modulus of 18.50 mag, we will retain this value here. Therefore, their *relative* distances will not be affected should future work definitively change the adopted value of the LMC distance.

The distance of NGC 247 seems very well determined now. Within their respective uncertainties, the TRGB distance of 27.9 ± 0.1 mag of Davidge (2006) and the Tully–Fisher distance determination of 27.81 ± 0.21 mag of Karachentsev et al. (2006) agree with the present distance determination of the galaxy from Cepheid variables. The new Cepheid distance to NGC 247 reported in this paper has an uncertainty that is similar to the TRGB measurement of the distance, but more accurate than the distance of this spiral derived from the Tully–Fisher method.

From the previous discussion, we estimate that the systematic uncertainty of our present distance determination is about 0.09 mag. This leads to a final, adopted value for the true distance modulus of NGC 247 of $(m - M)_0 = 27.80 \pm 0.09$ (random) ± 0.09 (systematic) mag, corresponding to 3.63 Mpc, with a

total uncertainty of about 6%. We expect to improve on this value and significantly reduce its uncertainty with our planned near-infrared work on the NGC 247 Cepheids.

6. CONCLUSIONS

We have conducted an extensive wide-field imaging survey in the Sculptor Group spiral galaxy NGC 247 in the optical *V* and *I* bands that has led to the discovery of 23 Cepheid variables with periods between 17 and 131 days. These are the first Cepheid variables with published data reported in this galaxy.

From the periods and mean magnitudes of the Cepheids derived from our photometry, we have constructed PL relations in the *V*, *I*, and *W_I* bands. The data define tight PL relations which are well fitted with the slopes of the corresponding LMC Cepheid PL relations adopted from the OGLE-II project. We have derived reddened distances for the three bands, which lead to a determination of the total mean reddening of the NGC 247 Cepheids of $E(B - V) = 0.13$ mag. With an adopted foreground reddening toward NGC 247 of 0.02 mag from Schlegel et al. (1998), we determine a reddening value of 0.11 mag produced *inside* NGC 247 that affects its Cepheid population. We adopt a final true distance modulus of 27.80 mag for NGC 247 from the reddening-free Wesenheit magnitude PL relation, which is in very good agreement with the reddening-corrected values coming from the *V* and *I* bands. The total uncertainty on this distance value, including the contribution from systematic errors, is estimated to be $\pm 6\%$.

The Cepheid distance to NGC 247 derived in this paper agrees very well, within the respective 1σ uncertainties, with the recent determinations of Davidge (2006) from the *I*-band TRGB method and of Karachentsev et al. (2006) from the Tully–Fisher method.

The distance of NGC 247 of 3.63 Mpc is about twice as large as the respective distances of two other Sculptor Group galaxies, NGC 300 (Gieren et al. 2005a) and NGC 55 (Gieren et al. 2008a). This supports the evidence that the Sculptor Group has a filament-like structure (Jerjen et al. 1998) with a large depth extension in the line of sight.

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