Using $\delta$ Cep Stars to study Northern Dwarf Irregular Galaxies of the Local Group

C.A. Gössl$^1$, J. Snigula$^{2,1}$, and U. Hopp$^{1,2}$

1 Universitätssternwarte München, Scheinerstr. 1, D-81679 München, Germany
2 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstr., D-85748 Garching, Germany
e-mail: cag@usm.uni-muenchen.de

Abstract. Dwarf galaxies in the Local Group provide a unique astrophysical laboratory. Despite their proximity some of these systems still lack a reliable distance determination as well as studies of their stellar content and star formation history. We present first results of our survey of variable stars in a sample of six Local Group dwarf irregular galaxies. We describe observational strategies and data reduction, and discuss the lightcurves of newly found and rediscovered $\delta$ Cep stars in DDO 216, Leo A and GR8. Based on these data, we present newly derived independent Cepheid distances. Other variable stars found in our survey are discussed in a related article of this volume (Snigula et al.).

Key words. Galaxies: distances – Galaxies: dwarf – Galaxies: individual: Leo A – Galaxies: individual: DDO 216 – Galaxies: individual: GR8 – Cepheids – Local Group

1. Introduction

The main aim of the Wendelstein (WST) monitoring project is to determine numbers and properties of the bright variable stars in six northern dwarf irregular galaxies: LGS 3 (Pisces), UGCA 92 (EGB 0427+63), DDO 69 (Leo A), DDO 155 (GR8), DDO 210 (Aquarius), and DDO 216 (Pegasus). Those will be used to put further constraints on their stellar content, and thus on their evolutionary history, (Snigula et al. 2004, Snigula et al. this volume) and for distance estimates. Here we present the results of our survey for classical Cepheids in Leo A, DDO 216, and GR8. We derive distance moduli and compare them with recently published ones.

Table 1. Epochs per filter, telescope and object.

| object   | WST | CA |
|----------|-----|----|
| Leo A    | 31  | 94 | 13  | 47  | 29 |
| DDO 216  | 17  | 70 | 2   | 2   | 2  |
| GR8      | 23  | 106| 14  | 49  | 31 |

2. Observations

The relatively small 0.8 m Wendelstein telescope has the necessary long-term availability for monitoring projects (i.e. 130 clear nights per year, unrestricted access). Although the telescope does not take full advantage of the good ($\leq 1''$) seeing quality of the site, we regularly obtain images of 1 to 1.5" FWHM.
Table 2. Parameters of our δ Cep stars: identifier, position, most significant Lomb period, significance (p-level), flux averaged apparent R-band magnitude, RMS error of R-band magnitude. Error of period \( \delta P < 0.01 \text{d}. \) V01 to V05 = • and V06 to V07 = ▲ in Fig. 2. P01 to P03 = • and P04 to P06 = ▲ in Fig. 3.

| Id  | RA-2000 [h] | Dec-2000 [deg] | period [d] | significance \( p \)-level | \( < R_f > \) [mag] | \( \delta < R_f > \) [mag] |
|-----|-------------|----------------|----------|--------------------------|-----------------|------------------|
| V01 | 09:59:28.679 | +30:44:35.38    | 6.487    | 6.93e-10                 | 20.62           | 0.11             |
| V02 | 09:59:27.762 | +30:44:57.42    | 1.685    | 8.78e-03                 | 21.45           | 0.25             |
| V03 | 09:59:23.914 | +30:45:13.06    | 3.354    | 5.86e-04                 | 21.47           | 0.25             |
| V04 | 09:59:29.115 | +30:43:48.70    | 2.049    | 9.80e-03                 | 22.10           | 0.44             |
| V05 | 09:59:30.472 | +30:44:03.65    | 1.685    | 3.43e-05                 | 22.26           | 0.52             |
| V06 | 09:59:25.918 | +30:44:36.70    | 1.607    | 2.61e-04                 | 21.68           | 0.30             |
| V06a|             |                | 2.630    | 1.63e-04                 |                 |                  |
| V07 | 09:59:35.672 | +30:44:41.79    | 1.564    | 5.47e-04                 | 22.07           | 0.44             |
| P01 | 23:28:32.702 | +14:43:15.49    | 3.889    | 3.1e-02                  | 21.03           | 0.24             |
| P02 | 23:28:36.217 | +14:44:02.64    | 3.712    | 1.06e-02                 | 21.71           | 0.45             |
| P03 | 23:28:37.310 | +14:43:45.33    | 2.642    | 5.07e-03                 | 22.23           | 0.73             |
| P04 | 23:28:33.753 | +14:44:27.68    | 3.188    | 2.93e-02                 | 21.09           | 0.26             |
| P05 | 23:28:28.990 | +14:44:41.88    | 1.118    | 1.75e-02                 | 21.41           | 0.34             |
| P06 | 23:28:32.340 | +14:44:47.06    | 8.593    | 5.99e-02                 | 22.17           | 0.69             |
| GR8 | 12:58:41.389 | +14:13:09.47    | 15.436   | 9.47e-07                 | 21.47           | 0.07             |

Fig. 1. Phase convolved R-band lightcurves for the δ Cep stars used to derive the distance moduli. ■ = Wendelstein 0.8 m, • = Calar Alto 1.23 m, + = measurements having \( S/N < 1 \) obtained at either site, all plotted with 1σ error bars. Top: Leo A, bottom: DDO 216.

[Riffeser et al. 2001]. The Wendelstein observations, starting with test observations in 1999, sparsely sample a five year interval in \( R \) and \( B \) filter bands. We added observations in the \( R \), \( B \) and \( I \)-bands, obtained with the 1.23 m telescope at Calar Alto (CA) observatory (Tab. I). The Wendelstein data are used to find variable sources and to determine their periodicities, while the CA data, if present, serve as an independent consistency check. The typical limiting magnitude of an individual exposure is about \( R \sim 22.5 \) (\( M_R = -2.0 \) for Leo A, \( M_R = -2.5 \) for DDO 216, \( M_R = -4.0 \) for GR8, respectively). Thus, we have access to all kinds of red long period variable stars, blue and red irregular variables, and also Novae and Supernovae but so far none of either type of exploding stars were detected. RR Lyr stars are certainly too faint, while classical δ Cep stars are well within the limits of our data. Tab. I displays the number of collected and reduced epochs so far. We restrict the results presented in this article to periods of \( P < 130 \) days, the longest period values known for δ Cep stars.
3. Data Reduction

All images were bias subtracted, flat-fielded, and cleaned of particle events. After an astro-
metrical alignment signal-to-noise maximising stacks per night were built. For every
stack, representing an epoch, a difference image against a common deep reference
frame was created applying an implementation (Gössl & Riffeser 2002, 2003) of the Alard al-
gorithm (Alard & Lupton 1998). These difference images were finally convolved with a stellar PSF. Our codes propagate individual pixel
errors through every step of the data reduction.

We find variable star candidates by first
building a (cumulative) mask frame counting where and how often individual dif-
ference frames deviate from zero by at least 1σ (i.e. propagated error). For all candidates indicated
by this variability mask, a Lomb (1976) algo-
rithm in the interpretation from Scargle (1982)
is used to search for periodic signals.

To get rid of false and problematic clas-
sifications we apply rigorous selection cri-
teria. (See detailed discussion in Hopp et al.
2005). Finally we fit the R-band period lumi-
nosity relation (PLR) for fundamental mode
(FM) LMC Cepheids $M_R = -3.04(\log P - 1.0) - 4.48[\pm0.25]$ of Madore & Freedman
(1991) corrected for galactic extinction follow-
ing Schlegel et al. (1998) to the remaining can-
didate(s) of each object. Tab. 2 lists the found
$\delta$ Cep stars, Fig. 1 and 4 show the lightcurves
of all stars used for the distance moduli.

4. Results

4.1. Leo A

For Leo A we find a distance modulus of
$m - M = 24.47 \pm 0.10 \pm 0.06_{2P}$
(Fig. 2) which is consistent with the find-
ings of Dolphin et al. (2002), Tolstoy et al.
(1998), and Schulte-Ladbeck et al. (2002).

Dolphin et al. searched for RR Lyr stars in
Leo A and derived $m - M = 24.51 \pm 0.12$. Tolstoy et al. used a combination of ground-
based and HST data to derive a tip-of-the-red-
giant-branch (TRGB) distance of $m - M = 24.5 \pm 0.2$. They also used red clump stars
yielding a discrepant $m - M = 24.2 \pm 0.2$.

4.2. DDO 216

Fitting the Madore & Freedman FM PLR to
P02, P03, and to P01 (the latter with a dou-
bled period, see below) we derive a distance modulus of $m - M = 24.92 \pm 0.20 \pm 0.06_{2P}$
(Fig. 3) for the Pegasus dwarf irregular. P01 to
P04 are four out of six candidates already in-
dependently proposed by Aparicio (1994). He
could not provide any period solutions lacking
a sufficient number of observed epochs. Using
HST imaging data (Gallagher et al. 1998) we
find P04 to be artificially brightened by crowd-
ning while P01 seems to be pulsating in the
1$^{st}$ overtone mode. We confirm the TRGB dis-
tance $m - M = 24.9 \pm 0.1$ of Aparicio.
4.3. GR8

In GR8 we only find one δ Cep star with $m_R = 21.47 \pm 0.07$ and $P = 15.44$ d (Fig. 4). We derive a distance modulus of $m - M = 26.45 \pm 0.07 \pm 0.06_{ZP}(\pm 0.25_{PLR})$ taking into account a galactic extinction of $A_R = 0.07$ [Schlegel et al. 1998]. Since this distance is based on a single detection the full intrinsic scatter of the PLR has to be considered as an additional uncertainty. This δ Cep star had already been discovered by Tolstoy et al. [1995] with $m_{\nu,0} = 22.12$ and $P = 16.166$ d. They derived a distance modulus of $m - M = 26.75 \pm 0.35$ which Dohm-Palmer et al. [1998] claim to be consistent with their HST based TRGB observations.

5. Summary

We confirmed by independent discoveries and measurements of δ Cep stars recently derived distance moduli of the three Northern Local Group dwarf irregular galaxies Leo A, DDO 216, and GR8.

References

Alard, C. & Lupton, R. H. 1998, ApJ, 503, 325
Aparicio, A. 1994, ApJ, 437, L27
Dohm-Palmer, R. C., Skillman, E. D., Gallagher, J., et al. 1998, AJ, 116, 1227
Dolphin, A. E., Saha, A., Claver, J., et al. 2002, AJ, 123, 3154
Gössl, C. A. & Riffeser, A. 2002, A&A, 381, 1095
Gössl, C. A. & Riffeser, A. 2003, in ASP Conf. Ser. 295, 229+(1)
Gallagher, J. S., Tolstoy, E., Dohm-Palmer, R. C., et al. 1998, AJ, 115, 1869
Hopp, U., Gössl, C. A., Snigula, J., & Riffeser, A. 2005, A&A, submitted
Lomb, N. R. 1976, Ap&SS, 39, 447
Madore, B. F. & Freedman, W. L. 1991, PASP, 103, 933
Riffeser, A., Fliri, J., Gössl, C. A., et al. 2001, A&A, 379, 362
Scargle, J. D. 1982, ApJ, 263, 835
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schulte-Ladbeck, R. E., Hopp, U., Drozdovsky, I. O., et al. 2002, AJ, 124, 896
Snigula, J., Gössl, C., Hopp, U., & Barwig, H. 2004, in ASP Conf. Ser. 310, 70+(1)
Tolstoy, E., Gallagher, J. S., Cole, A. A., et al. 1998, AJ, 116, 1244
Tolstoy, E., Saha, A., Hoessel, J. G., & Danielson, G. E. 1995, AJ, 109, 579