

Part 2

**What variable stars tell us
about the Local Group,
including the distance scale**

The DIRECT Project

Lucas M. Macri¹

*National Optical Astronomy Observatory, 950 N. Cherry Avenue,
Tucson, AZ 85719, USA*

Abstract. The DIRECT project aims to determine direct distances to two important galaxies in the cosmological distance ladder – M31 and M33 – using detached eclipsing binaries (DEBs) and Cepheids. I summarize the results of the project and present some results from follow-up observations.

1. Introduction

The DIRECT project (as in “direct distances”) started in 1996 with the long-term goal of obtaining distances to two important galaxies in the cosmological distance ladder – M31 and M33 – using detached eclipsing binaries (DEBs) and Cepheids. These two nearby galaxies are the stepping stones in most of the current effort to understand the evolving universe at large scales. Not only are they essential to the calibration of the extragalactic distance scale, but they also constrain population synthesis models for early galaxy formation and evolution. However, accurate distances are essential to make these calibrations free from large systematic uncertainties.

Detached eclipsing binaries have the potential to establish distances to M31 and M33 with an unprecedented accuracy of better than 5%, and possibly to better than 1%. Current uncertainties in the distances to these galaxies are in the order of 10 to 15%, as there are discrepancies of 0.2 – 0.3 mag between various distance indicators. Detached eclipsing binaries (Paczyński 1997) offer a single-step distance determination to nearby galaxies (Fitzpatrick et al. 2003) and may therefore provide an accurate zeropoint calibration for other distance indicators, including Cepheids.

2. DIRECT Observations and Results

The DIRECT project obtained time-series observations of M31 and M33 during 170 nights between 1996 September 6 and 2000 January 2 using the Fred L. Whipple Observatory 1.2-m telescope. Additional observations were carried out during 36 nights in 1996 and 1997 at the Michigan-Dartmouth-MIT Observatory 1.3-m telescope. In 1996 and 1997, images were obtained using a camera with $\sim 11' \times 11'$ field of view. In 1998 and 1999, data were collected using a camera

¹Hubble Fellow

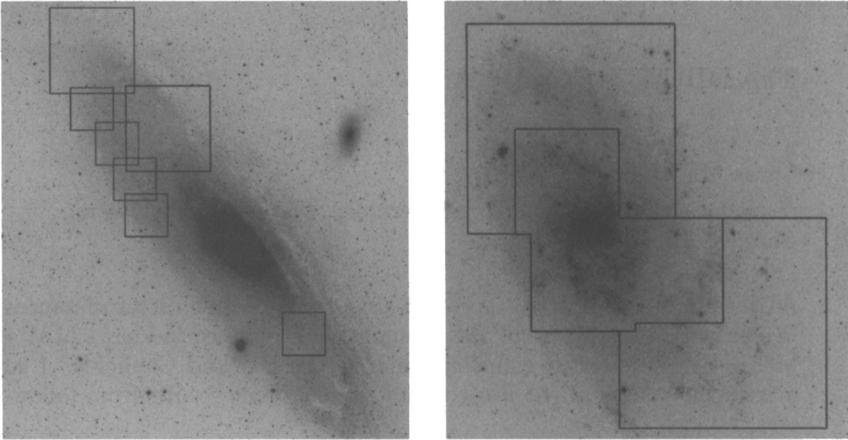


Figure 1. DIRECT fields in M31 and M33. The small and large fields are $11'$ and $22'$ on a side, respectively. M31 image: Schoening & Harvey/REU/NOAO/AURA/NSF. M33 image: DPOSS II © CalTech.

with a $\sim 22' \times 22'$ field of view. Observations were obtained mainly in the V and I bands, with some additional data in the B band. The total area covered by the observations was $\sim 0.5 \square$ in M31 and $\sim 0.3 \square$ in M33 (see Fig. 1).

Most of the fields have been analyzed and published (Bonanos et al. 2003; Kaluzny et al. 1998; Kaluzny et al. 1999; Macri et al. 2001a; Mochejska et al. 1999; Stanek et al. 1998; Stanek et al. 1999). These publications contain a total of ~ 130 eclipsing binaries, ~ 600 Cepheid variables, and ~ 500 miscellaneous variables. Representative light curves of Cepheid variables and eclipsing binaries discovered in M33 can be seen in Figs 2 and 3. Two additional publications will appear in the near future with the analysis of the remaining fields (Bonanos et al. 2004; Macri et al. 2004).

Additional publications related to the DIRECT project include: the discovery of cessation of pulsations in a long-period Cepheid in M33 (Macri, Sasselov, & Stanek 2001); the study of the influence of unresolved blends on the Cepheid Distance Scale (Mochejska et al. 2000, 2001a); a catalog of globular clusters in M31 and M33 (Mochejska et al. 1998); ancillary stellar catalogs and additional short-period variables (Macri et al. 2001b; Mochejska et al. 2001b,c,d).

3. Follow-up observations

3.1. Detached eclipsing binaries

Four promising detached eclipsing binary systems have been discovered in the DIRECT fields; two in M31 and two in M33. As a first step in their follow-up, higher quality light curves were obtained through observations conducted at the Kitt Peak National Observatory 2.1-m telescope in 1999 and 2001. Recently, a program was started to measure radial velocities of the DEBs using the Echelle Spectrograph and Imager (ESI) at Keck Observatory. Fig. 4 shows the radial

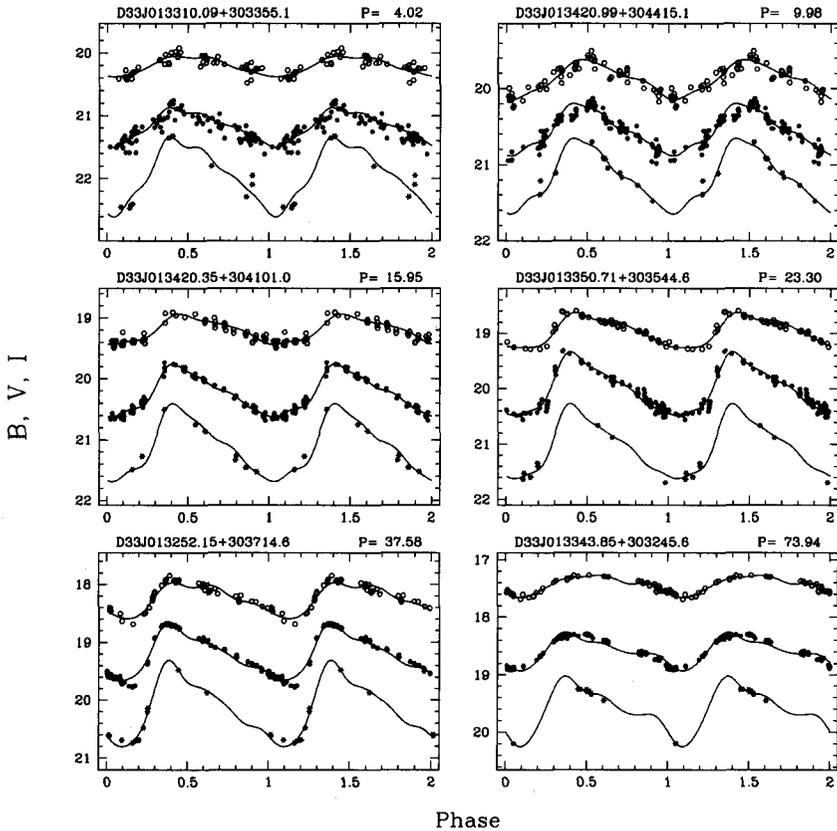


Figure 2. Representative light curves of Cepheid variables discovered by DIRECT in M33 (Macri et al. 2001a).

velocities measured for a system in M33 during the first two nights of that program, plotted against the radial velocity predicted by the photometric data.

3.2. Cepheid variables

M33 has one of the largest abundance gradients among nearby spiral galaxies, ~ 0.2 dex/kpc (Henry & Howard 1995; Monteverde, Herrero, & Lennon 2000). The DIRECT Cepheid sample in this galaxy exceeds 700 variables and covers the majority of the disk, making it ideal for a study of the metallicity dependence of the Cepheid Period-Luminosity relation. A previous observational determination (Kennicutt et al. 1998) based on a similar differential test, but using Cepheids in M101, obtained a value for the dependence in the *VI* bands that is at odds with theoretical predictions (Bono et al. 1999). However, a recent

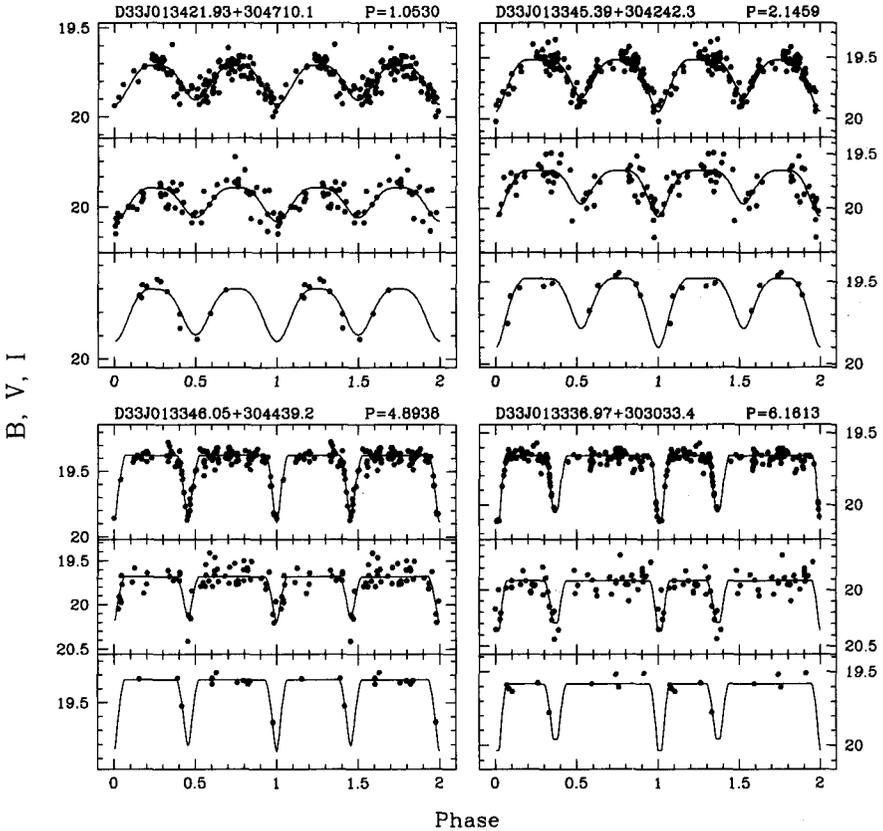


Figure 3. Representative light curves of eclipsing binaries discovered by DIRECT in M33 (Macri et al. 2001a).

analysis by Fiorentino et al. (2002) has postulated a possible solution for the disagreement.

Follow-up observations of M33 Cepheids were started in 2002 August using the MiniMosaic CCD imager at the WIYN 3.5-m telescope. Once these observations conclude in 2004 January, we expect to have obtained ~ 15 epochs in *BVI* with a greatly improved image quality relative to the original DIRECT survey ($0.7''$ vs. $1.5''$), which in turn will result in greatly improved photometric accuracy. We should be able to detect the metallicity effect predicted by Fiorentino et al. (2002) in the *BVI* bands at the 6σ level.

Additionally, we are carrying out near-infrared (*JHK_s*) observations, using the Near Infrared Imager (NIRI) on the 8.1-m Fred Gillett Gemini North telescope, of a subsample of ~ 200 Cepheids well distributed across the disk of M33. Fig. 5 shows preliminary *H* and *K_s* P-L relations for a subset of 95 variables located in the inner part of the galaxy. Once all data are collected, we should

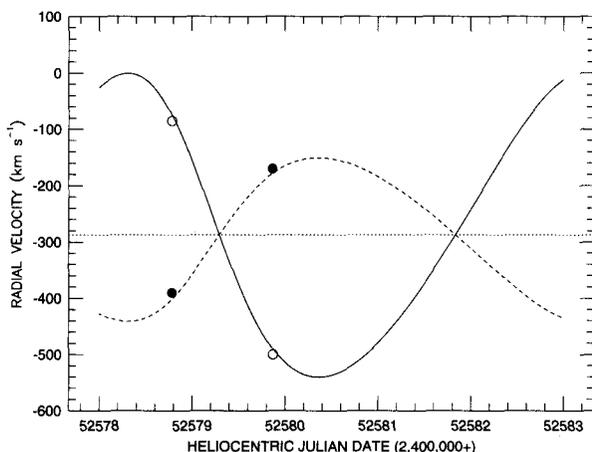


Figure 4. Radial velocities for one detached eclipsing binary system discovered by DIRECT, obtained during two nights of observation with ESI on Keck. The solid and dashed lines show the variation with phase predicted by the photometric data.

be able to detect the metallicity effect predicted by Fiorentino et al. (2002) in the K_s -band at the 4σ level.

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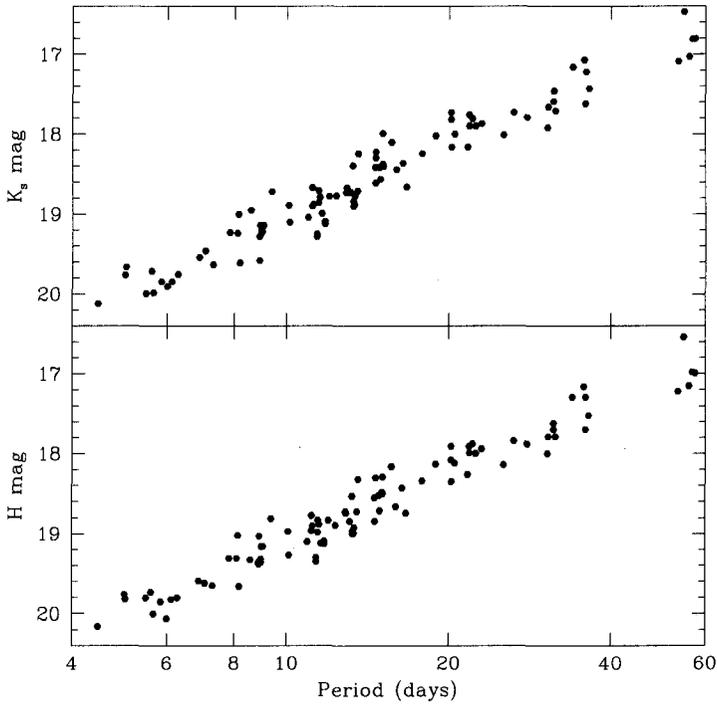


Figure 5. K_s and H -band Period-Luminosity relations for a sub-sample of 95 Cepheids located in the central part of M33. Based on observations obtained with NIRI on Gemini North.

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Discussion

Bono: Comment: The change in the slope of Cepheid PL Relations in the optical bands is also predicted by theoretical models if you account for Cepheids with periods longer than ~ 60 d.

Macri: Ok, thank you for that information.

Feast: What LMC slope did you adopt?

Macri: In the *BVI* bands we use the slopes derived by Udalski et al. (1999); in the near infrared we use the slopes derived by Persson et al (in preparation), both based on LMC Cepheids.

McNamara: Does the slope change at ~ 25 d in the P–L relations?

Macri: There seems to be a hint of that, but I would like to await the results from Cepheids in the outer regions of M33 before analyzing that possibility.

Romaniello: How do you determine the metallicity for Cepheids in M31 and M33?

Macri: For now, all we can do is rely on the metallicity gradient of the galaxy, determined from observations of H II regions and early-type stars. In a couple of years there will be direct measurements from HR spectroscopy (Barnes).

Dambis: Did you compute the Wesenheit index based on optical data and does its zero point show any dependence on galactocentric distance (metallicity)?

Macri: Yes, I have computed it, but the photometric accuracy of the original survey data was not good enough to show that variation. The follow-up observations should be accurate enough to reveal the effect.



The conference banquet was held in the International Antarctic Centre where the participants experienced the “Great White South” where the temperature was -5 C and there was a wind-chill machine to take it down to -20 C .
Participants handled the cold with aplomb!