Determining Accurate Distances to Nearby Galaxies

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ABSTRACT

We have undertaken several projects with the purpose of determining accurate distances to nearby galaxies to calibrate the extragalactic distance scale. Specifically, I describe the DIRECT project which aims to derive the distance to M31 and M33 directly, using detached eclipsing binaries and the Baade-Wesselink method for Cepheids. I also present a “hybrid” method of discovering Cepheids with ground-based telescopes using image subtraction and then following them up with the HST to derive Cepheid period-luminosity distances.

1. Introduction

Distances to extragalactic objects are known with an accuracy of less than 10-15%. This is due to the fact that standard candles available to astronomers are not completely understood theoretically and most importantly, that there are large uncertainties in the current anchor galaxy of the extragalactic distance scale, the Large Magellanic Cloud (LMC). Cepheids are examples of such distance indicators: the periods of Cepheid variables are tightly correlated with their luminosities. The correlation seems to depend on metallicity, but this dependence is not well understood and is controversial. Also, the distances to the LMC obtained with the same technique but different calibrations disagree (see Benedict et al. 2002, Figure 8). The LMC has the advantages of being nearby and easy to observe, however it introduces problems as the anchor galaxy for the extragalactic distance scale. The sources of systematic error associated with the LMC include the differential reddening across the LMC, the elongation along the line of sight, the metallicity of the galaxy and the zeropoint of the Cepheid period-luminosity (PL) relation.

The uncertainty in the LMC distance not only translates into uncertainty in the Hubble constant, but also in the calibration of stellar luminosities and in constraining population synthesis models for early galaxy formation and evolution. We therefore propose to use other nearby galaxies, such as M31 and M33, as anchors of the extragalactic distance scale bypassing the LMC and the systematic errors associated with it.
2. Hybrid Method for Measuring Distances

We have proposed a “hybrid” approach for obtaining distances to nearby galaxies with Cepheids (Bonanos & Stanek 2003). Cepheids in nearby galaxies can be discovered and characterized using large ground-based telescopes and then followed-up with the HST to obtain precise distances. We demonstrated this by re-analyzing the excellent 8.2 meter VLT data of M83, obtained by Thim et al. (2003), using the image subtraction method.

Blending must be taken into account in deriving the Cepheid distance to nearby galaxies. For example, at the distance of M83 which is $\sim 4.5$ Mpc (Thim et al. 2003), the median seeing of 0.76″ of the VLT data corresponds to 17 pc. As first discussed by Mochejska et al. (2000), blending is the close association of a Cepheid with one or more intrinsically luminous stars, which is the result of the higher value of the star-star correlation function for massive stars, such as Cepheids, compared to random field stars. This effect cannot be detected within the observed PSF by usual analysis. In M83, a large fraction of the flux of a blended Cepheid could come from its companions and would result in a significant distance bias. The discovery of Cepheids in nearby galaxies can be done adequately from the ground given good signal-to-noise photometry; however, deriving the Cepheid PL distance requires high spatial resolution HST imaging.

With the image subtraction package ISIS (Alard & Lupton 1998; Alard 2000), we were able to detect 112 Cepheids, a nine-fold increase compared to the number detected by Thim et al. (2003) with the “traditional” method of PSF photometry. We therefore demonstrate the power of image subtraction, which should especially be used in crowded fields. These additional Cepheids are valuable for determining the PL distance to M83 accurately. However, HST observations are necessary to resolve blending effects.

3. The DIRECT Project

Starting in 1996 we undertook a long term project, DIRECT (i.e. “direct distances”), to obtain the distances to two important galaxies in the cosmological distance ladder, M31 and M33. These “direct” distances will be obtained by determining the distance to Cepheids using the Baade-Wesselink method and by measuring the absolute distance to detached eclipsing binaries (DEBs). DEBs (for reviews see Andersen 1991; Paczyński 1997) offer a single step distance determination to nearby galaxies and have the potential to establish distances to M31 and M33 with an unprecedented accuracy of 5%. However, DEBs are not easy to detect since they are intrinsically rare objects (massive unevolved stars) and only certain configurations produce eclipses. Now that large-format CCD detectors are available and that CPUs are inexpensive, the DIRECT project has undertaken a massive search for periodic variables, which is producing some good DEB candidates.

We have so far analyzed observations taken with the 1.2 meter FLWO telescope of six
fields in M31, A-D, F (Kaluzny et al. 1998, 1999; Stanek et al. 1998, 1999; Mochejska et al. 1999; Macri et al. 2001, Papers I-VI) and recently field Y (Bonanos et al. 2003, Paper IX). A total of 674 variables, mostly new, were found in M31: 89 eclipsing binaries, 332 Cepheids, and 253 other periodic, possible long-period or non-periodic variables. We have analyzed two fields in M33, A and B (Macri et al. 2001, Paper VI) and found 544 variables: 47 eclipsing binaries, 251 Cepheids and 246 other variables. Follow up observations with the 2.1 meter KPNO telescope of fields M33A and M33B produced 280 and 612 new variables, respectively (Mochejska et al. 2001a,b, Papers VII, VIII).

Of the ~130 eclipsing binaries, we have found 4 DEB systems suitable for follow-up spectroscopy, 2 in M31 and 2 in M33. In October 2002, we obtained spectra of the two systems in M33 with ESI on Keck-II but did not have enough phase coverage (see Figure 1) to derive the radial velocity amplitude accurately. However, we concluded that M33A is a resolved double line eclipsing binary of early B type that is suitable for distance determination and obtained spectra with ESI on 3 more nights in September 2003. Deriving a radial velocity curve is challenging, because early type stars have few absorption lines in the visible spectrum, which are often broadened and blended. We are currently analyzing these spectra and will soon have the first direct measurement of the distance to M33.

Fig. 1.— Radial velocity curve for the 4.89 day period DEB M33A, from two nights of data on Keck-II in October 2002.

We have also undertaken the first CCD variability study of the Draco dwarf spheroidal galaxy with the FLWO 1.2 m telescope, producing 163 variable stars, 146 of which were RR Lyrae (Bonanos et al. 2004). Using the short distance scale statistical parallax calibration of Gould & Popowski (1998) for 94 RRab detected in our field, we obtained a distance
modulus of \((m - M)_0 = 19.40 \pm 0.02 \text{ (stat)} \pm 0.15 \text{ (syst)} \) mag, corresponding to a distance of \(75.8 \pm 0.7 \text{ (stat)} \pm 5.4 \text{ (syst)} \) kpc to the Draco dwarf spheroidal galaxy.

4. Summary

The need for a new anchor galaxy or preferably for several anchor galaxies to calibrate the extragalactic distance scale is long overdue. The systematic effects introduced by using the LMC as the anchor galaxy can be avoided now that 10-meter class telescopes have become available. Large telescopes can be used for the detection of Cepheids from the ground and later followed-up with the HST to obtain accurate distances, as demonstrated in M83. The DIRECT project will determine geometric distances to M31 and M33 with an accuracy of 5% with DEBs and the Baade-Wesselink method for Cepheids. Both of these Local Group galaxies are excellent anchor galaxies for the calibration of the extragalactic distance scale.

REFERENCES

Alard, C., & Lupton, R. 1998, ApJ, 503, 325

Alard, C. 2000, A&AS, 144, 363

Andersen, J. 1991, A&AR, 3, 91

Benedict, G. F., McArthur, B. E., Fredrick, L. W., Harrison, T. E., Lee, J., Slesnick, C. L., Rhee, J., et al. 2002, AJ, 123, 473

Bonanos, A. Z., & Stanek, K. Z. 2003, ApJ, 591, L111

Bonanos, A. Z., Stanek, K. Z., Sasselov, D. D., Mochejska, B. J., Macri, L. M., & Kaluzny, J. 2003, AJ, 126, 175

Bonanos, A. Z., Stanek, K. Z., Szentgyorgyi, A.H., Sasselov, D. D., Bakos, G.Á 2004, AJ, in press

Gould, A., & Popowski, P. 1998, ApJ, 508, 844

Kaluzny, J., Stanek, K. Z., Krockenberger, M., Sasselov, D. D., Tonry, J. L., Mateo, M. 1998, AJ, 115, 1016 (Paper I)

Kaluzny, J., Mochejska, B. J., Stanek, K. Z., Krockenberger, M., Sasselov, D. D., Tonry, J. L., Mateo, M. 1999, AJ, 118,346 (Paper IV)

Macri, L. M., Stanek, K. Z., Sasselov, D. D., Krockenberger, M., Kaluzny, J. 2001, AJ, 121, 870 (Paper VI)
Mochejska, B. J., Kaluzny, J., Stanek, K. Z., Krockenberger, M., Sasselov, D. D. 1999, AJ, 118, 2211 (Paper V)
Mochejska, B. J., Macri, L. M., Sasselov, D. D., & Stanek, K. Z. 2000, AJ, 120, 810
Mochejska, B. J., Kaluzny, J., Stanek, K. Z., Sasselov, D. D., Szentgyorgyi, A. H. 2001a, AJ, 121, 2032 (Paper VII)
Mochejska, B. J., Kaluzny, J., Stanek, K. Z., Sasselov, D. D., Szentgyorgyi, A. H. 2001b, AJ, 121, 2032 (Paper VIII)
Paczyński, B. 1997, in The Extragalactic Distance Scale, ed. M. Livio, M. Donahue & N. Panagia (Cambridge: Cambridge Univ. Press), 273
Stanek, K. Z., Kaluzny, J., Krockenberger, M., Sasselov, D. D., Tonry, J. L., Mateo, M. 1998, AJ, 115, 1894 (Paper II)
Stanek, K. Z., Kaluzny, J., Krockenberger, M., Sasselov, D. D., Tonry, J. L., Mateo, M. 1999, AJ, 117, 2810 (Paper III)
Thim, F., Tammann, G. A., Saha, A., Dolphin, A., Sandage, A., Tolstoy, E., & Labhardt, L. 2003, ApJ, 590, 256