Part 6

Binary stars and pulsation

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Eclipsing binaries in local group galaxies: Physical properties of the stars and calibration of the zero-point of the cosmic distance scale

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Abstract. We report on the progress of the program to study eclipsing binaries (EBs) in the Local Group galaxies. The primary goals of the program are to determine accurate distances and physical properties of the stars, and to probe the structure and evolution of the host galaxies. In particular, the distance to the Large Magellanic Cloud (LMC) is critically important because this nearby galaxy is used to calibrate most of the important cosmic distance indicators such as Cepheid and RR Lyr variables. Over the last several years, we have demonstrated that the distance of the LMC can be reliably measured using selected eclipsing binaries. The combined analyses of the UV/optical spectrophotometry, radial velocities, and light curves yield the stars' physical properties (mass, radius, $T_{\rm eff}$, luminosity, metal abundance) and accurate (2–3%) distances. So far, the physical properties and distances of four LMC EBs have been completed and give a distance to the centroid of the LMC of 48.3 ± 1.6 kpc. Several additional EBs in the LMC and the Small Magellanic Cloud have been observed and are being analyzed. Also several LMC EBs have been observed with FUSE ($92 - 119$ nm) to further refine values of $T_{\rm eff}$ and interstellar absorption. As an extension of these studies, 19–20$^{\rm th}$ mag EBs in M31 are being observed photometrically and spectroscopically. The results of this extragalactic EB program are discussed along with plans to use EBs to study the host galaxy structure.

1. Introduction

Accurate distance measurements to the major Local Group galaxies are crucial to calibrating the Cosmic Distance Scale and to determining the age and evolution of the Universe. As major rungs on the cosmic distance ladder, these galaxies serve as calibrators for distance indicators which reach far beyond the bounds of the Local Group (e.g., Hodge 1981). Once a Local Group galaxy's distance is known, all of its various stellar populations (e.g., Cepheid variables) are available as potential "standard candles".

The Large Magellanic Cloud (LMC), in particular, has been exploited for this purpose because of its proximity to the Milky Way (MWG) and the relative

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brightness of its young population. As noted by Mould et al. (2000), "*The largest contributor to the uncertainty in $H_\circ$ is the distance to the LMC, which takes up the first 6.5% of the 9% error budget.*" In spite of recent progress, there remains considerable disagreement about the LMC distance. LMC distance moduli determined from Cepheids, RR Lyrae stars, Red Clump, and other stars currently range from $18.2 < (V - M_V)_\circ < 18.7$ mag (Clementini et al. 2003), depending on the methods and data sets used. Furthermore, the independent approach of establishing the LMC distance from analysis of the expanding ring of SN 1987A yields distance moduli ranging from 18.34 to 18.55 mag (Gould & Uza 1998; Panagia 1999). The current uncertainty in the LMC distance is thus 10–15%.

The main issues when using the LMC as distance calibrator are its limited stellar content and, especially, its low metallicity (~50% solar), which have posed some difficulties, chiefly in the calibration of metallicity effects in the Cepheid period-luminosity relationship. In addition, some recent results (see below) and theoretical studies (Weinberg 2000) suggest that the LMC may have a significant line-of-sight extension and irregular geometry, which could complicate its value as a fundamental calibrator. On the other hand the Andromeda Galaxy (M31) has well defined structure and is composed of stars with properties and ages more similar to the MWG, but located some ten times farther than the LMC.

2. Results from our studies of the eclipsing binaries in the Large Magellanic Cloud

Guinan et al. (1998), Fitzpatrick et al. (2002), Ribas et al. (2002), and Fitzpatrick et al. (2003) show that the analysis of well-observed eclipsing binaries (EBs) has the potential to yield accurate distances to the binary system and thus to the host galaxy. In these studies, we analyze ground-based light curves, HST/FOS and HST/STIS UV/optical spectrophotometry (115–800 nm) and radial velocities derived from HST/GHRS (HV 2274), HST/STIS (EROS 1044), and CTIO 4-m (HV 982 and HV 5936) spectroscopy. Analysis of the light curves yields the orbital inclination, the fractional radii of the components ($r \equiv R/a$, where a is the orbital semi-major axis and R is the stellar absolute radius), and the temperature ratio. Analysis of the UV/optical spectrophotometry, using Kurucz ATLAS9 models, yields stellar temperatures to high accuracy (~1%), the reddening of the system, the metallicity, and the ratio $(R/d)^2$ (where d is the distance). Analysis of the radial velocity curves yields the stellar masses ($M \sin^3 i$) and the absolute size of the orbit ($a \sin i$). With the orbital inclination (i) known from the light curve analysis, absolute masses and orbital dimensions are determined. From a, the fractional radii can be converted into absolute stellar radii ($R = r \cdot a$) and the distance derived from the ratio $(R/d)^2$.

These distance determinations are extremely robust. The analysis consists of a detailed study of well-understood objects (B stars) in a well-understood evolutionary phase (core H burning). The results are entirely consistent with – but do not depend on – stellar evolution calculations. There are no "zeropoint" uncertainties as, for example, with the use of Cepheid variables. Neither is the result subject to sampling biases, as may affect techniques which utilize whole stellar populations, such as red giant branch stars. Moreover, the analysis is

Table 1. EBs in the sample and data status of our program for the determination of the LMC distance using eclipsing binaries.

Target	Light curve	RV curve	Spectroph.
HV 982	New Zealand	CTIO 4-m	FOS+STIS
HV 2241	La Silla	CTIO 4-m	FOS+STIS
HV 2274	New Zealand	GHRS	FOS+STIS
HV 5936	La Silla	CTIO 4-m	FOS+STIS
HV 12634	La Silla	CTIO 4-m	FOS+STIS
EROS 1044	OGLE+EROS	STIS	FOS+STIS
EROS 1066	MACHO+EROS	STIS	STIS
MACHO 82.9130.25	OGLE+MACHO	STIS	STIS
MACHO 78.6097.13	OGLE+MACHO	CTIO 4-m	STIS
MACHO 79.4779.34	OGLE+MACHO	CTIO 4-m	STIS
OGLE16_070662	OGLE+MACHO	VLT UT2	STIS
OGLE09_121729	OGLE+MACHO	VLT UT2	STIS

insensitive to stellar metallicity (although the metallicity of the stars is explicitly determined) and the effects of interstellar extinction are determined for each object studied.

The analysis described above has been completed for four systems (HV 2274, HV 982, EROS 1044, and HV 5936) and the analysis is nearly complete for two additional EBs (EROS 1066 and MACHO 82.9130.25). Table 1 gives the complete list of EBs in the sample and Fig. 1 illustrates their locations within the LMC. The orbital and stellar properties, and distances for HV 2274, HV 982, EROS 1044 and HV 5936 are given in Tables 2 and 3. Examples of the three datasets involved in the analysis can be found in Fig. 2 for HV 982.

While we concentrate on distances, EBs in the LMC provide a splendid opportunity to study the structure and evolution (opacities, convective overshooting) of stars in environments with chemical histories significantly different from the solar neighborhood (see discussion in Guinan et al. 1996). Recent estimates of the chemical abundances of young stars in the LMC indicate an decreased metal content of 1/3 to 1/2 with respect to nearby galactic stars. Moreover, the fundamental stellar properties (M, $T_{\rm eff}$, $\log g$, R, $\ldots$) determined for these LMC EBs will also yield the first *direct* determination of the mass–luminosity law for stars outside our galaxy.

3. Hints about depth and structure of the Large Magellanic Cloud

Interestingly, the distances obtained for HV 2274 and EROS 1044 and listed in Table 3 are in very good agreement, but they are not compatible at the 1σ level with the distances found for HV 982 and HV 5936. This is a tantalizing result that, given the robustness of our analysis, might be indicative of a true physical origin. Indeed, recent n-body simulations of the tidal interaction of

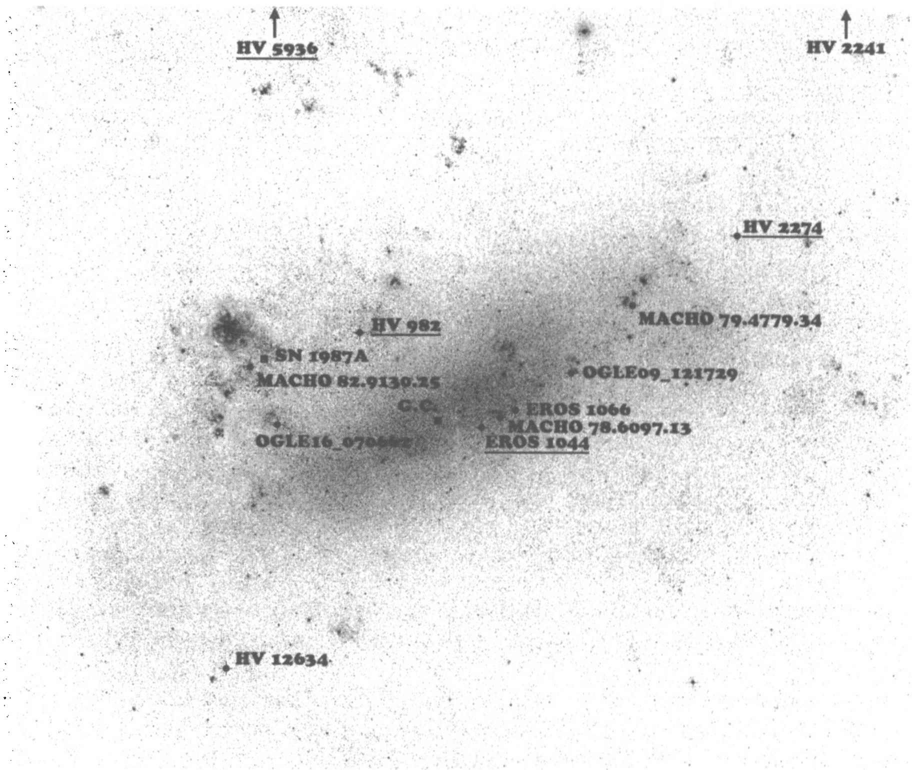

Figure 1. A photo of the LMC indicating the locations of the 12 EB systems in our program sample. The four targets with published complete studies thus far are underlined. The locations of the optical center of the LMC (G.C.) and SN 1987A are also indicated.

the MWG with the LMC indicate that its structure may be more extended and complex than presently assumed (see Weinberg 2000). Our results for these four EB systems may give a hint of such complexity. Remarkably, our distance to HV 982 (50.2 ± 1.2 kpc) is consistent to within 1σ with Panagia's (1999) estimate for SN 1987A (51.4 ± 1.2 kpc), located only $30'$ away. If our interpretation of the eclipsing binary results is correct, this suggests that the whole 30 Doradus complex may lie significantly behind the LMC disk and bar.

Further support, although not proof, for a depth hypothesis comes from a comparison of the H I emission and absorption column densities from Lyman α observations: EROS 1044 has little LMC H I in front of it, HV 2274 lies behind about 50% of the LMC H I along its line of sight, HV 5936 has no LMC H I gas in front of it, while HV 982 lies behind essentially all of the H I in its direction. EROS 1044 and HV 2274 appear to be associated with the LMC's H I disk while

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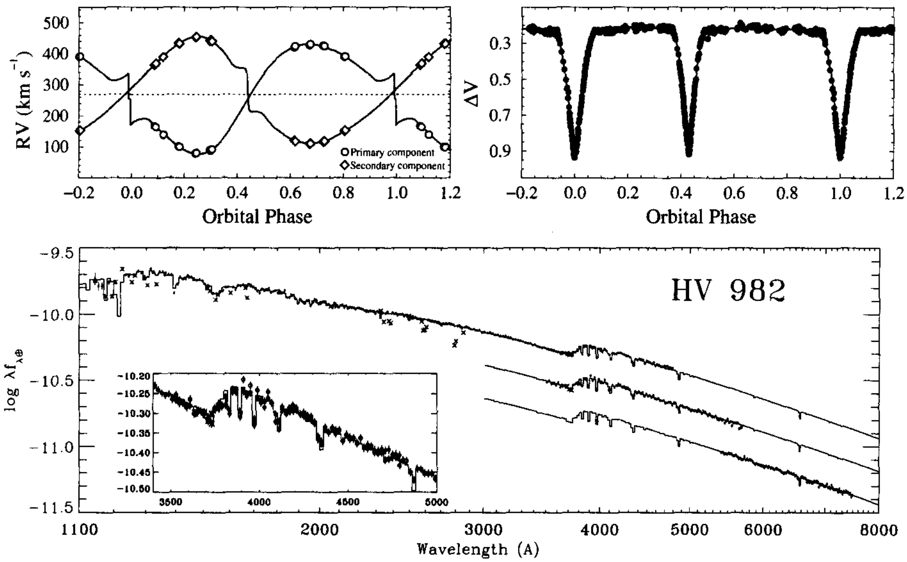

Figure 2. *Top:* Light (V band) and radial velocity curves of the LMC system HV 982. *Bottom:* The observed UV/optical energy distribution of the HV 982 system (small filled circles; FOS, STIS/G430L, STIS/G750L), superimposed with the best-fitting Kurucz *ATLAS9* atmosphere model.

HV 5926 and HV 982 could lie at any distance in front and behind the H I disk, respectively.

4. The distance to the Andromeda Galaxy using eclipsing binaries

The Andromeda Galaxy (M31) is potentially an excellent cosmic distance calibrator. Its main advantages are a simple geometry, a large and diverse stellar population and a chemical composition and morphology very similar to those of the MWG and other galaxies used for distance estimation (see Freedman et al. 1994). Also, as the nearest normal spiral galaxy, M31 can provide an absolute calibration of the important Tully-Fisher relationship. Individual EBs in M31 are fainter by about 6 mag than their counterparts in the LMC ($(V_0 - M_V)_{M31} \simeq 24.4$ mag), which has greatly limited their study. Since 1999 we have been carrying out a wide field survey ($34' \times 34'$) with the INT 2.5-m telescope at La Palma (Spain) that has led thus far to the detection of over 200 new EBs. This survey provides accurate light curves and an excellent master list of EBs from which optimal targets for further study can be selected.

Currently we are carrying out a pilot program to secure spectroscopic radial velocity curves for two EBs in M31 (see the light curves in Fig. 3). These spectroscopic observations are planned to be carried out with GMOS at the 8-m

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Table 2. Results for the LMC EBs HV 2274, HV 982, EROS 1044, and HV 5936.

	HV 2274	HV 982	EROS 1044	HV 5936
V (mag)	14.2	14.6	15.3	14.8
P (days)	5.726006(12)	5.335220(3)	2.727125(4)	2.8050681(15)
e	0.136(12)	0.156(5)	0.0	0.0
i (deg)	89.6(1.3)	89.3(7)	87.2(9)	80.0(2)
a ($R_\odot$)	38.58(93)	36.5(5)	20.5(4)	21.2(5)
γ (km s^{-1})	+312(4)	+288(3)	+261(5)	+314(6)
M_A ($M_\odot$)	12.1(7)	11.3(5)	7.1(5)	11.6(5)
M_B ($M_\odot$)	11.4(7)	11.6(5)	8.4(5)	4.7(2)
R_A ($R_\odot$)	9.84(24)	7.17(12)	4.20(13)	5.75(23)
R_B ($R_\odot$)	9.03(20)	7.83(13)	6.61(14)	6.48(16)
$\log g_A$ (cgs)	3.54(3)	3.78(2)	4.04(4)	3.98(4)
$\log g_B$ (cgs)	3.58(3)	3.72(2)	3.72(3)	3.49(3)
T_A (K)	23000(180)	24200(250)	21400(525)	26450(250)
T_B (K)	23110(180)	23600(250)	20500(470)	17600(330)
$[Fe/H]$	−0.58(6)	−0.46(5)	−0.34(6)	−0.63(5)
$E(B-V)$	0.120(9)	0.085(5)	0.066(4)	0.047(5)

Table 3. Distance data for the four LMC EBS in the program analyzed thus far. The corrections to the LMC centroid have been computed according to the LMC geometry in van der Marel & Cioni (2001).

EB system	d_{EB}		d_{LMC}		Ref.
	kpc	DM	kpc	DM	
HV 2274	47.0±2.2	18.36±0.10	47.0	18.36	1,2
HV 982	50.2±1.2	18.50±0.05	50.7	18.52	2
EROS 1044	47.5±1.8	18.38±0.08	47.4	18.38	3
HV 5936	43.2±1.8	18.18±0.09	44.7	18.25	4

References: 1. Guinan et al. (1998); 2. Fitzpatrick et al. (2002); 3. Ribas et al. (2002); 4. Fitzpatrick et al. (2003).

Gemini North telescope. As was done with the LMC EBs, we will combine the radial velocity and light curves (already in hand) and perform a detailed study with multiple scientific goals. We will determine the distances to these systems, and thus to M31, with an accuracy of ~5–7% per object. Currently the M31 distance is known to no better than ~15% (Huterer et al. 1995). In addition, this program will yield the first direct determination of masses and radii of stars in M31. These results, combined with the luminosities, will be very useful

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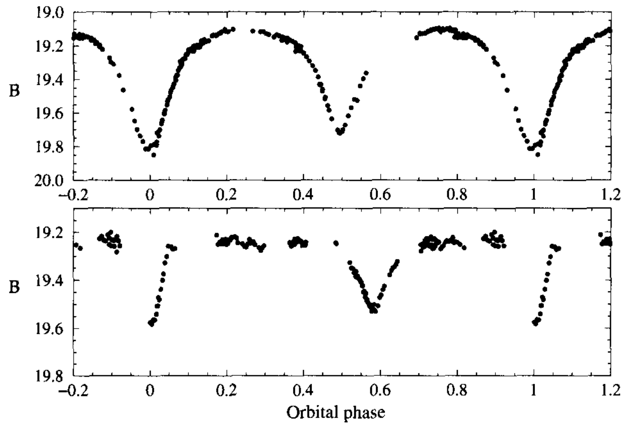

Figure 3. Light curves of two M31 EBs selected for further spectroscopic and spectrophotometric study.

for studying the structure and evolution of stars in M31 and to test massive binary-star evolution models (e.g., Wellestein et al. 2001). Also it is planned to submit a proposal to HST to obtain STIS UV/optical spectrophotometry to determine accurate stellar temperatures, chemical abundances, and interstellar absorptions.

5. Conclusions

As discussed, our combined photometric (light curves), spectroscopic (radial velocities) and UV/optical spectrophotometric observations of EBs are leading to the establishment of an accurate distance to the LMC. Currently, the average centroid distance (LMC Bar region), found from the three EBs located near the LMC center, is $d = 48.3 \pm 1.6$ kpc. Once the remaining 8 EBs in our initial program are analyzed, the LMC distance should be determined with an error better than $\sigma_{\mathrm{dLMC}} < 0.6$ kpc. Next year we plan to expand this program by securing radial velocity observations of over a hundred LMC and SMC EBs using multi-object spectroscopy (e.g., Harries et al. 2003). This should permit the determination of the physical properties and distances of large numbers of LMC and SMC stars. These data provide a probe of the depth and structure of the LMC and SMC along with reliable determinations of the mass-luminosity-radius relations for the binary component stars. In addition, we soon hope to secure the necessary spectroscopic observations of M31 EBs to permit the determination of the orbital and physical properties and also to make a first cut at an accurate distance to M31. Also important are the LMC and SMC EBs that have recently been discovered to contain Cepheid and RR Lyrae components. These systems have the potential to calibrate directly the “zero points” of the Cepheid and RR Lyrae distance scales and provide their fundamental stellar properties. In

2000 we have included in our program the two LMC EBs (OGLE16_119952 and OGLE21_40876) that have Cepheid components. Observations are underway.

At this conference, the initial results of photometric studies of several faint dwarf galaxy members of the Local Group were discussed (see Clementini et al. and Monelli et al., these proceedings). Even though these studies focused primarily on studying pulsating stars such as RR Lyr stars, Cepheids and Mira variables, they also revealed the presence of an increasing number of faint 19–23rd mag EBs in several of these lesser (but interesting) members of the Local Group. Some of the galaxies studied where EBs have been discovered include Leo I, Fornax, NGC 6822 and the Carina galaxies. The EBs in these galaxies have formed and evolved in environments far different from those of the MWG, M31 or the Magellanic Clouds. Thus, these EBs could make interesting astrophysical laboratories for studying, for example, the effects of low metal abundances and widely differing galaxy morphologies on stellar formation, structure, and evolution.

6. Acknowledgments

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Discussion

Cassisi: The method for distance measurement you have outlined still relies on theoretical ingredients as model atmospheres so what are the main error sources in this method?

Guinan: Yes. Probably the largest source of possible systematic errors arises from the model atmosphere fluxes. We do use both the Kurucz & Hubeny (Non-LTE) models to determine the fits to observed spectrophotometric flux distributions and see no significant differences in the fits using each model. Moreover, we have tested these codes with nearby single hot stars and no measurable discrepancies have been uncovered.

Chambliss: You didn't give the specifics of the LMC binaries that you have studied, but I judge that they are early B stars ($T_c = 20\,000$ to $21\,000$ K) with detached configurations. Can you extend this to late-B to early-A stars with your database?

Guinan: Most of stars in our program are detached 14.5-16th mag eclipsing binaries with spectral types of B0 V-IV to B3V-IV. It would be useful to extend the study to fainter LMC systems with spectral types of B5-A0.

Rucinski: There exist other projects, such as DIRECT, which have similar goals as your project. Is your selection of the targets done in such a way to avoid the targets of other groups, or are they the same?

Guinan: The targets are the same. The groups such as OGLE and DIRECT are generous in sharing information with us. In fact, we select the best of these targets.

Wing: Has the filter been selected yet? Can there be more than one?

Guinan: Only one broad filter is planned.