

Eclipsing Binaries: Tools for Calibrating the Extragalactic Distance Scale

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Abstract. In the last decade, over 7000 eclipsing binaries have been discovered in the Local Group through various variability surveys. Measuring fundamental parameters of these eclipsing binaries has become feasible with 8 meter class telescopes, making it possible to use eclipsing binaries as distance indicators. Distances with eclipsing binaries provide an independent method for calibrating the extragalactic distance scale and thus determining the Hubble constant. This method has been used for determining distances to eclipsing binaries in the Magellanic Clouds and the Andromeda Galaxy and most recently to a detached eclipsing binary in the Triangulum Galaxy by the DIRECT Project. The increasing number of eclipsing binaries found by microlensing and variability surveys also provide a rich database for advancing our understanding of star formation and evolution.

1. Introduction

The last decade has seen a dramatic increase in the number of extragalactic eclipsing binaries discovered. Most of these have been found as a side product of the microlensing surveys towards the Large and Small Magellanic Clouds (LMC and SMC). Starting in the early 1990s the EROS Experiment, the MACHO Project, the Microlensing Observations in Astrophysics (MOA) and the OGLE Project began monitoring the Magellanic Clouds with 1 meter telescopes in a search for dark matter in the form of massive compact halo objects. As a side product they have discovered thousands of variable stars, including many eclipsing binaries. The 75 EROS binaries in the LMC published by Grison *et al.* (1995) doubled the known binaries in the galaxy at the time. The Microlensing Observations in Astrophysics (MOA) group soon after released a catalog of 167 eclipsing binaries in the SMC (Bayne *et al.* 2002), followed by the extensive catalogs of the OGLE-II Project which comprise of 2580 eclipsing binaries in the LMC (Wyrzykowski *et al.* 2004) and 1350 in the SMC (Wyrzykowski *et al.* 2004). A catalog of the eclipsing binaries found by the MACHO project with ~ 4500 binaries in the LMC and 1500 in the SMC is underway. Note, that some of these binaries are foreground or galactic. The SuperMACHO project, using the CTIO Blanco 4-m telescope, has surveyed the Magellanic Clouds down to $V_R \sim 23$ mag (Huber *et al.* 2005), extending the sample to include solar type stars, some of which will be W UMa variables. The first extragalactic W UMa detection was recently made by Kaluzny *et al.* (2006), with photometry from the 6.5-m Magellan telescopes at Las Campanas, Chile.

Fewer eclipsing binaries are known in more distant galaxies, partly due to their faintness and the necessity of large amounts of time on medium size telescopes (2-4 meters) to obtain good quality light curves. Two microlensing surveys are underway toward M31. The Wendelstein Calar Alto Pixellensing Project (WeCAPP, Fliri *et al.* 2006) discovered 31 eclipsing binaries in the bulge of M31. The variable star catalog released by the POINT-AGAPE Survey (An *et al.* 2004) has not been searched systematically for eclipsing binaries, but is bound to contain some among the 35000 variables.

The DIRECT Project (see Stanek *et al.* 1998; Bonanos *et al.* 2003) began monitoring M31 and M33 in 1996, specifically for Cepheids and detached eclipsing binaries (DEBs) with the 1.2-m telescope on Mt Hopkins, Arizona. In M31, a total of 89 eclipsing binaries were found in the 6 fields surveyed. A variability survey using the 2.5-m Isaac Newton telescope by Vilardell *et al.* (2006) has found 437 eclipsing binaries in M31, bringing the total to over 550 eclipsing binaries. In M33, the DIRECT Project has found 148 eclipsing binaries (see Mochejska *et al.* 2001, and references within). Eclipsing binaries have also been discovered in NGC 6822, a dwarf irregular galaxy in the Local Group, by the Araucaria Project (Mennickent *et al.* 2006).

It is worth mentioning the eclipsing binaries discovered beyond the Local Group. The first such discovery was made back in 1968 by Tammann & Sandage, who presented the light curve of a 6-day period binary in NGC 2403 (M81 group) with $B \sim 22$ mag. More recently, the Araucaria Project has discovered a binary in NGC 300 (Sculptor group). Mennickent *et al.* (2004) present the light curve of the $B \sim 21.5$ mag detached eclipsing binary in this galaxy.

Finally, the discovery of 3 Cepheid binaries in the LMC by Udalski *et al.* (1999), Alcock *et al.* (2002) provides a new way of calibrating the Cepheid period-luminosity relation and the extragalactic distance scale.

2. Eclipsing Binaries as Distance Indicators

Eclipsing binaries provide an accurate method of measuring distances to nearby galaxies with an unprecedented accuracy of 5% – a major step towards a very accurate and independent determination of the Hubble constant. Reviews and history of the method can be found in Andersen (1991) and Paczynski (1997). The method requires both photometry and spectroscopy of an eclipsing binary. From the light and radial velocity curve the fundamental parameters of the stars can be determined accurately. The light curve provides the fractional radii of the stars, which are then combined with the spectroscopy to yield the physical radii and effective temperatures. The velocity semi-amplitudes determine both the mass ratio and the sum of the masses, thus the individual masses can be solved for. Furthermore, by fitting synthetic spectra to the observed ones, one can infer the effective temperature, surface gravity and luminosity. Comparison of the luminosity of the stars and their observed brightness yields the reddening of the system and distance.

Measuring distances with eclipsing binaries is an essentially geometric method and thus accurate and independent of any intermediate calibration steps. With the advent of 8-m class telescopes, eclipsing binaries have been used to obtain accurate distance estimates to the LMC, SMC, M31 and M33; these results are presented below.

3. Eclipsing Binary Distances to the Magellanic Clouds and M31

The first extragalactic distance measurement using a detached eclipsing binary system was published by Guinan *et al.* (1998), demonstrating the importance of EBs as distance indicators. The detached system 14th mag system HV 2274 was observed with the Faint Object Spectrograph (FOS) onboard the *Hubble Space Telescope*. The UV/optical spectrophotometry was used to derive the radial velocity curve and reddening. The distance to HV 2274 was determined to be 47.0 ± 2.2 kpc (Guinan *et al.* 1998, Fitzpatrick *et al.* 2002). Distances to 3 more systems in the LMC have been determined: the detached 15th magnitude system HV 982 (Fitzpatrick *et al.* 2002) at a distance of 50.2 ± 1.2 kpc, the 15th magnitude detached system EROS 1044 (Ribas *et al.* 2002) at 47.5 ± 1.8 kpc

and the 14th magnitude semi-detached system HV 5936 at 43.2 ± 1.8 kpc (Fitzpatrick *et al.* 2003). These support a “short” distance scale to the LMC, in contrast to the LMC distance of 50 kpc adopted by the Key Project (Freedman *et al.* 2001). The spread in the distances is most likely an indication of the intrinsic extent of the LMC along the line of sight.

Harries *et al.* (2003) and Hilditch *et al.* (2005) have conducted a systematic spectroscopic survey of eclipsing binaries in the SMC, obtaining fundamental parameters and distances to 50 eclipsing binary systems. Their sample was selected from the OGLE-II database of SMC eclipsing binaries as the brightest systems ($B < 16$ mag) with short periods ($P_{\text{orb}} < 5$ days) to increase the efficiency of multi-fiber spectroscopy over a typical observing run. The mean true distance modulus from the whole sample is $18.91 \pm 0.03(\text{random}) \pm 0.1(\text{systematic})$ and the implied LMC distance is $18.41 \pm 0.04(\text{random}) \pm 0.1(\text{systematic})$, again in support of the “short” distance scale.

M31 and M33, being the nearest spiral galaxies, are crucial stepping-stones in the extragalactic distance ladder. Ribas *et al.* (2005) have determined the first distance to a spiral galaxy, specifically to a semi-detached system ($V = 19.3$ mag) in M31. Note that at such distances, the location of the binary within the galaxy has an insignificant effect on the distance ($< 1\%$). Light curves for the system in M31 were obtained from the survey of Vilardell *et al.* (2006) with the 2.5-m Isaac Newton telescope and spectroscopy with the 8-m Gemini telescope using GMOS. Such stars are at the limit of current spectroscopic capabilities. The resulting distance is 772 ± 44 kpc and distance modulus is 24.44 ± 0.12 mag, in agreement with previous distance determinations to M31.

4. DIRECT Distance to a Detached Eclipsing Binary in M33

4.1. Motivation

The DIRECT Project (see Stanek *et al.* 1998; Bonanos *et al.* 2003) aims to measure distances to the nearby Andromeda (M31) and Triangulum (M33) galaxies with eclipsing binaries and the Baade-Wesselink method for Cepheids. It began surveying these galaxies in 1996 with 1-m class telescopes. The goal of the DIRECT Project is to replace the current anchor galaxy of the extragalactic distance scale, the LMC, with the more suitable spiral galaxies in the Local Group, M31 and M33. These are the nearest spiral galaxies to ours, yet more than ten times more distant than the LMC and therefore more difficult to observe stars in them. The Cepheid period-luminosity relation is used to measure distances to a few tens of Mpc, while Type Ia supernovae are used to probe distances out to a few hundred Mpc. Galaxies hosting both Cepheids and Type Ia supernovae become calibrators of the luminosities of supernovae, which are used to determine the Hubble constant, H_0 .

How is the Cepheid period-luminosity calibrated? Benedict *et al.* (2002) in their Figure 8 show 84 recent measurements of the distance modulus of the LMC using 21 methods. The large spread in the different measurements is quite disturbing. There are several problems with using the LMC as the anchor of the distance scale, which demand its replacement. The zero point of the period-luminosity relation is not well determined and the dependence on metallicity remains controversial. There is increasing evidence for elongation of the LMC along the line of sight that complicates a distance measurement. One has to additionally include a model of the LMC when measuring distances, which introduces systematic errors. Finally, the reddening across the LMC has been shown to be variable (Nikolaev *et al.* 2004), which has to be carefully accounted for. These effects add up to a 10-15% error in the distance to the LMC, which in the era of precision

cosmology is unacceptable. The replacement of the current anchor galaxy of the distance scale with a more suitable galaxy or galaxies is long overdue. Furthermore, the *Hubble Space Telescope* Key Project (Freedman *et al.* 2001) has measured the value of H_0 by calibrating Cepheids measured in spiral galaxies and secondary distance indicators and found $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This result is heavily dependent on the distance modulus to the LMC they adopt (18.50 mag or 50 kpc).

4.2. DIRECT Observations

The DIRECT project involves three stages: surveying M31 and M33 in order to find detached eclipsing binaries and Cepheids; once discovered selecting and following up the best targets with medium size telescopes (2-4 m class) to obtain more accurate light curves and lastly, obtaining spectroscopy which requires 8-10 m class telescopes. DIRECT completed the survey stage in 1996-1999 with 200 full/partial nights on 1-m class telescopes in Arizona. Follow up observations of the 2 best eclipsing binaries were obtained in 1999 and 2001 using the Kitt Peak 2.1-m telescope in Arizona. The total number of eclipsing binaries found in M33 were 237, however only 4 are bright enough ($V_{\text{max}} < 20 \text{ mag}$) for distance determination with currently available telescopes. The criteria for selection include a detached configuration (stars are well within their Roche lobes) and deep eclipses, which remove degeneracies in the modeling and a short period ($< 10 \text{ days}$) that makes follow up observations feasible.

Bonanos *et al.* (2006) presented the first distance determination to a detached eclipsing binary (DEB) in M33 that was found by Macri *et al.* (2001). D33J013346.2+304439.9 is located in the OB 66 association. Follow up optical data were obtained in order to improve the quality of the light curve and additional infrared observations were made using the 8-m Gemini telescope in order to better constrain the extinction to the system. Spectra of the DEB were obtained in 2002-2004 with the 10-m Keck-II telescope and 8-m Gemini telescope on Mauna Kea. Note that ~ 4 hours of observations per epoch were required for radial velocity measurements, a large investment of 8-10 m class telescope time. Absorption lines from both stars are clearly resolved in the spectrum, making it a double lined spectroscopic binary.

Careful modeling with non-local thermodynamic equilibrium model spectra yielded effective temperatures $T_{\text{eff1}} = 37000 \pm 1500 \text{ K}$ and $T_{\text{eff2}} = 35600 \pm 1500 \text{ K}$. The primary star is defined as the hotter star eclipsed at phase zero. We measured radial velocities from the spectra and from the light and radial velocity curves derived the parameters of the DEB components. The V -band light curve model fit for the DEB is shown in Figure 1. Note that the deviation of the secondary eclipse from phase 0.5 is due to the eccentricity of the system. The radial velocity curve is presented in Figure 2. The rms residuals are 26.0 km s^{-1} for the primary and 28.0 km s^{-1} for the secondary star. We find the DEB components to be O7 type stars with masses: $M_1 = 33.4 \pm 3.5 M_{\odot}$, $M_2 = 30.0 \pm 3.3 M_{\odot}$ and radii $R_1 = 12.3 \pm 0.4 R_{\odot}$, $R_2 = 8.8 \pm 0.3 R_{\odot}$.

4.3. Distance Determination

Having measured the temperatures of the stars from the spectra, we computed fluxes and fit the optical and near-infrared $BVRJHKs$ photometry. The best fit that minimized the photometric error over the 6 photometric bands yielded a distance modulus to the DEB and thus M33 of $24.92 \pm 0.12 \text{ mag}$ ($964 \pm 54 \text{ kpc}$). The fit of the reddened model spectrum to the photometry is shown in Figure 3.

There are several avenues for improving the distance to M33 and M31 using eclipsing binaries. Wyithe & Wilson (2002) propose the use of semi-detached eclipsing binaries to be just as good or better distance indicators as detached eclipsing binaries, which

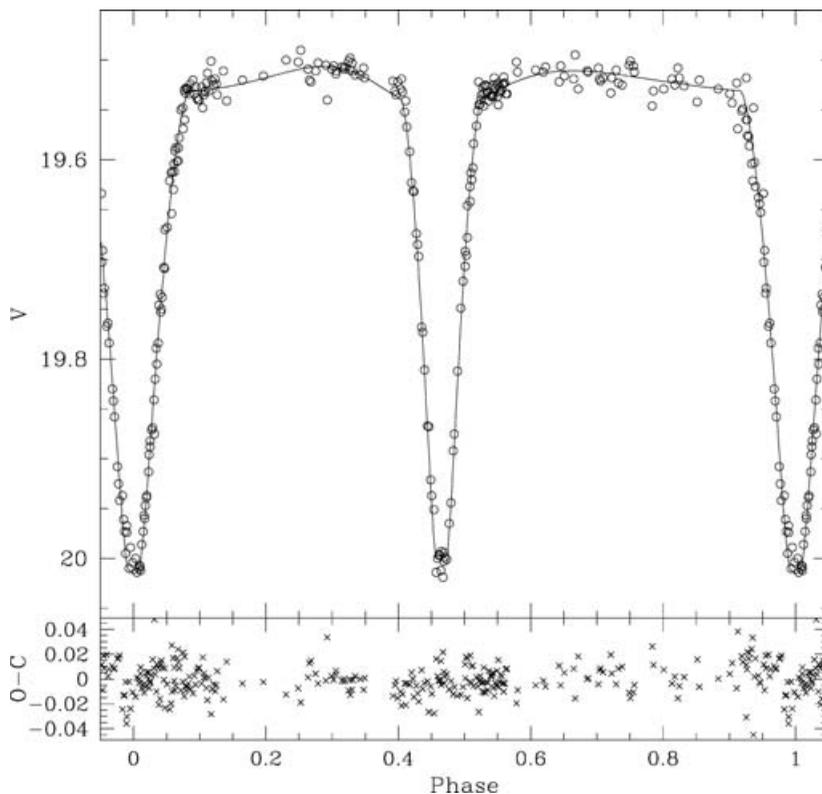


Figure 1. V -band light curve of the M33 DEB with model fit from the Wilson-Devinney program. Circles correspond to the 278 V -band observations and the solid line to the model; the rms is 0.01 mag (from Bonanos *et al.* 2006).

have been traditionally considered to be ideal. Semi-detached binaries provide other benefits: their orbits are tidally circularized and their Roche lobe filling configurations provide an extra constraint in the parameter space, especially for complete eclipses. Bright semi-detached binaries in M33 or M31 are not as rare as DEBs, and are easier to follow-up spectroscopically, as demonstrated by Ribas *et al.* (2005) in M31. Thus, for the determination of the distances to M33 and M31 to better than 5% we suggest both determining distances to other bright DEBs and to semi-detached systems found by DIRECT and other variability surveys. Additional spectroscopy of the DEB would also improve the current distance determination to M33, since the errors are dominated by the uncertainty in the radius or velocity semi-amplitude.

How does our M33 distance compare to previous determinations? Table 1 (adapted from Bonanos *et al.* 2006) presents a compilation of 13 recent distance determinations to M33 ranging from 24.32 to 24.92 mag, including the reddening values used. Our measurement although completely independent yields the largest distance with a small 6% error, thus is not consistent with some of the previous determinations. This possibly indicates unaccounted sources of systematic error in the calibration of certain distance indicators. Note the Freedman *et al.* (2001) distance to M33 is not consistent with the DIRECT measurement. This could be due to their ground based photometry which is likely affected by blending, but highlights the importance of securing the anchor of the

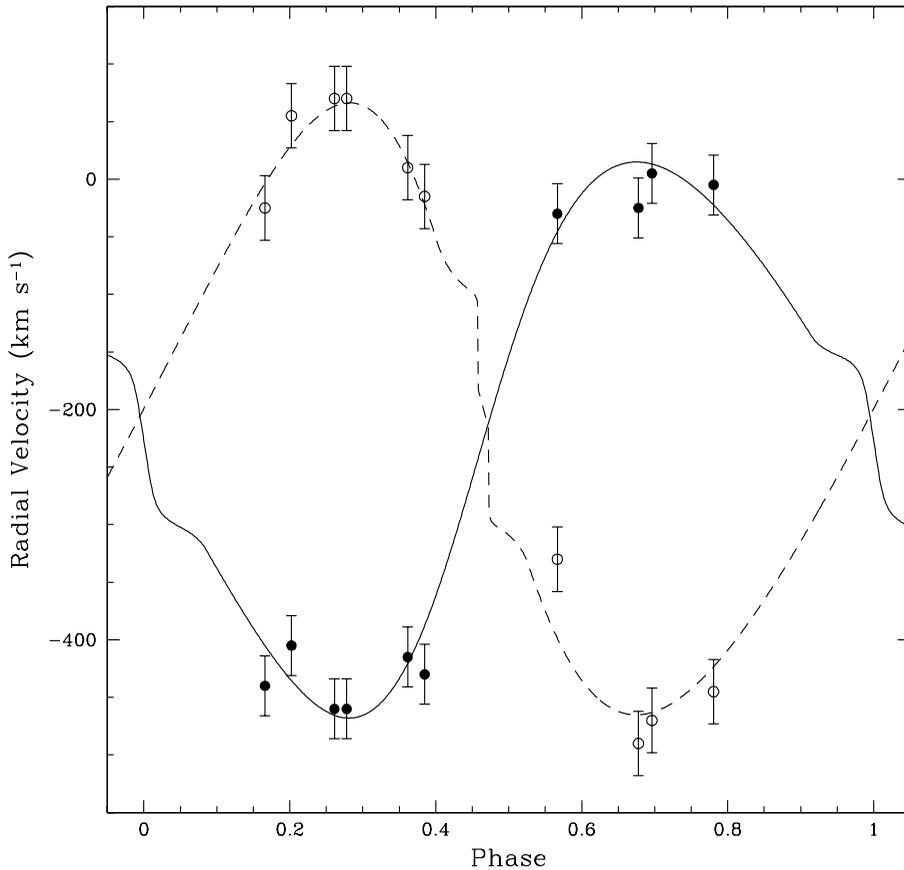


Figure 2. Radial velocities for the DEB measured by two-dimensional cross correlation with synthetic spectra. Model fit is from Wilson-Devinney program. Error bars correspond to the rms of the fit: 26.0 km s^{-1} for the primary (filled circles) and 28.0 km s^{-1} for the secondary (open circles).

extragalactic distance scale. The eclipsing binary distances to the LMC presented above indicate a shorter distance to the LMC. Combined with eclipsing binary distances to M31 and M33, we should soon be able to reduce the errors in the distance scale and thus the Hubble constant to 5% or better.

4.4. Epilogue

The accelerating rate of discovery of eclipsing binaries provides immense opportunities. With current spectroscopic capabilities it has become possible to measure distances to Local Group galaxies out to 1 Mpc, thus providing distances independent of the controversial LMC distance and the calibration of Cepheids, which most methods rely on. An independent calibration of the extragalactic distance scale has become possible. The recent distance determinations to the LMC, SMC, M31 and M33 are providing 6% distances to these galaxies that will improve over the next few years. Combined with geometric distances to the maser galaxy NGC 4258, the extragalactic distance scale will soon be anchored to several spiral galaxies (M31, M33, NGC 4258).

In addition to their use as distance indicators, eclipsing binaries provide many more opportunities to advance our understanding of star formation and evolution. In

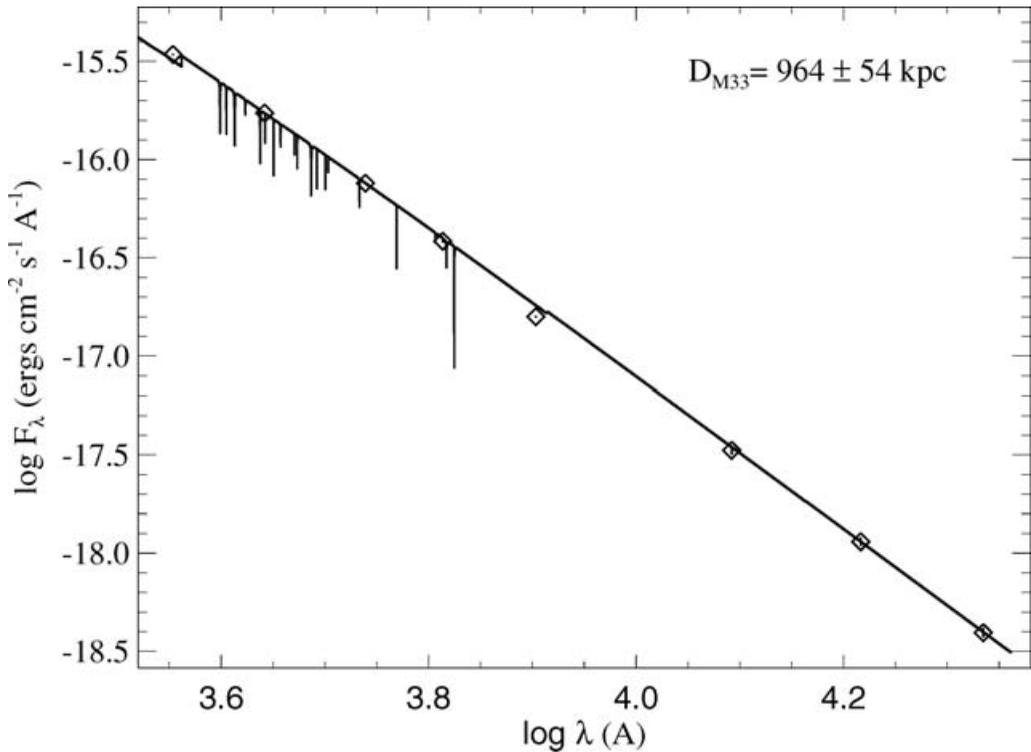


Figure 3. Fit of the reddened DEB model spectrum to the $BVRJHK_s$ ground-based photometry. Overplotted is the U and I photometry from Massey *et al.* (2006). The distance modulus to the DEB and thus M33 is found to be 24.92 ± 0.12 mag (964 ± 54 kpc).

Table 1. RECENT DISTANCE DETERMINATIONS TO M33

Study	Method ^a	Distance Modulus	Reddening
Bonanos <i>et al.</i> (2006)	DEB	24.92 ± 0.12	$E(B - V) = 0.09 \pm 0.01$
Sarajedini <i>et al.</i> (2006)	RR Lyrae	24.67 ± 0.08	$\sigma_{E(V-I)} = 0.30$
Brunthaler <i>et al.</i> (2005)	Water Masers	24.32 ± 0.45	—
Ciardullo <i>et al.</i> (2004)	PNe	$24.86^{+0.07}_{-0.11}$	$E(B - V) = 0.04$
Galleti <i>et al.</i> (2004)	TRGB	24.64 ± 0.15	$E(B - V) = 0.04$
McConnachie <i>et al.</i> (2004)	TRGB	24.50 ± 0.06	$E(B - V) = 0.042$
Tiede <i>et al.</i> (2004)	TRGB	24.69 ± 0.07	$E(B - V) = 0.06 \pm 0.02$
Kim <i>et al.</i> (2002)	TRGB	$24.81 \pm 0.04(r)^{+0.15}_{-0.11}(s)$	$E(B - V) = 0.04$
Kim <i>et al.</i> (2002)	RC	$24.80 \pm 0.04(r) \pm 0.05(s)$	$E(B - V) = 0.04$
Lee <i>et al.</i> (2002)	Cepheids	$24.52 \pm 0.14(r) \pm 0.13(s)$	$E(B - V) = 0.20 \pm 0.04$
Freedman <i>et al.</i> 2001	Cepheids	24.62 ± 0.15	$E(V - I) = 0.27$
Pierce <i>et al.</i> (2000)	LPVs	24.85 ± 0.13	$E(B - V) = 0.10$
Sarajedini <i>et al.</i> (2000)	HB	24.84 ± 0.16	$< E(V - I) > = 0.06 \pm 0.02$

[†]DEB: detached eclipsing binary; TRGB: tip of the red giant branch; PNe: planetary nebulae; RC: the red clump; LPVs: long period variables; HB: horizontal branch stars.

particular, they provide direct means of measuring masses, radii and luminosities of stars. For example, applications to the extremes of stellar mass ranges are underway in order to provide constraints to theoretical models of stellar atmospheres and evolution, such as for M-dwarfs and at the other extreme for very massive ($> 50 M_{\odot}$) O-stars and

Wolf-Rayet stars. Future projects such as the wide field imaging surveys Pan-STARRS and the Large Synoptic Survey Telescope (LSST) will survey the sky down to 24th mag and yield thousands of binaries in the Galaxy, the Local Group and beyond.

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Discussion

CARLSON CHAMBLISS: A problem with very distant eclipsing binaries is that the component stars are necessarily very hot. This leads to substantial uncertainties in bolometric corrections since the photometry is *UBV*. Is this a major source of error?

BONANOS: We have used one of the best available non-LTE codes (from Rolf Kudritzki's group) to determine the temperatures of these stars. We do not use bolometric corrections, but fit synthetic photometry of the reddened model spectrum to observed optical and infrared photometry. Finally, we have adopted a conservative error in the temperature of 1500K.