

THE DISTANCE TO THE LARGE MAGELLANIC CLOUD FROM THE ECLIPSING BINARY HV 2274

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ABSTRACT

The distance to the Large Magellanic Cloud (LMC) is crucial for the calibration of the cosmic distance scale. We derive a distance to the LMC based on an analysis of ground-based photometry and *Hubble Space Telescope* (*HST*)–based spectroscopy and spectrophotometry of the LMC-eclipsing binary system HV 2274. Analysis of the optical light curve and the *HST*/Goddard High-Resolution Spectrograph, radial velocity curve provides the masses and radii of the binary components. Analysis of the *HST*/Faint Object Spectrograph, UV/optical spectrophotometry provides the temperatures of the component stars and the interstellar extinction of the system. When combined, these data yield a distance to the binary system. After correcting for the location of HV 2274 with respect to the center of the LMC, we find $d_{\text{LMC}} = 45.7 \pm 1.6$ kpc or $(V_0 - M_v)_{\text{LMC}} = 18.30 \pm 0.07$ mag. This result, which is immune to the metallicity-induced zero-point uncertainties that have plagued other techniques, lends strong support to the “short” LMC distance scale as derived from a number of independent methods.

Subject headings: binaries: eclipsing — distance scale — Magellanic Clouds — stars: distances — stars: fundamental parameters — stars: individual (HV 2274)

1. INTRODUCTION

We present the first accurate distance determination to the Large Magellanic Cloud (LMC) using an eclipsing binary system, which resulted from an international collaboration studying the physical properties of these important objects. This program includes both ground-based and *Hubble Space Telescope* (*HST*) observations and is aimed primarily at determining the stellar properties (masses, radii, luminosities, and ages) and the distances of about a dozen selected $14 < V < 16$ mag eclipsing binaries in the Clouds (see Guinan, Bradstreet, & DeWarf 1996). It is well known that studies of eclipsing binaries yield the most fundamental determinations of the basic stellar properties. We demonstrate here their great value as “standard candles” for distance determination.

The distance to the LMC is a critical rung on the cosmic distance ladder, and numerous independent methods (utilizing, for example, RR Lyrae stars, Cepheids, SN 1987a, and “red clump” stars) have been employed to determine it. Unfortunately, and despite the use of the eagerly awaited *Hipparcos* parallaxes, there remains considerable disagreement about this important measurement, and as summarized by Cole (1998; see also Westerlund 1997), the current uncertainty is about 10%–15%. In this Letter, we show that the analysis of several eclipsing LMC binaries could reduce the uncertainty in the LMC distance to the level of several percent.

These first results deal with the LMC-eclipsing binary Harvard Variable 2274 (hereafter HV 2274; $\langle V \rangle_{\text{max}} \approx 14.2$; B1–2 IV–III + B1–2 IV–III; $P = 5.73$ days). This system is relatively bright, lightly reddened, and has complete CCD light curves showing it to have deep eclipses and uncomplicated

out-of-eclipse light variations (Watson et al. 1992). Moreover, it is a detached system with nearly identical bright stars located in an uncrowded field. To provide an accurate distance to the system and hence the LMC, absolute radii, temperatures, and reddening corrections are needed (Guinan 1993; Giménez et al. 1994; Guinan et al. 1996). The radii are obtained from the light and radial velocity curves and the temperatures and reddening from UV/optical spectrophotometry. The following sections present the *HST* and ground-based observations used in this study (§ 2), describe our analysis techniques (§ 3), and present our distance determination for the LMC along with a discussion of the uncertainties in this result (§ 4).

2. OBSERVATIONS

The ground-based *V*-band light-curve data for HV 2274 are taken from Watson et al. (1992) and are shown in the lower panel of Figure 1 (*crosses*). The light curve is well defined and shows two minima of about equal depth (~ 0.7 mag) and nearly constant light outside of the eclipses. The more shallow minimum (secondary eclipse) occurs at orbital phase 0.53, indicating an eccentric orbit ($e = 0.136$). We also adopt the very recently available *V* and *B* – *V* measurements from Udalski et al. (1998), i.e., $V = 14.16$ and $B - V = -0.13$.

The spectrophotometry and radial velocity curves needed to complete the analysis of HV 2274 were obtained by *HST* as part of our larger project on eclipsing binaries in the Clouds. Four Faint Object Spectrograph (FOS) spectra, covering four different wavelength regions, were acquired, calibrated, and merged to produce a single spectrum spanning 1150–4820 Å. These observations were made at orbital phases outside of the eclipses, when both stars were completely unobscured.

We also obtained 16 *HST*/Goddard High-Resolution Spectrograph (GHRS) medium-resolution ($R = 23,000$) spectra at a number of selected orbital phases in order to construct the radial velocity curve. The spectra covered 34 Å and were centered at two different wavelengths: one near 1305 Å and the other near 1335 Å. These regions contain strong UV photospheric lines in early-B stars (see Massa 1989). Stellar Fe III $\lambda 1292.2$, Si III 1300 Å triplets ($\lambda\lambda 1294.5, 1296.7, \text{ and } 1298.9$), and C II $\lambda 1323.9$ were fitted with double Gaussians, which

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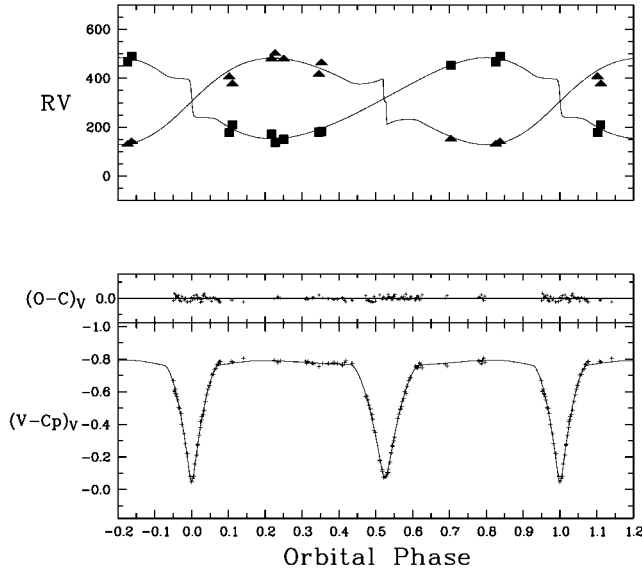


FIG. 1.—The upper panel shows the radial velocity measurements of the two components of the HV 2274 binary system as derived from medium-resolution *HST*/GHRS spectra (*filled symbols*) and the radial velocity curve solution derived from the Wilson-Devinney analysis (*solid curves*). The discontinuous jumps seen in the model curves, known as the “Rossiter effect,” occur when rotating stars are partially eclipsed. The lower panel shows the ground-based light-curve data from Watson et al. (1992), based on differential photometry (variable minus comparison) in the *V* band (*V-Cp*; *crosses*). The fit to the light curve is shown (*solid curve*) as well as the observed minus computed residuals (*O-C*).

gave the radial velocities for each component. The individual line measurements for each component were averaged to obtain its radial velocity at each phase. In the upper panel of Figure 1, these radial velocities are plotted against orbital phase as determined by Watson et al. (1992; *filled symbols*). The mean uncertainties in the radial velocity measures are approximately $\pm 15 \text{ km s}^{-1}$.

3. ANALYSIS

3.1. Modeling Light and Radial Velocity Curves

The radial velocity and light-curve data were analyzed using an improved Wilson-Devinney light-curve analysis code (Wilson & Devinney 1971; Wilson 1990) that includes Kurucz atmosphere models for the computation of the stellar radiative parameters (Milone et al. 1994). The Wilson-Devinney code is a standard tool in the analysis of eclipsing binaries.

The radial velocity and the light-curve solutions for HV 2274 are shown in the top and bottom panels of Figure 1, respectively (*solid curves*). For the light curve, the differences between observed and computed values at $V [(O-C)_V]$ are also shown. Table 1 lists the values determined for the orbital period (P), eccentricity (e), orbital inclination (i), longitude of periastron (ω), velocity semiamplitudes (K), systemic velocity (γ), temperature ratio (T_B/T_A), luminosity ratio (L_B/L_A), absolute stellar radii (r), masses (M), and surface gravities (g).

The accurate measurement of the radii (r) of the components is critically important for deriving the distance to HV 2274. The radii are determined by combining the fractional radii ($r_f = r/a$) obtained from the light-curve analysis with the orbital semimajor axis (a) derived chiefly from the spectroscopic orbit. Thus, the absolute radius of each star is $r = r_f a$, and the calculated uncertainties in the radii are about 2.3%. The precision

TABLE 1
ORBITAL AND STELLAR PARAMETERS

Orbital Solution and Stellar Properties ^a	
$P = 5.726006(12)$ days	$e = 0.136(12)$
$i = 89^\circ 6(1.3)$	$a = 38.58(93) R_\odot$
$\omega(1990.6) = 73^\circ 3(1.5)$	$\gamma = 312(4) \text{ km s}^{-1}$
$K_A = 166.2(5.9) \text{ km s}^{-1}$	$K_B = 177.3(5.8) \text{ km s}^{-1}$
$T_B/T_A = 1.005(5)$	$L_B/L_A(V) = 0.844(5)$
$r_A = 9.84(24) R_\odot$	$r_B = 9.03(20) R_\odot$
$M_A = 12.1(4) M_\odot$	$M_B = 11.4(4) M_\odot$
$\log g_A = 3.54(3)$	$\log g_B = 3.58(3)$
Stellar Properties from UV/Optical Spectrophotometry ^b	
$T_A = 23000(180) \text{ K}$	$T_B = 23110(180) \text{ K}$
$[\text{Fe}/\text{H}]_{AB} = -0.45(6)$	$\mu_{AB} = 1.9(7) \text{ km s}^{-1}$
$E(B - V) = 0.120(9) \text{ mag}$	$(r_A/d)^2 = 2.249(63) \times 10^{-23}$
Distance to HV 2274	
$d = 46.8(1.6) \text{ kpc}$	$V_0 - M_v = 18.35(0.07) \text{ mag}$
Distance to Center of LMC	
$d = 45.7(1.6) \text{ kpc}$	$V_0 - M_v = 18.30(0.07) \text{ mag}$

^a The uncertainties in the parameters resulting from the light-curve and radial velocity curve analyses were set at 3 times the rms scatter of several solutions obtained from different initial conditions.

^b The uncertainties in the parameters derived from the analysis of the UV/optical spectrophotometry are 1σ internal errors derived from a nonlinear least-squares fitting procedure (see § 3.2).

achievable in the measurement of fundamental properties, such as radius, is one of the keys to the usefulness of eclipsing binaries as standard candles.

3.2. Modeling the Spectrophotometry

The observed energy distribution of HV 2274, $f_{\lambda\oplus}$, as obtained by the FOS between 1150 and 4800 Å is shown in Figure 2 (*filled circles*; the lower of the two full spectra). The observed fluxes depend both on the surface fluxes of the binary’s components and on the attenuating effects of distance and interstellar extinction. This relationship can be expressed as

$$f_{\lambda\oplus} = \frac{1}{d^2} (r_A^2 F_\lambda^A + r_B^2 F_\lambda^B) \times 10^{-0.4A(\lambda)} \quad (1)$$

or, substituting for the total extinction, $A(\lambda)$,

$$f_{\lambda\oplus} = \left[\frac{r_A^2}{d^2} \right] [F_\lambda^A + (r_B/r_A)^2 F_\lambda^B] \times 10^{-0.4E(B-V)[k(\lambda-V)+R]}, \quad (2)$$

where F_λ^i [$i = A, B$] are the emergent fluxes at the surfaces of the two components of the binary, the r_i are the radii of the components, and d is the distance to the binary. $A(\lambda)$ is the total extinction along the line of sight to the system at each wavelength λ and is expressed in equation (2) as a function of $E(B - V)$, the normalized extinction curve $k(\lambda - V) \equiv E(\lambda - V)/E(B - V)$, and the ratio of selective to total extinction in the *V* band $R \equiv A(V)/E(B - V)$. Our analysis consists of modeling the observed energy distribution of HV 2274 via a nonlinear least-squares procedure to derive values of the parameters $(r_A/d)^2$, F_λ^i , $E(B - V)$, and $k(\lambda - V)$ in equation (2).

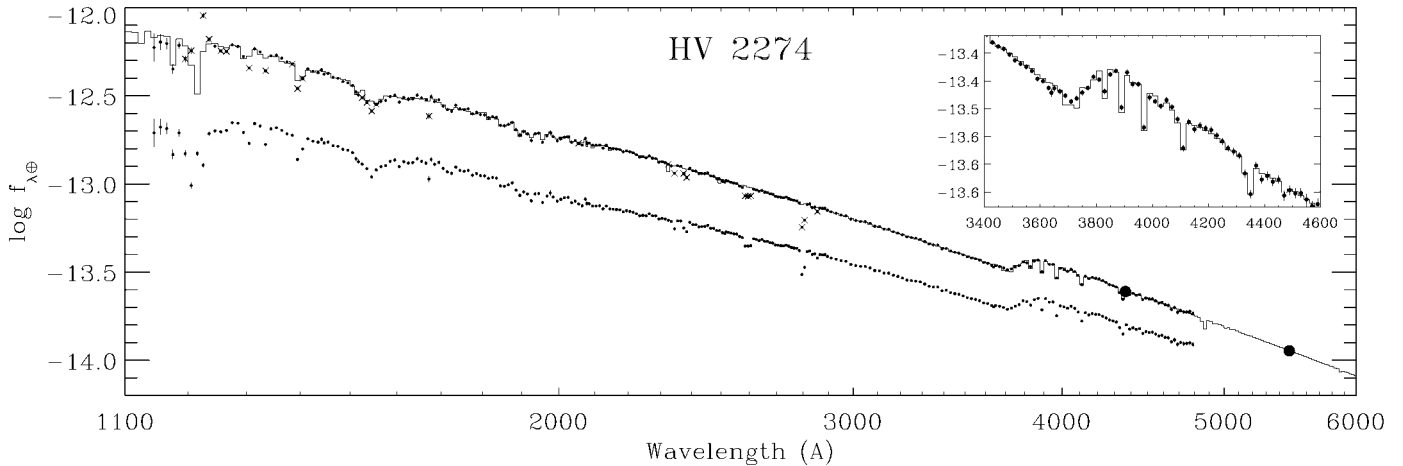


FIG. 2.—The UV/optical energy distribution of HV 2274, in units of $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$. The lower full spectrum shows the observed *HST*/FOS energy distribution; the upper spectrum shows the extinction-corrected energy distribution, superimposed with the best-fitting ATLAS9 atmosphere model (plotted in histogram style). The vertical lines through the data points indicate the 1σ observational errors. The crosses indicate data points excluded from the fit because of contamination by interstellar absorption lines. The large filled circles show dereddened *B* and *V* photometry from Udalski et al. (1998). An expanded view of the fit near the Balmer jump is shown within the inset.

Ultimately, the distance to the binary will be determined from $(r_B/r_A)^2$.

We represent the stellar surface fluxes F_λ^i by ATLAS9 atmosphere models from R. L. Kurucz, which each depend on four parameters: effective temperature (T_{eff}), surface gravity (g), metallicity (normally z), and microturbulence velocity (μ). The eight parameters needed to define the surface fluxes of the two binary components are constrained by the results of the light and radial velocity curve analyses, and we adopt the effective temperature ratio T_B/T_A and $\log g$ values listed in Table 1. In addition, we assume that both components of the binary have the same metallicity and the same microturbulence velocity. The ratio of the stellar radii $(r_B/r_A)^2$ in equation (2) is determined from the light and radial velocity curve solutions (see Table 1), and we adopt the standard Galactic value of $R = 3.1$ (see § 4).

The normalized extinction curve $k(\lambda - V)$ is modeled using the results of Fitzpatrick & Massa (1990), who showed that the functional form of the extinction wavelength dependence in the UV is tightly constrained. The parameters describing the shape of the curve are determined from the fitting procedure. The method of smoothly joining UV and optical extinction curves is discussed by Fitzpatrick (1999).

This technique of solving simultaneously for both the stellar parameters of a reddened star and the shape of the UV/optical extinction curve is described in detail by Fitzpatrick & Massa (1999; FM99). They demonstrate that the new ATLAS9 models can reproduce the observed UV/optical continua of unreddened main-sequence (and slightly evolved) B stars to a level consistent with the uncertainties in currently available spectrophotometric data. They further show that both the model atmosphere parameters and the wavelength dependence of interstellar extinction can be extracted from analysis of UV/optical spectra of reddened stars. This is possible because the spectral “signature” of interstellar extinction is very different from the “signatures” of temperature, surface gravity, metallicity, or microturbulence.

The dereddened energy distribution of HV 2274 is shown as the upper spectrum in Figure 2 (small filled circles with observational error bars) superposed with the best-fitting

model (solid histogram curve). The inset shows a blowup of the Balmer jump region. The dereddened *V* and *B* data from Udalski et al. (1998), converted to flux units, are shown by the large filled circles. The excellence of this fit (the reduced χ^2 is close to 1) is illustrative of the fits achieved by FM99 for B stars in general. The parameters of the fit are listed in Table 1. For B-type stars, the “metallicity” measured from modeling the UV/optical flux is most heavily influenced by absorption from iron-group elements in the UV region. Therefore, in Table 1, we refer to the derived metallicity as $[\text{Fe}/\text{H}]$, and the result is quite reasonable for an LMC star. The uncertainties indicated in Table 1 are 1σ internal errors and incorporate the full covariance (or interdependence) of all the parameters. That is, if any of the parameters are changed by $\pm 1 \sigma$, the total χ^2 of the best fit—after all the other parameters are reoptimized—increases by 1. The small size of these uncertainties is testament to the lack of covariance among the parameters and the quality of the data.

The best-fit model found in this Letter differs significantly from that reported in an earlier version of this work (Guinan et al. 1998). This results entirely from the inclusion here of the *V* and *B - V* measurements from Udalski et al. (1998). The earlier work incorporated very uncertain optical photometry from Watson et al. (1992), but these data were weighted so low that results were based essentially entirely on the FOS data. This had an important effect because, unless the observations extend through the 4400–5500 Å region, a possible degeneracy exists between the best-fit values of $E(B - V)$ and the normalized extinction curve $k(\lambda - V)$. That is, very similar relative extinction corrections, $E(B - V) \times k(\lambda - V)$, can be obtained with a range of $E(B - V)$ values. In Guinan et al. (1998), the degeneracy region was found to be $E(B - V) \approx 0.08\text{--}0.12$, with the best fit given by $E(B - V) \approx 0.08$ —the solution reported in that paper. This result appeared reasonable since, combined with the Watson et al. photometry ($B - V = -0.18$), it yielded an intrinsic color of $(B - V)_0 \approx -0.26$, which is compatible with the spectral type of HV 2274. Using the more accurate (and thus more heavily weighted) Udalski et al. photometry, the reddening degeneracy disappears, and a reasonable fit to the entire observed spectrum

can only be achieved with $E(B - V) = 0.12$ —a value at the opposite end of the degeneracy “valley” from that reported in Guinan et al. (1998), as expected from Murphy’s Law.

4. THE DISTANCE TO THE LMC

The distance to HV 2274 is computed from the values of $(r_A/d)^2$ and r_A derived above, and the uncertainty in this result is found by propagating the uncertainties in each quantity. The total uncertainty in $(r_A/d)^2$ has internal and external components. The internal 1σ fitting error is listed in Table 1. The external effects include uncertainty in the extinction ratio R , which we take to be $1\sigma(R) = \pm 0.3$, and uncertainty in the zero point of the FOS spectrophotometry, which we assume to be $1\sigma(\text{FOS}) = \pm 2\% - 3\%$ (Bohlin 1996; Bless & Percival 1996). Quadratically combining these independent influences yields a total uncertainty of $\sigma[(r_A/d)^2] \approx 4.5\%$. The uncertainty in r_A is taken from the Wilson-Devinney analysis and is listed in Table 1. From these results, we derive $d_{\text{HV 2274}} = 46.8 \pm 1.6$ kpc or $(V_0 - M_v)_{\text{HV 2274}} = 18.35 \pm 0.07$ mag. This result is 0.14 mag smaller than that reported by Guinan et al. (1998) because of the resolution of the aforementioned reddening degeneracy.

To obtain the distance to the center of the LMC, the above result must be corrected for the position of HV 2274 in the LMC. The line of sight to the HV 2274 binary system projects onto the end of the western region of the central bar of the LMC. The *HST*/GHRS spectra show strong interstellar medium lines from LMC gas in O I $\lambda 1302.2$ and Si II $\lambda 1304.4$. These lines show only one component with a heliocentric radial velocity of 285 km s^{-1} , similar to the HV 2274 systemic velocity of 312 km s^{-1} . These data suggest that HV 2274 lies in or close to the disk of the LMC. To transform the distance of HV 2274 to the LMC optical center, we assumed that the position angle of the line of nodes is 168° and that the disk inclination is 38° (Schmidt-Kaler & Goehermann 1992). Simple trigonometry then implies that HV 2274 is located on the farside of the LMC, about 1100 pc behind the center. The distance of the center of the LMC is then $d_{\text{LMC}} = 45.7 \pm 1.6$ kpc or $(V_0 - M_v)_{\text{LMC}} = 18.30 \pm 0.07$ mag.

This result lends strong support to the “short” LMC distance scale (see Cole 1998). Its importance, however, lies not only in the value of the distance itself but in the precision that appears possible from using eclipsing binaries. This precision can be understood by noting two facts: (1) the values of $\log g$ for the two binary members are *very* well determined by the light and radial velocity curve analysis, and (2) the best-fitting model atmosphere reproduces the HV 2274 energy distribution over the entire observed range (1200–5500 Å) to within the small observational uncertainties (see Fig. 2). These imply that the stellar temperature must—like the gravity—be well determined, since features such as the Balmer jump are sensitive to both properties. Furthermore, a correct temperature could not be found unless the distorting effects of interstellar extinction were properly estimated and removed, since the possibility of a degeneracy in the reddening solution has been eliminated by the inclusion of *V*-band data in the analysis (§ 3.2). Finally, we note that this technique is immune to the metallicity-induced zero-point uncertainties that have plagued many other LMC distance estimates because the determination of the stellar metallicity is an explicit part of the analysis and because the derived distance is actually extremely insensitive to the metallicity.

The result from a single binary system—as precise as it appears to be—does not by itself resolve the LMC distance issue. Unanticipated external systematic effects, such as a peculiar location of the star within the LMC, could compromise the derived distance. Such effects can only be addressed through the analysis of more systems, preferably with a variety of locations within the LMC and covering a range of stellar properties. The ultimate precision of the LMC distance will best be evaluated by the range of results derived from such analyses. The results presented here, however, demonstrate the power of eclipsing binaries to address fundamental astrophysical issues, such as the derivation of basic stellar properties, and cosmologically important issues, such as the LMC distance.

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