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# A PROJECT TO DETERMINE AN ACCURATE DISTANCE TO M31 USING ECLIPSING BINARIES AS STANDARD CANDLES

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RESUMEN

La galaxia de Andrómeda (M31) es potencialmente un calibrador clave para la Escala Cósmica de Distancias, y por ello, para la determinación de la edad y la evolución del Universo. Actualmente la distancia a M31 se conoce con una incertidumbre del ∼15%. Con nuestro trabajo sobre la Gran Nube de Magallanes hemos demostrado que las binarias eclipsantes con líneas dobles constituyen excelentes indicadores de distancia. Estas distancias son básicamente geométricas y están libres de las muchas hipótesis e incertidumbres que sufren otros métodos menos directos. Presentamos aquí la extensión de nuestro proyecto sobre las binarias eclipsantes como indicadores estandares de distancias a M31. Las observaciones fotométricas que propocionan las curvas de luz se están realizando con el telescopio Isaac Newton de 2.5 m en el Observatorio del Roque de los Muchachos (La Palma). Las observaciones espectrofotométricas estan previstas para el *Telescopio Espacial Hubble*, y la adquisición de espectros para las curvas de velocidad radial obligará a recurrir a grandes telescopios (por ejemplo el GTC), dadas las magnitudes aparentes de las binarias en estudio ($V \sim 19$–20). Basándonos en nuestra experiencia previa, esperamos reducir la incertidumbre en la distancia a M31 por debajo del 5%, lo que implicará una calibración firme de la Escala Cósmica de Distancias.

ABSTRACT

The Andromeda Galaxy (M31) is potentially a crucial calibrator for the cosmic distance scale and thus for determining the age and evolution of the Universe. Yet currently, the distance to M31 is known to no better than ∼15%. We have demonstrated in our work on the distance of the Large Magellanic Cloud that double-line eclipsing binaries can serve as excellent "standard candles". Distances derived from eclipsing binaries are basically geometric and essentially free from many assumptions and uncertainties that plague other less direct methods. We present the extension of our program of using eclipsing binaries as standard candles to determine an accurate distance to M31. The photometric observations that will provide the light-curves are under way with the Isaac Newton Telescope at the Roque de los Muchachos Observatory (La Palma). Spectrophotometric observations will be conducted with the *Hubble Space Telescope*, and large ground-based telescopes (for example, the GTC) will be necessary to acquire the spectra for the radial velocity curves because of the faintness of the target stars ($V \sim 19$–20). Based on our previous experience, we expect to reduce the uncertainty of the distance of M31 to better than 5%, thereby firmly calibrating the cosmic distance scale.

*Key Words:* **BINARIES: ECLIPSING — COSMOLOGY: DISTANCE SCALE — GALAXIES: LOCAL GROUP — STARS: EARLY-TYPE — STARS: EVOLUTION**

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## 1. INTRODUCTION

Accurate distance measurements to the Local Group galaxies are crucial for calibrating the cosmic distance scale, and for determining the age and evolution of the Universe. As the first rungs on the cosmic distance ladder, these galaxies serve as calibrators for distance indicators that reach far beyond the bounds of the Local Group. 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 and the relative brightness of its young population. However, its limited stellar content and especially its low metallicity (∼ 50% solar) have posed some difficulties, chiefly in the calibration of metallicity effects in the Cepheid period–luminosity relationship. In addition, some recent results (Weinberg 2000) suggest that the LMC may have a significant line-of-sight extension, which compromises its value as a fundamental calibrator.

The Andromeda Galaxy (M31), however, is po-

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tentially a first-class distance calibrator. Its main advantages are its simple geometry, a chemical composition and morphology very similar to those of the Milky Way (and other galaxies used for distance estimation, such as M81, M100, and M101; see, for example, Freedman et al. 1994), and its large and diverse stellar population. Given the potential importance of M31 as a robust anchor for the distance scale, we have undertaken an observational project with the fundamental goal of carrying out, for the first time, a direct and accurate determination of its distance using observations of individual double-line eclipsing binary (EB) systems. Individual stars in M31 are fainter by about 6 mag than their counterparts in the LMC ($(V_0 - M_V)_{\rm M31} \simeq 24.3$ mag), which has greatly limited their study. However, recent rapid increases in instrumental efficiencies and perspectives in the near future make detailed investigations of early-type EB systems in M31 technically feasible.

## 2. DOUBLE-LINED ECLIPSING BINARIES

Orbital and physical parameters, and thus masses and radii for the components of a double-lined EB, are derived from the modeling of light- and radial velocity curves. Both spectroscopic and photometric data must be simultaneously available to obtain the absolute dimensions of the binary components. The inclination of the orbit, which is obtained only from the light curves, is needed for the computation of the individual masses through the radial velocity curve results. In addition, the semi-major axis of the orbit, derived from the radial velocity curve, is needed to transform the fractional radii deriving from analysis of the light-curves into absolute radii.

The effective temperature, chemical composition, and interstellar extinction are determined by applying the same techniques as for single stars. For early-type eclipsing systems, UV/optical spectrophotometry is especially useful as hot stars emit most of their fluxes in that wavelength domain and accurate determinations of the stellar radiative properties can be obtained. The only complication added to the analysis by the binary nature of eclipsing systems is that we can measure only the combined flux emitted by the two components, which might have different physical properties. However, the parameters obtained from the analysis of light-curves (most notably the luminosity ratio) can be used to constrain the analysis and derive the individual temperatures.

In addition to making excellent standard candles, EBs have also been shown to yield a wealth of useful information. For example, masses and radii are

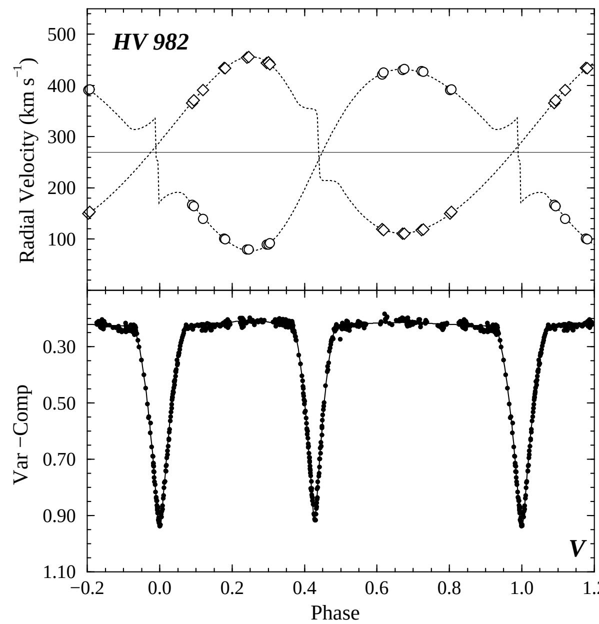


Fig. 1. *Top:* Radial velocity curve of the LMC system HV 982 obtained with the 4 m telescope at CTIO (Chile). *Bottom:* Light-curve of HV 982 in the $V$ band.

crucial for establishing the mass–luminosity relationship and also for placing constraints on stellar structure and evolution models (Pols et al. 1997). Extragalactic EBs are thus exceedingly interesting because they can be used to probe stars in environments with chemical histories that differ from those in the solar neighborhood.

## 3. DISTANCE DETERMINATION

The technique we use to determine the distances to EB systems is described in detail by Guinan et al. (1998), Fitzpatrick et al. (2002), and Ribas et al. (2002). Briefly, it utilizes ground-based light-curves, low resolution UV/optical spectrophotometry, and radial velocities derived from medium resolution spectra. Examples of these datasets are shown in Figures 1 and 2 for the LMC system HV 982. Our analysis proceeds in three steps: 1) the classical EB light-curve analysis techniques provide orbital properties, the temperature ratio of the two binary components, and their relative radii (i.e, $R/a$, where $R$ is the radius and $a$ is the orbital semimajor axis); 2) the radial velocity analysis yields the orbital semimajor axis and the stellar masses; and 3) modeling the UV/optical spectrophotometry gives the stellar temperatures, metallicity, reddening, and a "distance attenuation factor," corresponding to $R^2/d^2$. Combining this with radii determined from 1) and 2) yields the distance.

Our analysis eliminates the need for applying

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uncertain spectral type–$T_{\rm eff}$ relations or bolometric corrections. In fact, using EBs to determine distances is more direct and based on fewer assumptions and approximations than any other procedure in use. The results from our analyses of LMC EBs are provocative. So far, three systems have been studied: HV 2274 (Guinan et al. 1998), HV 982 (Fitzpatrick et al. 2002), and EROS 1044 (Ribas et al. 2002). These give distances compatible with an average of $\sim$48.4$\pm$1.1 kpc. However, the larger value of the distance derived for HV 982 provides a tantalizing hint that there may be some spatial extension of the LMC along its line of sight, which passes near to that of SN 1987A. Indeed, Panagia (1999) finds a distance for SN 1987A that is consistent with our value for HV 982. The possible depth of the LMC's stellar population is not necessarily surprising, given the history of tidal interaction between the LMC and the Milky Way, but it is disturbing for distance calibration efforts since the centroids of various calibration populations may not coincide.

## 4. ECLIPSING BINARIES IN M31

The first discoveries of M31 EBs ($\sim$60 systems) are from photographic surveys dating back to the 1960s (Gaposchkin 1962; Baade & Swope 1963, 1965). More recently, a CCD survey by the DIRECT group has discovered about 40 new systems (Stanek et al. 1998, 1999; Kaluzny et al. 1998, 1999). Although the quality of the light-curves, secured with 1.2–1.3 m telescopes, is not sufficient for determining accurate physical properties of the binaries, these surveys provide a masterlist of EBs from which optimal targets for further study can be selected.

To avoid complications in the determination of effective temperatures resulting from NLTE effects and strong stellar winds, systems composed by late O and early B stars should be selected as distance indicators. This restriction leads to objects with apparent visual magnitudes of $V \sim$ 19–20, which certainly pose an observational challenge. With current high efficiency CCDs, light-curves for M31 EBs can be obtained with telescopes 2–3 m in diameter. However, while 3–4 m telescopes are sufficient to derive accurate radial velocity curves for EBs in the LMC ($V \sim$ 14–16), the EBs in M31 require 10+ m telescopes.

## 5. THE PROJECT AND ITS SCIENTIFIC GOALS

A few years ago, we began a comprehensive study of 21 EBs in M31. Along with the authors, a number of researchers from other institutions are also involved: E. F. Guinan and E. L. Fitzpatrick (Villanova University, USA), A. Giménez (ESA, Netherlands), and R. W. Hilditch (St. Andrews College, UK).

Our analysis is data-intensive, requiring precise photometry, high resolution spectroscopy, and UV/optical spectrophotometry. High precision ($\sim$0.01 mag) light curves in the $B$ and $V$ passbands are currently being obtained using the 2.5 m Isaac Newton Telescope (INT) at Roque de los Muchachos Observatory (La Palma, Spain) with the Wide Field Camera CCD mosaic. Eleven nights have been granted for this project so far. The region under study ($34' \times 34'$) covers the northern half of M31 including the areas observed by Stanek et al. (1998, 1999) and Kaluzny et al. (1998). Figure 3 shows examples of the light curves in construction for four of the EBs in the sample. Current observations prove that the light-curves have sufficient quality to achieve a reliable determination of the stellar physical properties. Moreover, our project will directly benefit from the database that the POINT–AGAPE microlensing experiment is collecting. This project has guaranteed time for observing M31 with the same telescope and instrumentation. The POINT–AGAPE observations will provide light-curves with optimal phase coverage ($\sim$250 observations).

Space-based UV/optical (1200–7000 Å) spectrophotometry with the STIS instrument aboard the *Hubble Space Telescope* is planned for the near future. The spectrophotometry will permit accurate determinations of the temperatures of the components (to a few percent) but also it will yield estimates of the metallicity of the systems and interstellar absorption ($A_\lambda$) in the line of sight. Finally, high resolution ($R \sim 20000$) and moderate S/N ($\sim$20) spectroscopy is required to obtain accurate radial velocity curves. The faintness of the targets and the phase criticality of the observations makes it necessary to use large-aperture telescopes. The GTC, when equipped with an echelle-type spectrograph, will certainly meet the requisites and potentially provide the necessary data to complete the project.

The detailed study of EBs in M31 has multiple scientific goals. This program will yield direct determinations of masses and radii of stars in M31, which, when combined with the luminosities, will be extremely useful for studying the structure and evolution of these stars. The program will include an analysis of convective overshooting, mass loss, internal structure, and chemical enrichment law (see Ribas et al. 2000a,b). Further, a direct empirical calibration of the $M$–$L$ law for the more massive

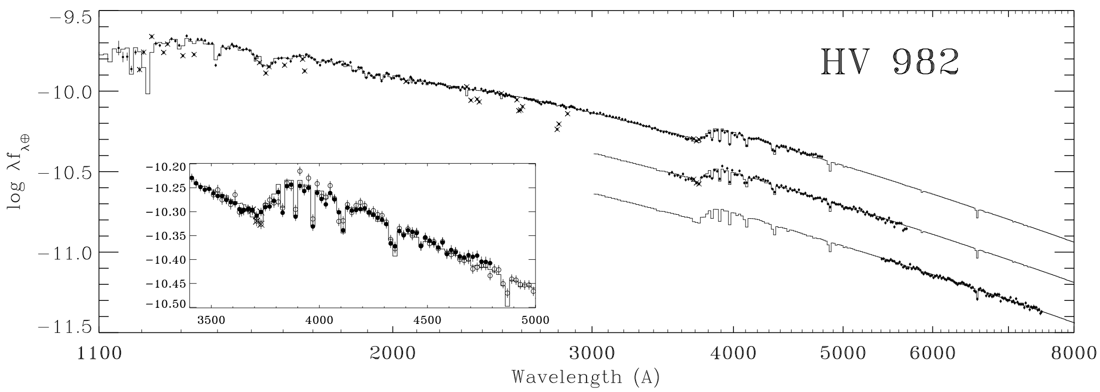


Fig. 2. The observed UV/optical energy distribution of the HV 982 system (small filled circles), superimposed on the best-fitting Kurucz ATLAS9 atmosphere model. The top spectrum shows the FOS data, the middle spectrum (shifted by −0.25 dex) the STIS/G430L data, and the lower spectrum (shifted by −0.5 dex) the STIS/G750L data.

stars of M31 will also be possible. Also, we shall be able to characterize the UV/optical interstellar extinction law along the lines of sight to the targets. But most importantly, using the method described above, we shall determine the distances to the EBs with a remarkable accuracy of about 5–7% per object. With a sufficient number of systems, we seek to reduce the uncertainty in M31's distance down to a level of a few percent.

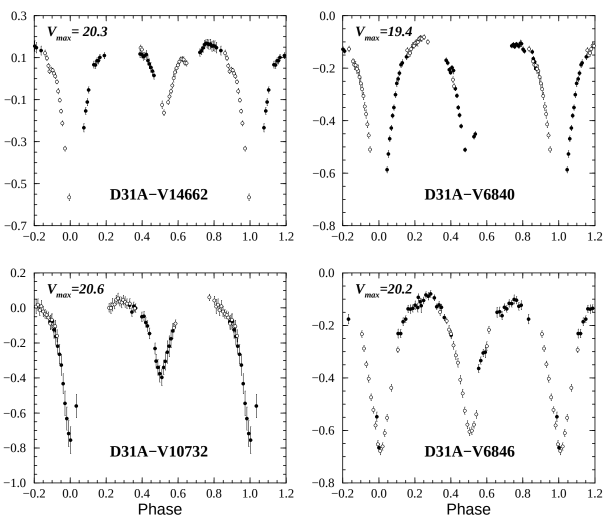


Fig. 3. Sample light-curves for four EBs systems in M31 with the WFC and the 2.5 m Isaac Newton Telescope. The integration time for each measurement was 15 min.

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