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ECLIPSING BINARIES AS CALIBRATORS OF THE EXTRAGALACTIC DISTANCE SCALE AND PROBES OF THE MOST MASSIVE STARS

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RESUMEN

Las masas, radios y luminosidades de estrellas distantes sólo pueden medirse con precisión para las binarias eclipsantes. Estos sistemas proveen además un método independiente para calibrar la escala de distancias extragaláctica y determinar la constante de Hubble. Han sido usadas como indicadores de distancia para las Nubes de Magallanes, la galaxia de Andrómeda y – más recientemente – la galaxia Triangulum, por el proyecto DIRECT, llevando las capacidades observacionales actuales al límite. A pesar de su gran potencial para ampliar nuestro conocimiento sobre estrellas de gran masa, las estrellas más masivas en pares eclipsantes siguen sin ser estudiadas. Un proyecto tendiente a cubrir dicho déficit se ha puesto en marcha. Aquí presento resultados de un relevamiento fotométrico del cúmulo de estrellas masivas Westerlund 1, el cual se espera que albergue algunas de las estrellas binarias eclipsantes más masivas de nuestra Galaxia.

ABSTRACT

Masses, radii and luminosities of distant stars can only be measured accurately in eclipsing binaries. These systems further provide an independent method for calibrating the extragalactic distance scale and thus determining the Hubble constant. They have been used as distance indicators to the Magellanic Clouds, the Andromeda Galaxy and most recently to the Triangulum Galaxy by the DIRECT Project, pushing the limit of our current observational capabilities. Despite their great potential for furthering our understanding of massive stars, the most massive stars in eclipsing binaries remain unexplored. A systematic study of such systems is currently underway. I present results from a photometric survey of the massive Westerlund 1 cluster, a likely host to some of the most massive stars in eclipsing binaries in our Galaxy.

Key Words: binaries: eclipsing — distance scale — open clusters and associations: individual (Westerlund 1) — stars: fundamental parameters

1. INTRODUCTION

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 Paczyński (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.

2. 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 14^{th} 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; Fitz-

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patrick et al. 2002). Distances to 3 more systems in the LMC have been determined: the detached 15^{th} magnitude system HV 982 (Fitzpatrick et al. 2002) at a distance of 50.2 ± 1.2 kpc, the 15^{th} magnitude detached system EROS 1044 (Ribas et al. 2002) at 47.5 ± 1.8 kpc and the 14^{th} 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 ($P_{orb} < 5$ days) to increase the efficiency of multi-fiber spectroscopy over a typical observing run. The mean true distance modulus from the whole sample is $18.91 \pm 0.03(random) \pm 0.1(systematic)$ and the implied LMC distance is $18.41 \pm 0.04(random) \pm 0.1(systematic)$, 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 meter Isaac Newton telescope and spectroscopy with the 8 meter 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.

3. DIRECT DISTANCE TO A DETACHED ECLIPSING BINARY IN M33

3.1. *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 $\sim 10\%$ 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 $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1}. This result is heavily dependent on the adopted distance modulus to the LMC (18.50 mag or 50 kpc).

3.2. *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 ($V_{max} < 20$ 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 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 meter 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 $T_{eff1} = 37,000 \pm 1500$ K and $T_{eff2} = 35,600 \pm 1500$ 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. 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 $R_1 = 12.3 \pm 0.4\ R_\odot$, $R_2 = 8.8 \pm 0.3\ R_\odot$.

3.3. *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 ± 0.12 mag (964 ± 54 kpc).

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 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? Bonanos et al. (2006) present 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 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. ECLIPSING BINARIES AS PROBES OF THE MOST MASSIVE STARS

Eclipsing binaries are extremely powerful tools that can be additionally used to probe the most massive stars. These objects are extremely rare, though their importance for astrophysics is large (see the Proceedings “The Fate of Most massive Stars”, ed. Humphreys & Stanek 2005). They generate most of the ultraviolet ionizing radiation in galaxies, power the far-infrared luminosities of galaxies through the heating of dust, provide the CNO enrichment of the interstellar medium and are progenitors of supernovae and gamma-ray bursts (e.g., Stanek et al. 2003).

The most massive candidates in the Milky Way are the Pistol Star (Figer et al. 1998) and LBV 1806-20 (Eikenberry et al. 2004), which have inferred masses up to $\sim 200\ M_{\odot}$. However, Figer et al. (2004) showed the latter to be a binary, highlighting the systematic effects involved in studying masses of 'single' stars. Similarly, Pismis 24-1, with an inferred mass of $\sim 200\ M_{\odot}$, was recently shown to be a multiple system with at least three components (Maíz Apellániz et al. 2007). Not only are parameters of single stars determined by untested theoretical stellar atmosphere and evolution models, but also frequently suffer from suspected multiplicity, which in many cases cannot be determined.

The physical parameters of very massive early-type stars, which emit mostly in the unreachable far ultraviolet, are not known well. Theoretical models of massive star formation and evolution are currently lacking observational constraints, thus accurate measurements of the masses, radii and luminosities of massive stars are long overdue. Massive stars in eclipsing binaries can provide fundamental parameters for the most massive stars in a variety of environments and at a range of metallicities and probe observationally the upper stellar mass limit.

Until recently, the most massive stars measured in eclipsing binaries were R136-38 in the Large Magellanic Cloud ($56.9 \pm 0.6\ M_{\odot}$, Massey et al. 2002) and WR 22 ($55.3 \pm 7.3\ M_{\odot}$, Rauw et al. 1996; Schweickhardt et al. 1999), an evolved star in our Galaxy. The current heavyweight champion is a Wolf-Rayet binary, WR 20a (Rauw et al. 2004; Bonanos et al. 2004), in the young compact cluster Westerlund 2, with component masses $83.0 \pm 5.0\ M_{\odot}$ and $82.0 \pm 5.0\ M_{\odot}$, making this the most massive binary known with an accurate mass determination. Such systems are of particular interest, since massive binaries might be an important avenue to create GRBs (e.g., Podsiadlowski et al. 2004), especially in the case of Population III, metal-free stars (see Bromm & Loeb 2006). Analogs of WR 20a, if not more massive binaries, are bound to exist in the young massive clusters at the center of the Galaxy (Center, Arches, Quintuplet), in super star clusters (such as Westerlund 1), in Local Group galaxies (e.g. LMC, SMC, M31, M33) and beyond (e.g. M81, M83, NGC 2403).

Measuring accurate masses of the most massive stars involves discovering eclipsing binaries in massive star clusters and nearby galaxies and selecting the brightest and thus most massive ones for follow-up spectroscopy. The OGLE and MACHO microlensing surveys toward the LMC and SMC have provided a large database of eclipsing binaries from which to select the brightest massive candidates. However, the massive galactic clusters remain unexplored. This motivates the study of the massive Westerlund 1 cluster presented below.

5. THE MASSIVE WESTERLUND 1 CLUSTER

Westerlund 1 is a unique laboratory for studying the elusive evolution of massive stars. It has recently emerged as the nearest known super star cluster, i.e. a globular cluster precursor, typically found in starburst galaxies. The high amount of reddening ($A_V \sim 12$ mag) obscured it until recent studies by Piatti et al. (1998) and Clark et al. (2005), that have discovered a massive stellar population of post-main sequence objects and determined it to be the most massive compact young cluster known in the Local Group, with an inferred mass $\log M = 4.75$ (Clark et al. 2005) in agreement with the recent dynamical mass measurement of $\log M = 4.8$ (Mengel et al. 2007), thus weighing more than the R136 or Arches clusters. It has an inferred age of 4.5–5 Myr (Crowther et al. 2006), more similar in age to the Quintuplet and Center cluster. However, it is less obscured by dust than the Galactic center clusters and much nearer than R136, which allows for observations in the optical.

Clark et al. (2005) obtained photometry of the cluster and spectroscopy of 53 stars, which were all classified as post main sequence objects, including OB supergiants, red supergiants, yellow hypergiants, a luminous blue variable and 14 Wolf-Rayet (WR) stars. Currently, 24 WR stars have been identified in Westerlund 1 (see Crowther et al. 2006, and references therein), concentrating 8% of the known galactic WR stars in one cluster (van der Hucht 2006). *Chandra* observations have revealed the presence of a magnetar in Westerlund 1 (Muno et al. 2006), which for the first time places a firm lower limit on the mass of a neutron star progenitor, as well as detections of 12 WR stars and a Be star (Skinner et al. 2006).

$BVRI$ observations of Westerlund 1 were obtained with the Direct CCD on the 1 m Swope telescope at Las Campanas Observatory, Chile on 17 nights between UT June 15 and July 25, 2006. The total number of exposures were 252×5 sec and 216×30 sec in the I filter, 217×30 sec in R, 200×600 sec in V, and 167×1200 sec in B. Two exposure times were taken in I to increase the sensitivity to both bright and faint cluster members. The $8.7' \times 8.7'$ images were processed with standard IRAF routines. The photometry of the variable stars was extracted using the ISIS image subtraction package

(Alard & Lupton 1998; Alard 2000) in each band separately.

Preliminary results in the $R-$band yield over 100 variable stars, including a dozen short period eclipsing binaries, some of which are located in the cluster core (Bonanos 2007, in prep). Among the variables are several field short period variables, including W Ursa Majoris and δ Scuti variables. Additionally, these data yield variability information on the 24 known WR stars, half of which are found to be variable. The cause of variability is not completely understood, it could either be due to a wind phenomenon or be the result of pulsations, as Dorfi, Gautschy, & Saio (2006) have recently proposed.

6. SUMMARY

With current spectroscopic capabilities it has become possible to measure distances to Local Group galaxies out to 1 Mpc with eclipsing binaries, thus providing distances independent of the controversial LMC distance and the calibration of Cepheids, which most methods rely on. 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).

Eclipsing binaries are also powerful probes of the most massive stars. Measurements of binaries, such as those discovered in Westerlund 1, will provide much needed constraints on massive star formation and evolution models, and insight into the progenitors of high-mass X-ray binaries, core-collapse supernovae, the connection between supernovae and gamma-ray bursts, and Population III stars.

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DISCUSSION

N. Walborn - Unresolved companions in distant systems and anomalous extinction laws could complicate the ABs results. It's curious that the M33 result implies a larger DM for the LMC while the LMC EBs themselves produce smaller DMs. The idea of depth effects in the LMC should be compared with localized results from other indicators such as Cepheids. I wonder if that idea is consistent with the well defined systemic relation derived from 2MASS data by van der Marel.
A. Bonanos - It is unlikely that third light is affecting our M33 distance. We checked archival HST data and Spitzer data for blue and red companions but did not find any. Furthermore, the high inclination of the eclipsing binary does not allow for much third light and in the case that it was present it would push the binary to an even greater distance. There is evidence for the LMC depth effect from several studies, most recently the supernova light echoes found by the SuperMACHO project.
A. Moffat - Since you asked for input on your WR light curves in Westerlund 1, let me say that your data for late type WN stars looks much like previous data and in particular our new MOST satellite data for WR 123 (WN 8) and WR 103 (WC9d). There we believe that the large, mostly stochastic, variability is due to pulsations of the underlying star. This is in line with spectral analysis by Goetz Graefener and Wolf Rainer Hamman that cannot account for the spectra of WN8 stars from radiation pressure alone driving the winds. Pulsations would then seem to be a natural candidate.
A. Bonanos - Thanks, I will definitely keep that in mind.

FCAG Postgraduate bunch. Also, members of the next meeting LOC,
only that they don't know it yet...