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LBT DISCOVERY OF A YELLOW SUPERGIANT ECLIPSING BINARY IN THE DWARF GALAXY HOLMBERG IX[1]

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ABSTRACT

In a variability survey of M81 using the Large Binocular Telescope we have discovered a peculiar eclipsing binary ($M_V \sim -7.1$) in the field of the dwarf galaxy Holmberg IX. It has a period of 271 days, and the light curve is well fit by an overcontact model in which both stars are overflowing their Roche lobes. It is composed of two yellow supergiants ($V - I \simeq 1$ mag, $T_{\rm eff} \simeq 4800$ K), rather than the far more common red or blue supergiants. Such systems must be rare. While we failed to find any similar systems in the literature, we did, however, note a second example. The SMC F0 supergiant R47 is a bright ($M_V \sim -7.5$) periodic variable whose All Sky Automated Survey (ASAS) light curve is well fit as a contact binary with a 181 day period. We propose that these systems are the progenitors of supernovae like SN 2004et and SN 2006ov, which appeared to have yellow progenitors. The binary interactions (mass transfer, mass loss) limit the size of the supergiant to give it a higher surface temperature than an isolated star at the same core evolutionary stage. We also discuss the possibility of this variable being a long-period Cepheid.

Subject heading: binaries: eclipsing

Online material: color figures

1. INTRODUCTION

Although small in number, massive stars are critical to the formation and evolution of galaxies. They shape the ISM of galaxies through their strong winds and high UV fluxes and are a major source of the heavy elements enriching the ISM (e.g, Massey 2003; Zinnecker & Yorke 2007 and references therein). A large fraction of massive stars are found in binaries (e.g., Kiminki et al. 2007). Eclipsing binaries are of particular use because they allow us to determine the masses and radii of the components and the distance to the system. Many young, massive eclipsing binaries have been found and studied in our Galaxy, the LMC, and the SMC, primarily in OB associations and young star clusters (e.g., Bonanos et al. 2004; Peeples et al. 2007; González et al. 2005; Hilditch et al. 2005). The study of massive eclipsing binaries beyond the Magellanic clouds has been limited until very recently, when variability searches using medium-sized telescopes with wide-field CCD cameras, coupled with spectroscopy using 8 m class telescopes, have yielded the first systems with accurately measured masses in M31 (Ribas et al. 2005) and M33 (Bonanos et al. 2006).

We conducted a deep variability survey of M81 and its dwarf irregular companion, Holmberg IX, using the Large Binocular Camera (LBC) mounted on the Large Binocular Telescope (LBT), between 2007 January and October. Holmberg IX is a young dwarf galaxy (age ≲200 Myr), with a stellar population dominated by blue and red supergiants with no signs of old stars in the red giant branch (Makarova et al. 2002). The dwarf may have formed during a recent tidal interaction between M81 and NGC 2976 (e.g., Boyce et al. 2001). The gas-phase metal abundance of Holmberg IX between $\frac{1}{8}$ and $\frac{1}{3}$ solar (e.g., Miller 1995; Makarova et al. 2002) is consistent with this hypothesis (e.g., Weilbacher et al. 2003). A normal, isolated dwarf on the luminosity-metallicity relationship would have a metallicity of $\sim \frac{1}{20}$ solar (Lee et al. 2006).

In this Letter, we report on the discovery of a 271 day period, evolved, massive eclipsing binary in Holmberg IX using data from the LBT. The overcontact system is the brightest periodic variable discovered in our LBT variability survey. It has an out-of-eclipse magnitude of $V_{\rm max} = 20.7$ mag and is located at $\alpha = 09^{\rm h}57^{\rm m}37.14^{\rm s}$, $\delta = +69°02'11''$ (J2000.0). In § 2 we discuss the observations and data reduction, in § 3 we present the light curve and the best-fit eclipsing binary model and note a similar eclipsing binary in the SMC. In § 4 we discuss the results and their possible implications for Type II supernovae. Throughout this Letter, we assume the *HST* Key Project distance to M81 of $\mu = 27.80$ mag (3.6 Mpc; Freedman et al. 2001) as the distance to Holmberg IX and correct only for a foreground Galactic extinction of $E(B - V) = 0.08$ mag (Schlegel et al. 1998).

2. OBSERVATIONS

Holmberg IX was observed as part of a variability survey of the entire M81 galaxy conducted between 2007 January and October with the LBT 8.4 m telescope (Hill et al. 2006), using the LBC-Blue CCD camera (Ragazzoni et al. 2006; E. Giallongo et al. 2008, in preparation) during Science Demonstration Time. The survey cadence and depth (1 minute single exposures, with ≥3 consecutive exposures) are optimized to detect and follow up Cepheid variables with periods between 10 and 100 days ($V \lesssim$ 24 mag), getting better than 10% photometry in the *B* and *V* filters. We obtained 168 *V*-band images on 24 different nights and 87 *B*-band images on 13 nights. We co-added the *B*-band images from each night (usually 3–4) to improve the signal-to-noise ratio in the combined images. The seeing (FWHM) varied between 0.7″
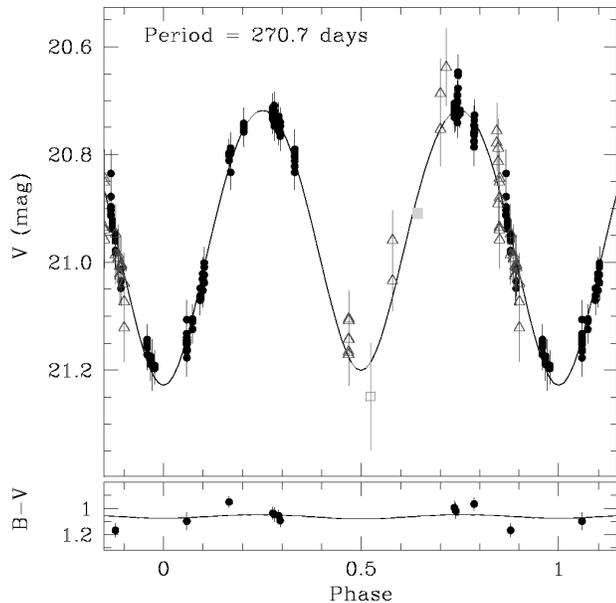
Fig. 1.—Phased V-band light curve of the 270.7 day period eclipsing binary in Holmberg IX (*top*) and its B − V color evolution (*bottom*). The different symbols correspond to photometry from different telescopes: LBT (*filled circles*), MDM (*open triangles*), HST ACS (*filled square*), and SDSS (*open square*). The solid line shows an overcontact eclipsing binary model that best fits the light V light curve. [*See the electronic edition of the Journal for a color version of this figure.*]

Fig. 2.—CMDs of stars in the field of Holmberg IX obtained from the LBT-BV reference images (*left*) and HST ACS-VI single-epoch observations (*right*). The ACS CMD shows well-defined stellar sequences for the main sequence (MS) and the evolved blue (BSG) and red supergiants (RSG). The eclipsing binary (*pentagon*) lies between the BSG and RSG sequences. [*See the electronic edition of the Journal for a color version of this figure.*]

and 2.0″ in V (median 1.4″), and between 1.0″and 3.3″ in B band (median 1.9″). Our program did not request especially good image quality for these queue-scheduled SDT observations.

We also observed Holmberg IX as part of a variability survey of M81 conducted with the 8 K Mosaic imager mounted on the MDM 2.4 m telescope. The observations were obtained in five 1 week runs between 2006 February and 2007 February. All the images were obtained in V band using 15 minute exposures. Due to weather loses and bad seeing, we ended up using only 36 images from 12 different nights. The typical seeing was ∼1.1″.

3. LIGHT CURVE

We used the ISIS difference image analysis package (Alard 2000; Hartman et al. 2004) to obtain the V-band light curves of all the point sources detected in the LBT reference image. The detection of all point sources and the transformation of difference-flux light curves to instrumental magnitudes were done using the DAOPHOT ALLSTAR package (Stetson 1987, 1992). After visual inspection of all the light curves of variable point sources selected by standard criteria (rms and AoV significance; Hartman et al. 2007), we detected ∼20 periodic variables in the field of Holmberg IX. These include Cepheids with periods of 10–60 days and one long-period variable. The analysis of the Cepheid PL-relation and the distance to Holmberg IX will be presented in a future paper (J. L. Prieto et al. 2008, in preparation). The brightest periodic variable is the peculiar, long-period ($P = 270.7$ days) eclipsing binary we discuss here (hereafter V1).

After discovering the binary in the LBT data, we also ran ISIS and DAOPHOT ALLSTAR on the MDM data to extract the light curve of the long-period binary. The variability data from LBT and MDM were complemented with single-epoch archival imaging of the field obtained from the Sloan Digital Sky Survey (SDSS) Data Release 6 (Adelman-McCarthy et al. 2007) in the gri bands (UT 2003 November 30), and the HST ACS Wide Field Camera (GO proposal 10605, PI: E. Skillman) in the F555W and
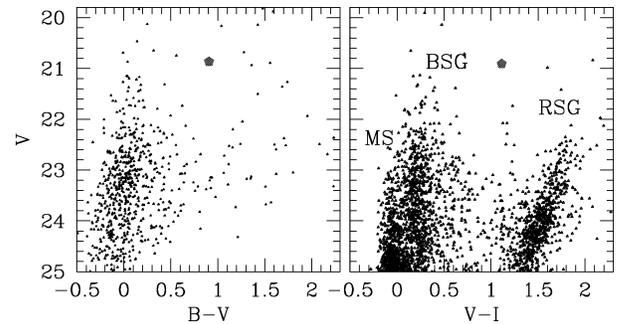
F814W filters (UT 2006 March 23). The high-resolution HST ACS images (FWHM ∼ 0.1″, corresponding to ∼2 pc at the distance of Holmberg IX) show that the binary is spatially coincident with a stellar association in the dwarf galaxy.

Figure 1 shows the phased V-band light curve and B − V color curve of the eclipsing binary system. We include all the LBT, MDM, SDSS, and HST ACS V-band photometry. The LBT and MDM photometry have been calibrated using SDSS photometry of several relatively bright ($r \lesssim 21.0$ mag) and unsaturated stars in the field, transforming the gr magnitudes to standard BV magnitudes with the transformations presented in Ivezić et al. (2007). The rms deviations of the absolute calibration are 0.02–0.03 mag for LBT-BV and ∼0.05 mag for MDM-V. The SDSS gri photometry of the binary was extracted in the same way as for LBT and MDM, using the DAOPHOT ALLSTAR package to obtain instrumental magnitudes calibrated using absolute photometry of the bright stars in the field. Our g and r magnitudes of the binary from the SDSS data are 0.2 and 0.5 mag brighter, respectively, than the magnitudes reported in the SDSS-DR6 catalog, while the i-band magnitude agrees at the 1% level. We think that this is due to problems in the SDSS photometry for faint sources in a crowded field (e.g., Smolčić et al. 2007). The details of the HST photometry can be found in D. R. Weisz et al. (2008, in preparation).

In Figure 2 we show the position of the binary in the color-magnitude diagrams (CMDs), obtained from calibrated LBT and HST ACS photometry. The CMDs show the well-populated blue and red supergiant sequences in Holmberg IX. The binary is among the most luminous stars in this dwarf galaxy, with $M_V \sim -7.1$ mag, and it has clearly evolved from the main sequence. With such a high intrinsic luminosity, the binary is bound to be massive. After correcting for Galactic foreground extinction, the B − V and V − I colors are consistent with an effective temperature of $T_{\text{eff}} = 4800 \pm 150$ K (Houdashelt et al. 2000). Both components seem to be G-type yellow supergiants given the equal depths of the eclipses and the lack of color variations (see Fig. 1).

We used the eclipsing binary model-fitting program NIGHT-FALL[10] to model the V-band light curve. As shown in Figure 1, we obtain a good fit to the light curve with an overcontact configuration where both stars are overflowing their Roche lobes. We fixed the effective temperature of the primary at $T_1 = 4800$ K obtained from the colors. We assumed equal masses for the stars, a linear limb-darkening law, circular orbits, and synchronous rotation. We fit for four parameters: the Roche lobe filling factors,

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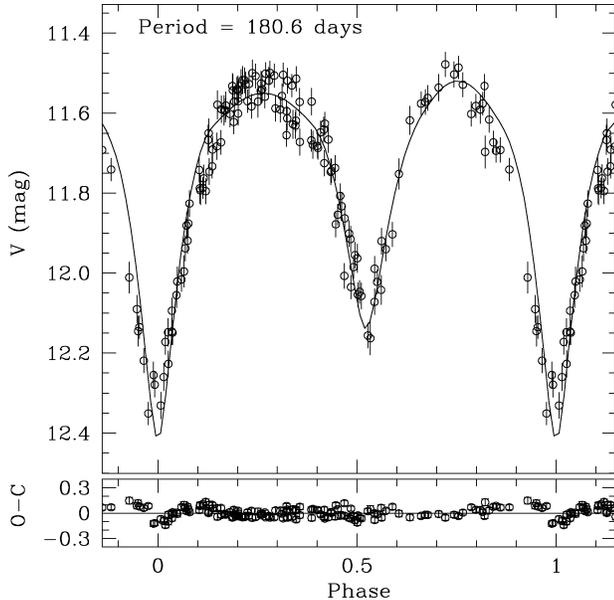[10] See http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html.

Fig. 3.—Phased V-band light curve of the long-period, evolved eclipsing binary SMC R47 obtained from the ASAS catalog (Pojmanski 2002). The star was classified spectroscopically as an F0 supergiant by Humphreys (1983). The solid line shows the contact eclipsing binary model that best fits the light curve. The lower panel shows the residuals of the fit (observed-calculated).

Fig. 4.—CMD of Holmberg IX from *HST* ACS *V* and *I* photometry. The connected filled symbols show the position of the evolved eclipsing binaries in Holmberg IX (*filled pentagons*) and the SMC (*filled triangles*) at maximum and minimum. The lines show evolutionary tracks with extended mass loss from the Geneva group (Lejeune & Schaerer 2001) for single stars with masses between 12 and 25 $M_\odot$, assuming two different metallicities: $\frac{1}{3}$ solar (*dashed line*) and $\frac{1}{5}$ solar (*solid line*). We use a distance modulus of $\mu = 27.80$ mag to Holmberg IX, and Galactic color-excess $E(B - V) = 0.08$ mag, to put the evolutionary tracks in the diagram. [*See the electronic edition of the Journal for a color version of this figure.*]

the inclination, and the temperature of the secondary. The time of the primary eclipse and the period were determined externally and were fixed for these fits. The main parameters of the binary are listed in Table 1. The light curve shows a hint of the O'Connell (1951) effect, in which the maxima (out-of-eclipse regions) show a difference in brightness (e.g., Pilecki et al. 2007).

We searched the literature for other examples of evolved, massive eclipsing binaries in the yellow supergiant phase and found none.[11] We also searched the available catalogs of eclipsing binaries in the LMC and SMC. The MACHO catalog of eclipsing binaries in the LMC (Derekas et al. 2007) contains 25 contact systems with red colors (i.e., evolved), $(V - R) > 0.5$ mag, and periods >200 days. However, these systems have absolute magnitudes $M_V \gtrsim -4$ ($V \gtrsim 14.5$ mag) that are ~3 mag fainter than the yellow supergiant eclipsing binary in Holmberg IX[12]. The All Sky Automated Survey (ASAS; Pojmanski 2002) contains complete Southern sky coverage for $V < 15$ mag. To our surprise, we found in the ASAS catalog a luminous ($M_V \sim -7.5$, $V_{max} \sim 11.5$ mag), 181 day period contact eclipsing binary in the SMC. The star, SMC R47 ($\alpha = 01^h29^m17.26^s$, $\delta = -72°43'20.2''$), had been spectroscopically classified as an F0 supergiant ($T_{eff} \simeq 7500$ K) with emission lines by Humphreys (1983). The ASAS *V*-band light curve of SMC R47, obtained between 2002 December and 2006 June, and the fit obtained with NIGHTFALL are shown in Figure 3. The best-fit eclipsing binary model requires a contact configuration, with nonzero eccentricity to account for the difference in timing between the eclipses. Even though we selected a clean part of the full ASAS light curve, there seems to be intrinsic variability from the binary components. The main parameters of this eclipsing binary are in Table 1. While substantially hotter than

the Holmberg IX binary, it does not lie on the SMC blue supergiant sequence (Grieve & Madore 1986).

4. DISCUSSION AND CONCLUSIONS

An eclipsing binary is the best explanation for the light curve of the brightest variable we have discovered in our LBT variability survey of the dwarf irregular companion of M81 Holmberg IX. The other possible explanation for the periodic variability of V1 is a long-period ($P = 135$ days) Cepheid. Such long-period Cepheids ($P > 100$ days) have been observed in dwarf galaxies like the LMC and SMC (e.g., Freedman et al. 1985), NGC 55 (e.g., Pietrzyński et al. 2006), NGC 300 (e.g., Pietrzyński et al. 2002), NGC 6822 (e.g., Pietrzyński et al. 2004), IC 1613 (e.g., Antonello et al. 1999), and I Zw 18 (Aloisi et al. 2007). The magnitude of V1 is consistent with the magnitude of a Cepheid with $P = 135$ days ($M_V \simeq -7.0$), extrapolating the period-luminosity relationship of Fouqué et al. (2007). However, while a few of these long-period Cepheids have quasi-sinusoidal light curves that are nearly symmetric

[11] Note, however, that a possible Galactic counterpart is the contact binary BM Cas (Fernie & Evans 1997), composed by an A7 Iab supergiant ($M_V \simeq -6.3$) and a late-type giant.

[12] Mennickent et al. (2006) obtained spectroscopy of 17 "peculiar" periodic variables in the SMC from the OGLE database, and found a 184 day period eclipsing binary composed by two yellow supergiants (F5Ie + G5-K0I). However, this system is ~2 mag fainter than the binary in Holmberg IX.
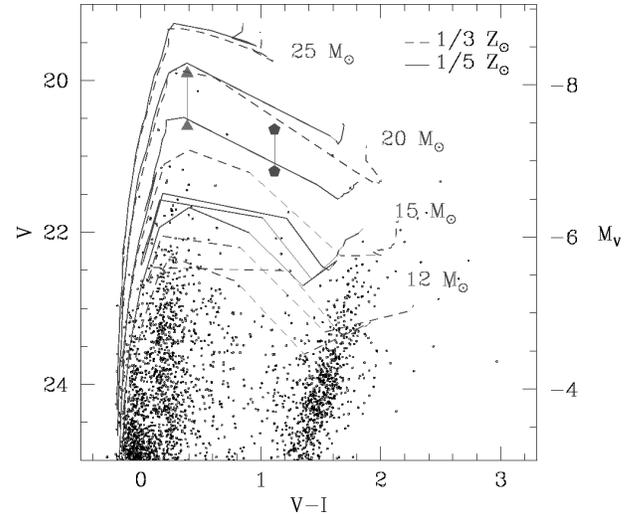
TABLE 1
BEST-FIT BINARY MODEL PARAMETERS.

Parameter	Holmberg IX V1	SMC R47
Period, P (days)	270.7 ± 2.3	181.58 ± 0.16
Time of primary eclipse, T_{prim}	2454186.0 ± 0.6	2452073.1 ± 0.2
Inclination, i (deg)	55.7 ± 0.6	82.2 ± 0.2
Primary temperature, T_1 (K)	4800 ± 150	7500 ± 100
Temperature ratio, T_2/T_1	1.05 ± 0.05	1.17 ± 0.02
Eccentricity, e	0.00	0.039 ± 0.002[a]
Roche lobe filling factors[b]	1.23 ± 0.02	1.02 ± 0.02
Semimajor axis, a^c ($R_\odot$)	547	418

NOTE.—The mass ratio was fixed at $q = 1$ for fitting both light curves.

[a] A nonzero eccentricity is required to fit the difference in timing between the primary and secondary eclipses. The best-fit longitude of the periastron is $w = 168.6° ± 1.1°$.

[b] Ratio of stellar to Roche lobe polar radius for each star.

[c] Separation between the stars assuming a total mass of 30 $M_\odot$ for each system.

under a time reversal, they all have larger amplitudes in bluer bands (B amplitudes 1.3–1.6 times V amplitudes) due to the changes in the effective temperature as the star pulsates (e.g., Freedman et al. 1985; Madore & Freedman 1991). Spectroscopy of V1, while challenging, would eliminate any remaining ambiguities in classifying this system.

We can safely rule out the possibility that the eclipsing binary is in our Galaxy. Using the period, estimated effective temperature, magnitude at maximum, and assuming that the stars are of similar size in a contact configuration, we can use Kepler's law and their total surface brightness to estimate a distance to the system of $D \simeq (M_{total}/M_{\odot})^{1/3}$ Mpc, where $M_{total} = M_1 + M_2$ (e.g., Gaposchkin 1962). Conversely, we can estimate the total mass of the binary system by assuming the distance $M_{total} \simeq 45 \ (D/3.6 \ \mathrm{Mpc})^3 \ M_{\odot}$. This should be taken as a rough estimate because of the overly simple model; to accurately constrain the total mass of the system, and its components, we need radial velocity measurements. Another piece of evidence that puts the binary system in Holmberg IX is its spatial coincidence with a stellar overdensity in the dwarf, observed in the *HST* ACS images.

We expected that such systems were rare[13] but were surprised to find none in the literature. However, we found a similar eclipsing binary system in the SMC (SMC R47) searching through the ASAS catalog. From the absolute magnitudes of both binaries and their colors, we estimate that at least one of the stars in each binary is ~15–20 $M_{\odot}$ (main-sequence age ~10–15 Myr) using the evolutionary tracks for single stars of Lejeune & Schaerer (2001; see Fig. 4).

The stellar evolutionary path of stars of a given mass in binary systems can differ significantly from their evolution in isolation (e.g., Paczyński 1971). In particular, binary interactions through mass loss, mass accretion, or common-envelope evolution play a very important role in the presupernova evolution (e.g., Pod-

siadlowski et al. 1992). Most of the massive stars with masses 30 $M_{\odot} \gtrsim M \gtrsim 8 \ M_{\odot}$ are expected to explode as supernovae when they are in the red supergiant stage, with a small contribution from blue supergiants (e.g., SN 1987A; West et al. 1987). Surprisingly, Li et al. (2005) identified the progenitor of the Type IIP supernova 2004et in pre-explosion archival images and determined that it was a yellow supergiant with a main-sequence mass of ~15 $M_{\odot}$. Also, the position in the CMD of the likely progenitor of the Type IIP supernova 2006ov (see Li et al. 2007, Fig. 10) is remarkably similar to the position of the eclipsing binary in Holmberg IX (see Fig. 4).

We propose that the binary we discovered in Holmberg IX and the binary found in the SMC[14] are the kind of progenitor objects of supernovae like SN 2004et and SN 2006ov that appeared to be the explosions of yellow supergiants. A close binary provides a natural means of slowing the transition from blue to red, allowing the star to evolve and then explode as a yellow supergiant. As the more massive star evolves and expands, the Roche lobe limits the size of the star forcing it to have a surface temperature set by the uncoupled core luminosity and the size of the Roche lobe. It can expand further and have a cooler envelope only by becoming a common envelope system, which should only occur as the secondary evolves to fill its Roche lobe. This delayed temperature evolution allows the core to reach SN II conditions without a red envelope.

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[13] While the relative numbers of eclipsing binaries is a much more complicated problem, we note that the relative abundances of red, blue and yellow supergiants is 4 : 13 : 1 for the Geneva evolutionary track (Lejeune & Schaerer 2001) of a single, nonrotating star with $M = 15 \ M_{\odot}$ and $Z = 0.004$.

[14] A possible earlier stage of these yellow supergiant binaries might be represented by the B-supergiant pair HD 1383 (Boyajian et al. 2006).

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