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A survey of the most massive stars in the Magellanic Clouds

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Abstract. Despite the large impact very massive stars ($> 30\,M_\odot$) have in astrophysics, their fundamental parameters remain uncertain. I present results of a survey aiming to characterize the most massive stars in the Magellanic Clouds. The survey targets the brightest, blue, eclipsing binaries discovered by the OGLE microlensing survey, for which masses and radii are measured to 5%. Such precise data are rare and provide constraints for theories of massive star formation and evolution at low metallicities.

Keywords. binaries: eclipsing, binaries: spectroscopic, stars: early-type, stars: fundamental parameters, stars: individual (LMC-SC1-105), Magellanic Clouds

1. Introduction

The fundamental parameters of very massive stars ($\geqslant 30\,M_\odot$) remain uncertain, despite the large impact massive stars have in astrophysics, both individually and collectively (see review by Massey 2003). The equations of stellar structure allow for stars with arbitrarily large masses, however the mechanisms to form massive stars (accretion and mergers; e.g., Bally & Zinnecker 2005) and the associated instabilities (see Elmegreen 2000; Zinnecker & Yorke 2007 and references therein) are not well understood, hindering theoretical predictions on the existence of an upper limit on the stellar mass. The "mass discrepancy" problem, i.e. the disagreement between masses derived from parameters determined by fitting stellar atmosphere models to spectra and from evolutionary tracks (see e.g., Massey *et al.* 2000; Repolust *et al.* 2004, for a comparison), still affects studies of single massive stars, even though significant progress has been made in both stellar atmosphere (see review by Herrero 2008) and stellar evolution models (e.g., Meynet & Maeder 2003). The parameters of single stars also suffer from suspected multiplicity, which in many cases cannot be determined.

The only model-independent way to obtain accurate fundamental parameters of distant massive stars and to resolve the "mass discrepancy" problem is to use eclipsing binaries (see review by Andersen 1991). In particular, double-lined spectroscopic binary systems exhibiting eclipses in their light curves are extremely powerful tools for measuring masses and radii of stars. The most massive stars measured in eclipsing binaries are galactic Wolf-Rayet stars of WN6ha spectral type: NGC 3603-A1 ($M_1 = 116 \pm 31\ M_\odot$, $M_2 = 89 \pm 16\ M_\odot$; Schnurr *et al.* 2008), and WR 20a ($M_1 = 83.0 \pm 5.0\ M_\odot$ and $M_2 = 82.0 \pm 5.0\ M_\odot$; Rauw *et al.* 2004; Bonanos *et al.* 2004) in Westerlund 2, presenting a challenge for both stellar evolution and massive star formation models (Yungelson et al. 2008; Zinnecker & Yorke 2007) and raising the issue of the frequency and origin of "binary twins" (Pinsonneault & Stanek 2006; Krumholz & Thompson 2007). Such systems are of particular interest, since massive binaries might be progenitors of gamma-ray bursts (e.g., Fryer *et al.* 2007), especially in the case of Population III, metal-free stars (see Bromm & Loeb 2006).

Analogs of these heavyweight champions, if not more massive binaries, are bound to exist in the young massive clusters at the center of the Galaxy (Center, Arches, Quintuplet), in nearby super star clusters (e.g., Westerlund 1, R 136), in Local Group galaxies (e.g., LMC, SMC, M 31, M 33) and beyond (e.g., M 81, M 83, NGC 2403). A systematic wide-ranging survey of these clusters and galaxies is currently underway. The goal is to provide data with which to test star formation theories, stellar atmosphere and stellar evolution models for both single and binary stars as a function of metallicity, and the theoretical predictions on the upper limit of the stellar mass. The adopted strategy involves two steps: a variability survey to discover eclipsing binaries in these massive clusters and nearby galaxies, which is followed by spectroscopy to derive parameters of the brightest — thus most luminous and massive — blue systems. Figure 1 illustrates the extent of our knowledge of precise fundamental parameters of massive stars. It presents published mass-radius measurements from eclipsing binaries, accurate to better than 10% for the more massive component. This Table consists of only 14 very massive stars with better than 10% mass-radius measurements, located in 3 galaxies. Of these, WR 20a and

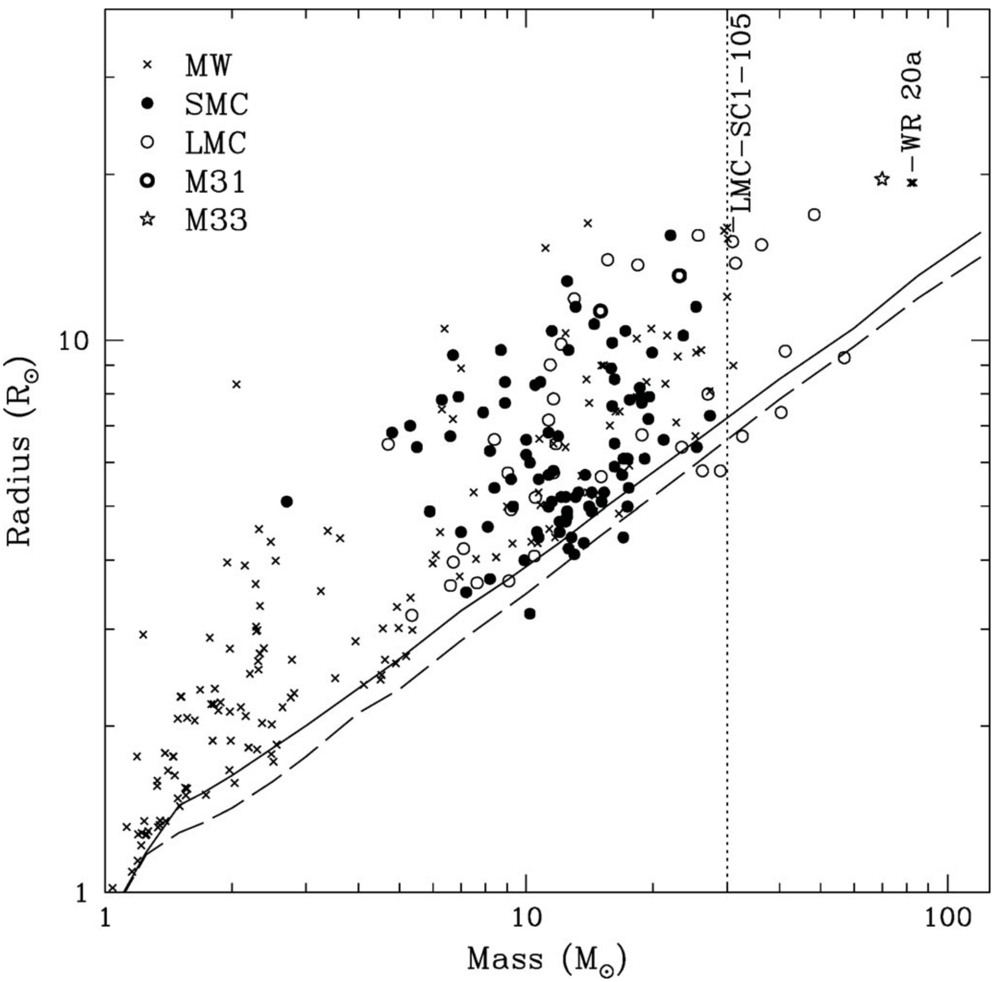

Figure 1. Mass and radius determinations of stars in eclipsing binaries, accurate to $\leqslant 10\%$ and complete $\geqslant 30\,M_\odot$ from the literature. The solid line is the $Z = 0.02$ ZAMS from Schaller *et al.* (1992); the dashed line is the $Z = 0.008$ ZAMS from Schaerer *et al.* (1993).

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M 33 X-7 (Orosz *et al.* 2007) are the most massive and noteworthy. M 33 X-7 contains a very massive 70.0 ± 6.9 $M_\odot$ O-type giant and a record-breaking 15.65 $M_\odot$ black hole, challenging current evolutionary models, which fail to explain such a large black hole mass. Without accurate measurements for a large sample of massive stars, theoretical models will remain unconstrained.

2. LMC-SC1-105

A survey to determine accurate parameters for several massive eclipsing binaries in the low metallicity ($Z = 0.008$) LMC was undertaken, with the purpose of increasing the sample and improving our understanding of these rare systems. Several candidates were selected from the OGLE-II catalog of eclipsing binaries in the LMC (Wyrzykowski *et al.* 2003) as the brightest systems with $B-V < 0$ mag. LMC-SC1-105, or OGLE 053448.26−694236.4, has $I_{max} = 13.04$ mag, $V_{max} = 12.97$ mag, $B_{max} = 12.81$ mag and a preliminary semi-detached classification (Figure 2). A total of 9 spectra of LMC-SC1-105 near

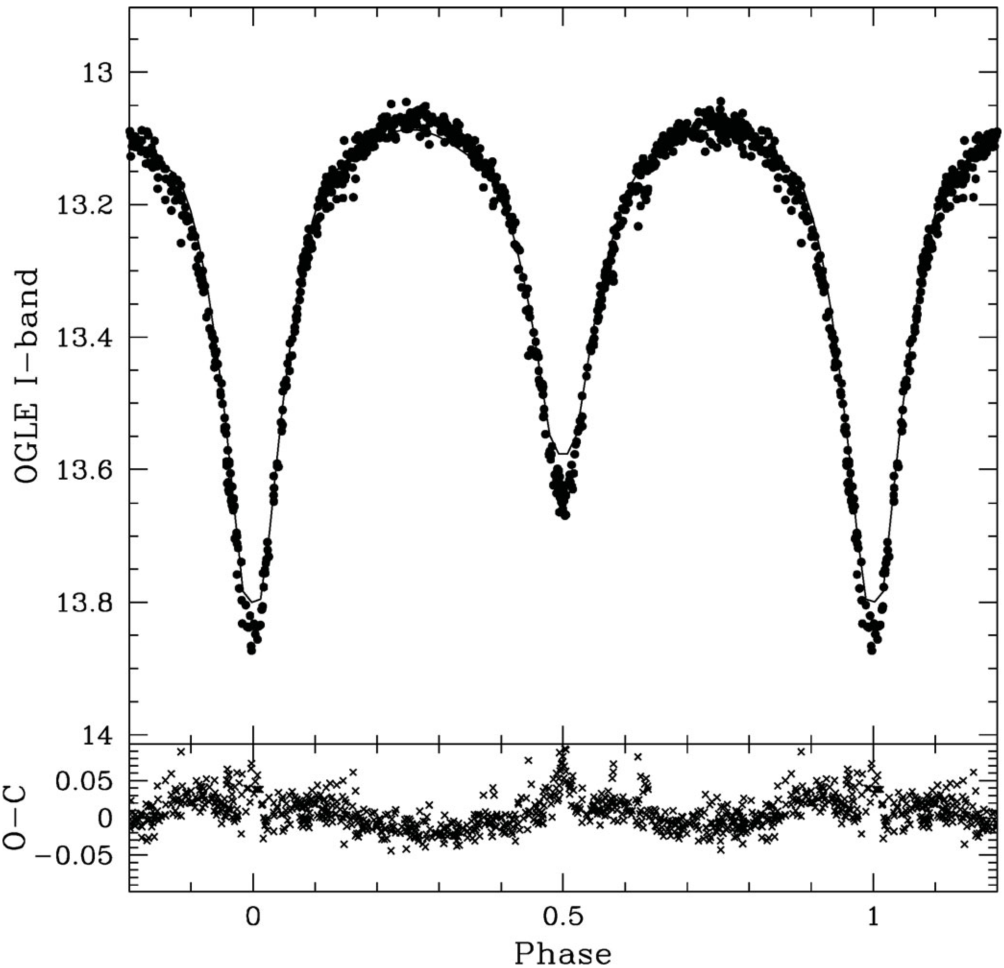

Figure 2. Phased OGLE I−band light curve of LMC-SC1-105. The best fit model from PHOEBE (solid curve) assumes a semi-detached configuration with the secondary filling its Roche lobe. The residuals suggest the presence of an accretion stream and hot spots (not modeled), arising from mass-transfer onto the primary.

quadrature phases were acquired over 4 runs on 2 telescopes at *Las Campanas Observatory*, Chile. Inspection of the quadrature spectra reveals that LMC-SC1-105 exhibits the *"Struve-Sahade effect"*. This term refers to the variable strength of the spectral lines of the secondary star (or primary star in some cases) in a double-lined spectroscopic binary (see Howarth *et al.* 1997 and references therein). Following the criteria of Walborn & Fitzpatrick(1990), the spectral types of the primary and secondary are O8 V and O8 III–V at phase 0.75, respectively. The Struve-Sahade effect causes the spectral types of both stars to change: at phase 0.25 the stars appear to have types O7V and O8.5 III-V.

Radial velocities were measured from the spectra via two dimensional cross correlation (Zucker & Mazeh 1994) and PHOEBE (Prša & Zwitter 2005) was used to derive the light curve parameters (Figure 3). The final values for the masses and radii are $M_1 = 30.9 \pm 1.0\ M_\odot$ and $R_1 = 15.1 \pm 0.2\ R_\odot$ for the primary, and $M_2 = 13.0 \pm 0.7\ M_\odot$ and $R_2 = 11.9 \pm 0.2\ R_\odot$ for the secondary. The semi-detached configuration of LMC-SC1-105 with the less massive star filling its Roche lobe, along with the main sequence classification of the primary and possible (sub)giant classification of the secondary, point to the system being

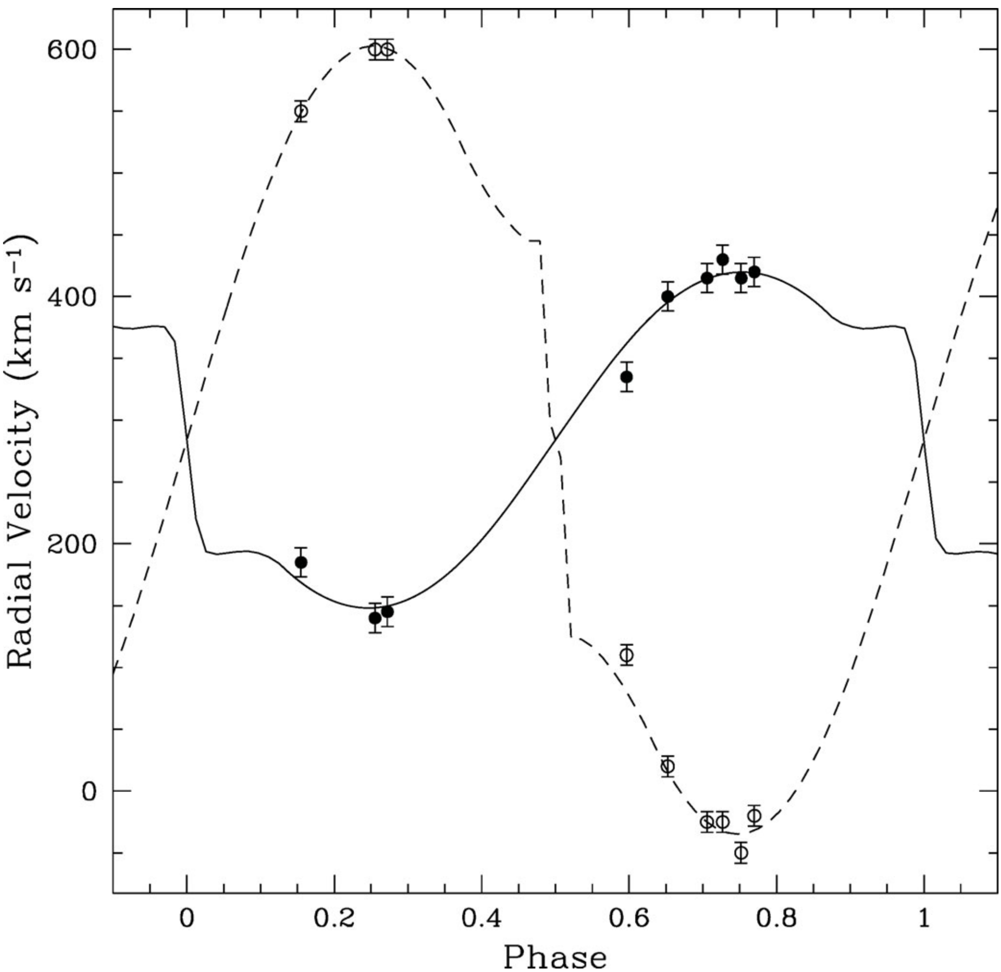

Figure 3. Radial velocity curve for LMC-SC1-105. The TODCOR measurements are shown as filled circles for the primary and open circles for the secondary; overplotted is the best fit model from PHOEBE, denoted by a solid line for the primary and a dashed line for the secondary.

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in a slow-mass-transfer stage of case A binary evolution (see Bonanos 2009 for further details).

3. Conclusions

The parameters of LMC-SC1-105 were determined from the light curves available from the OGLE and MACHO surveys and newly acquired high resolution spectroscopy that targeted quadrature phases. The system was found to contain a very massive main sequence primary (30.9 ± 1.0 $M_\odot$) and a possibly evolved Roche lobe-filling secondary. The spectra display the Struve-Sahade effect, which is present in all the He I lines, causing the spectral classification to change with phase, and could be related to the mass transfer occurring in the system. LMC-SC1-105 could further be used as a distance indicator to the LMC. However, in addition to accurate radii, accurate flux (i.e. effective temperatures) and extinction estimates are necessary for accurate distances. Eclipsing binaries have been used to derive accurate and independent distances to the LMC (e.g., Guinan *et al.* 1998), the SMC (Harries *et al.* 2003; Hilditch *et al.* 2005), M 31 (Ribas *et al.* 2005) and most recently to M 33 (Bonanos *et al.* 2006).

The accurate parameters determined for LMC-SC1-105 contribute valuable data on very massive stars, increasing the current sample of 14 very massive stars with accurate parameters to 15, which despite their importance remain poorly studied. Such data serve as an external check to resolve the "mass discrepancy" problem, as Burkholder *et al.* (1997) have shown, and to constrain stellar atmosphere, evolution and formation models. Further systematic studies of massive binaries in nearby galaxies are needed to extend the sample of 50 SMC eclipsing binaries (Harries *et al.* 2003; Hilditch *et al.* 2005) to higher masses and metallicities and populate the sparsely sampled parameter space (mass, metallicity, evolutionary state) with accurate measurements of their masses and radii. The method of targeting very massive stars in bright blue eclipsing binaries can therefore be employed towards this goal.

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Some more Pimms...

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