A Survey of the Most Massive Stars in the Local Universe

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Motivation

Very massive stars (>30 Mo) are extremely rare objects, though their importance for astrophysics is large (see review by Massey 2003). 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 core-collapse supernovae and long gamma-ray bursts. In total, only 15 stars with masses >30 Mo in the Local Group have accurate determinations of their parameters (see Figure 1). Theoretical models of massive star formation and evolution are currently lacking observational constraints (see Zinnecker & Yorke 2007, Meynet & Maeder 2003), thus **accurate measurements of the masses, radii and luminosities of massive stars, possible only with eclipsing binaries (EBs), are overdue**. Massive binaries, similar to WR20a, are bound to exist in the young massive clusters at the center of the Galaxy (Center, Arches, Quintuplet), in super star clusters (e.g. Westerlund 1), in Local Group galaxies (e.g. LMC, SMC, M31, M33) and beyond (e.g. M81, NGC 2403). **To remedy the situation, a systematic survey of these clusters and galaxies for massive stars in eclipsing binaries was undertaken.**

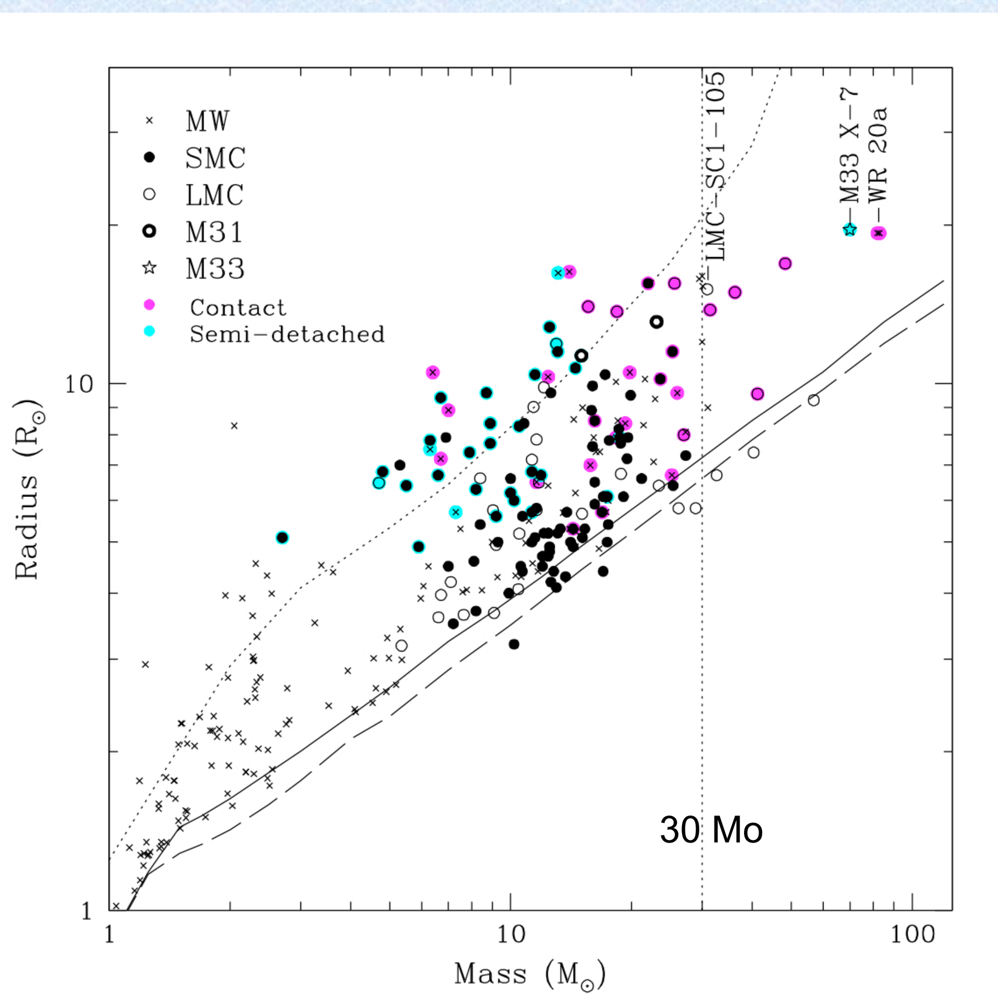

Figure 1. Mass and radius determinations of stars in eclipsing binaries from the literature, **accurate to 10%** and complete ≥30 Mo (from Bonanos 2009). The solid line is the Z=0.02 ZAMS from Schaller et al. (1992); the dashed line is the Z=0.008 ZAMS from Schaerer et al. (1993). Note the small number of measurements for stars with masses greater than 30 Mo, all published recently (since 2001). Contact systems and semi-detached stars are denoted by magenta and cyan symbols, respectively.

Massive Stars in Binaries

• >116 ± 33 Mo, >48 ± 20 Mo (Schnurr et al. 2009)	R145 (WN6ha)
• 116 ± 31 Mo, 89 ± 16 Mo (Schnurr et al. 2008)	NGC 3603-A1 (WN6ha)
• >87 ± 6 Mo, >53 ± 4 Mo (Niemela et al. 2008)	WR 21a (O3f*/WN6ha)
• 83 & 82 ± 5 Mo (Rauw et al. 2004, Bonanos et al. 2004)	WR 20a (WN6ha)
• 70.0 ± 6.9 Mo (Orosz et al. 2007)	M33 X-7 (O7 III + BH)
• 56.9 ± 0.6 Mo (Massey et al. 2002)	R136-38 (O3V+O6V)
• >55.3 ± 7.3 Mo (Schweickhardt et al. 1999)	WR 22 (WN7+ O9)

Strategy

The strategy of the survey involves discovering eclipsing binaries via photometric variability surveys, from which the brightest, blue, and thus most massive ones are selected for spectroscopic follow-up. The goal is to find and measure parameters accurate to ~5% of the most massive stars (~30-150 Mo) in eclipsing binaries located in a variety of environments, probing galaxies with both high and low metallicities. The nearest very massive stars are found in the young clusters near the Galactic Center and in young super star clusters, such as Westerlund 1.

LMC-SC1-105

Ten bright blue systems discovered by the OGLE survey (Wyrzykowski et al. 2003) were selected for spectroscopic follow up with the DuPont 2.5m and the Magellan 6.5m telescopes at Las Campanas Observatory, Chile, with the goal of measuring fundamental parameters for 20 massive stars accurate to ~5%. The light and radial velocity curves for LMC-SC1-105 (O8V+O8III-V), one of the brightest targets, are shown in Figure 2. The derived masses **confirm** that the brightest eclipsing binaries in the LMC contain very massive stars and contribute valuable data on very massive stars (see Bonanos 2009 for further details).

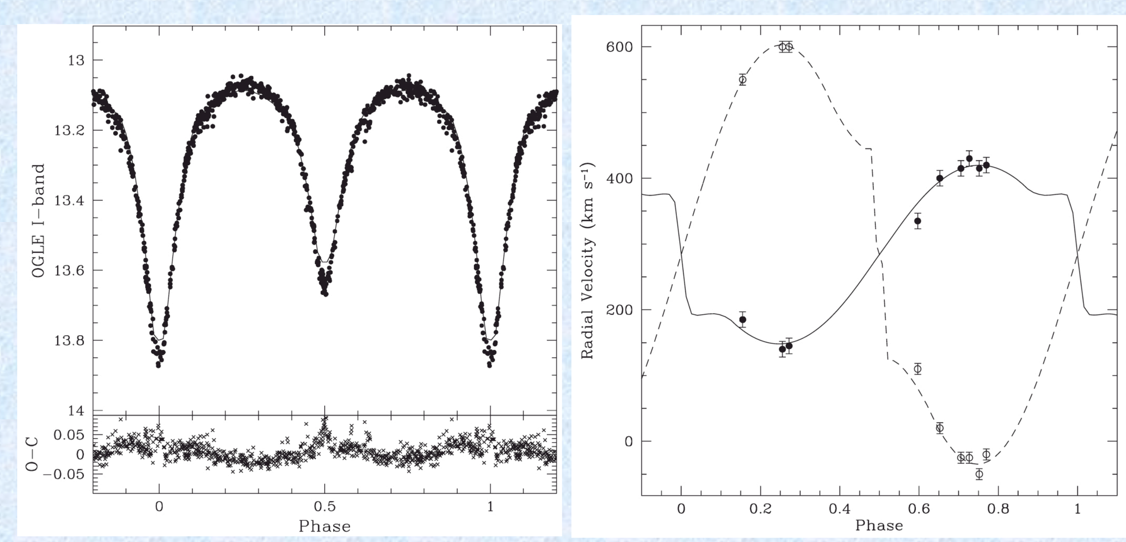

Figure 2. Left: Phased OGLE I-band light curve for LMC-SC1-105. A semidetached model (solid curve) with the secondary filling its Roche lobe is overplotted. The residuals suggest the presence of an accretion stream and hot spots (not modeled), arising from mass transfer onto the primary. Right: Radial velocity curve for LMC-SC1-105 (P = 4.25 days). The derived masses and radii are M_1= 30.9 ± 1.0 Mo and M_2 = 13.0 ± 0.7 Mo, and R_1= 15.1 ± 0.2 Ro and R_2 = 11.9 ± 0.2 Ro, demonstrating the success of the survey.

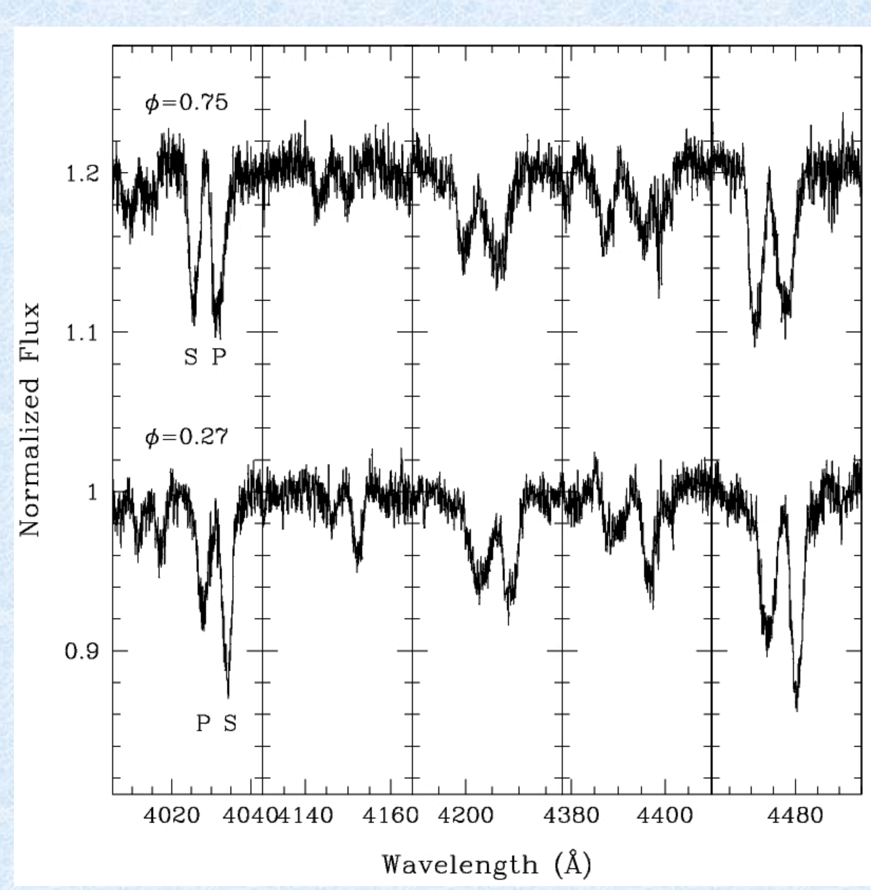

Figure 3. Quadrature spectra of LMC-SC1-105, obtained at phases φ = 0.75 and 0.27. The primary (P) and secondary (S) stars are labeled in the first panel. The panels display the He I λ4009 and He II λ4026, He I λ4144, He II λ4200, He I λ4387, and He I λ4471 lines, respectively. The system displays the Struve–Sahade effect, i.e. the lines of the secondary are stronger at φ=0.27.

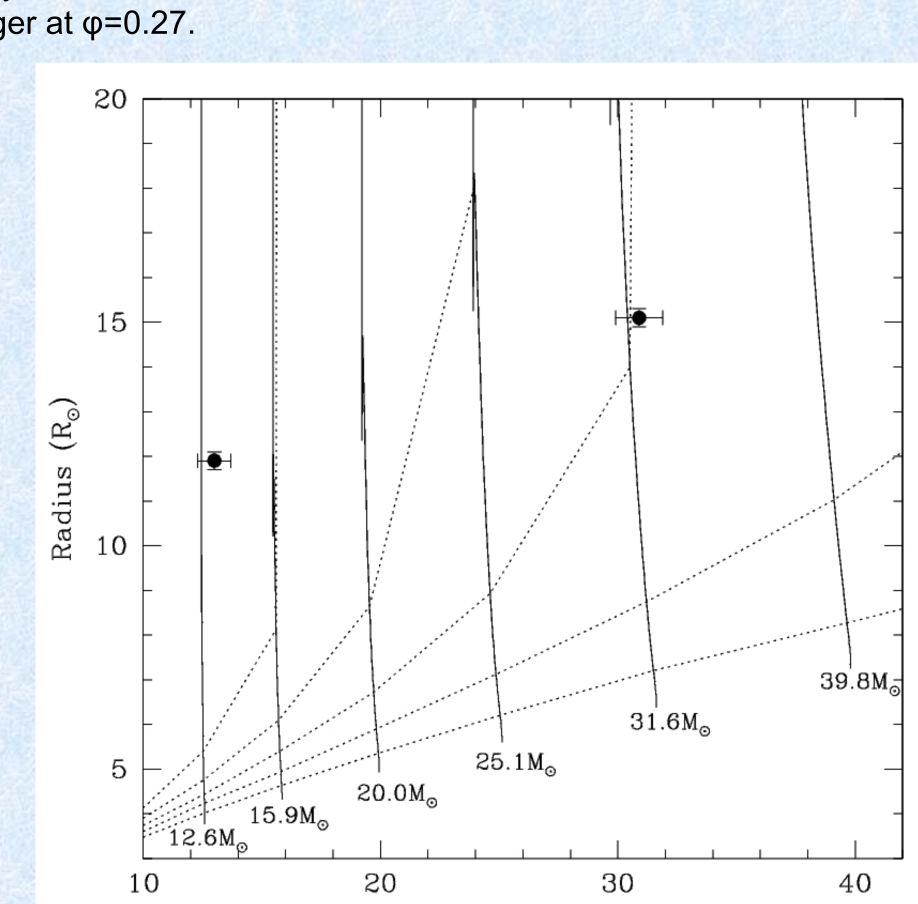

Figure 4. Comparison of the parameters of LMC-SC1-105 with evolutionary tracks (solid lines) and isochrones (dotted lines) for single stars at Z = 0.007 (Claret 2006). The isochrones, from the bottom up, correspond to 1, 3, 5, 7, and 10 Myr isochrones. Single star isochrones are not compatible with the measured parameters for the system, because it has undergone mass transfer.

Westerlund 1

Bonanos (2007) presented the first variability study of the Wd 1 super star cluster, in search of massive eclipsing binaries. At a distance of 3.5-4 kpc, Wd1 has a dynamical mass ~63,000 Mo (Mengel et al. 2007) and an age of 4.5-5 Myr (Crowther et al. 2006). Currently, 24 WR stars have been identified in Westerlund 1 (Crowther et al. 2006), concentrating ~8% of the known galactic WR stars in one cluster (van der Hucht 2006). The variability study revealed 129 new variable stars, including the **discovery of 4 eclipsing binaries that are cluster members**, 1 additional candidate, and 11 WR stars. The bright X-ray source corresponding to the Wolf-Rayet star WR77o (B) was found to be a 3.51 day eclipsing binary, thereby enabling the dynamical measurement of the mass and radius of a WR star. The discovery of a reddened detached eclipsing binary system implies the **first identification of main-sequence stars in Westerlund 1,** and provides constraints to the progenitor of the magnetar (Muno et al. 2006) .

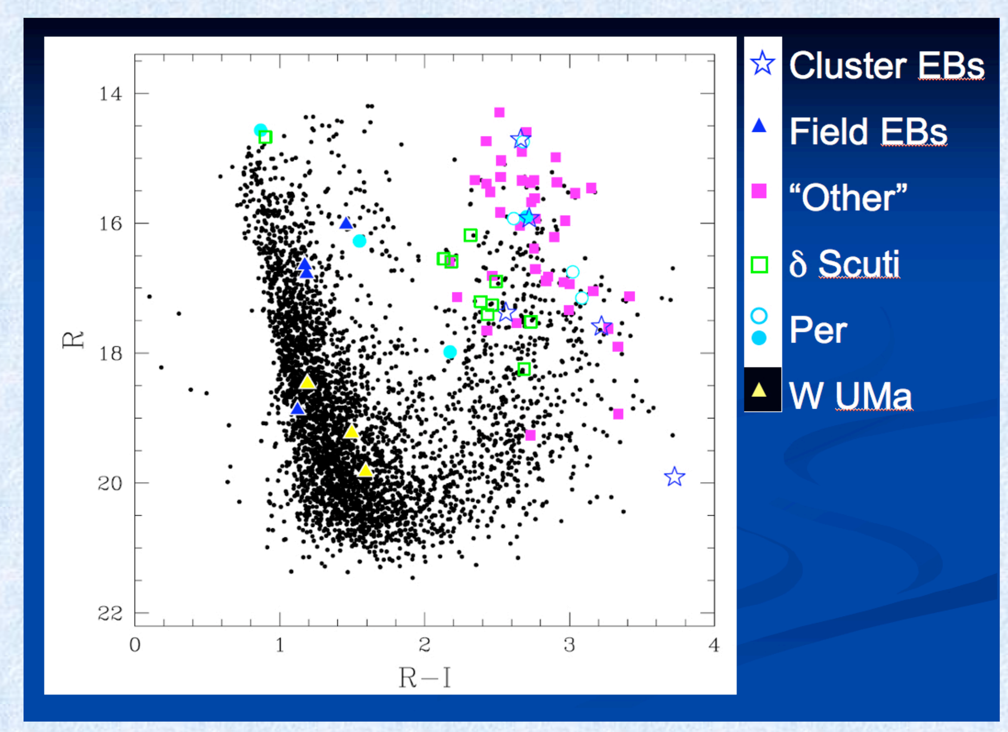

Figure 5. R vs. R-I CMD for Westerlund 1 showing the location of the variable stars with light curves in these bands (Bonanos 2007). Note that the location of the massive EBs is distinct from the foreground binaries.

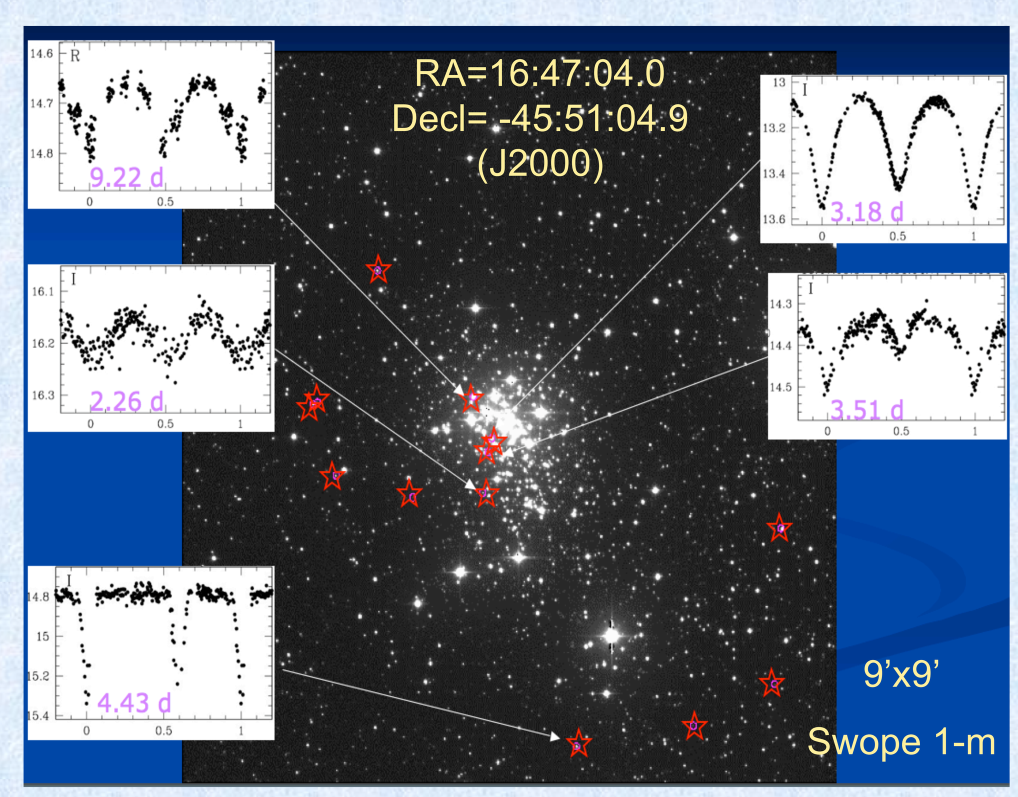

Figure 6. I-band image of Westerlund 1, showing the positions of the newly discovered eclipsing binaries (red stars) and phased light curves of the 5 eclipsing binaries that are cluster members (Bonanos 2007). The 3.51 day system corresponds to WR77o (B). High resolution spectroscopy to derive their parameters is underway with the 6.5 m Magellan/MIKE.

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