OBSERVING REQUEST
University of Arizona Observatories

Year: *2003* **Term:** *Sep - Dec* **Proposal Number:**

The Evolution of Massive Stars: Closing the Loop Observationally in the Local Group

PI: Phil Massey, Lowell Obs.

CoI(s): Kathleen DeGioia-Eastwood, Dept. Phys.& Astron., NAU

Proposal Type: short-term

Abstract of Scientific Justification

The evolved (He-burning) descendents of massive O-type stars include the Luminous Blue Variables (LBVs), Wolf-Rayet stars (WRs), and Red supergiants (RSGs). What mass ranges turn into which of these should depend upon the metallicity of the host galaxy, as mass-loss rates are metallicity dependent, and it is the amount of mass-loss which determines much about the evolution of massive stars. Evolutionary models for massive stars have advanced in recent years, but still fail to reproduce the observed relative number of RSGs and WRs by large factors. Here we propose a continuation of our work to establish the progenitor masses of LBVs, WRs, and RSGs directly by determining the mass of the most massive unevolved stars in clusters that contain these evolved objects. We see large differences between the Milky Way with the lower-metallicity SMC and LMC; completing such a study for M31 is more challenging (because the stars are much fainter) but it offers an unprecedented opportunity to determine what happens at a metallicity which is roughly two times solar.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Cage	Optimal months	Accept. months
1	MMT	Blue	3	dark	OPT	Sept-Oct	Sept-Nov
2							
3							
4							

Scheduling constraints and non-usable dates *(up to two lines).*

None

Is sharing nights possible and/or advisable?

OK

Approval for Instrument Use from PI? N/A

For MMT requests only: Percentage of time to be assigned to UAO and CfA 100, 0

Observing List (attach list if longer than 10 objects)

Object	RA	DEC	Magniude
8 slit positions (2 stars/position) in M31	00:40	40:45	18.6-19.5

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GRADUATE STUDENTS:

Whose second year project is this? ____________________

Whose thesis is this? ____________________

For **each** graduate student named on the front page, provide the following information:

Student's Name	Advisor's Name	Advisor's Signature

Scientific Justification

Massive stars are rare: for every $20\mathcal{M}_\odot$ star there are $\sim 10^5$ solar-type stars in the Galaxy; for every $100\mathcal{M}_\odot$ star, there are over a million. Nevertheless, massive stars have an importance far beyond their scant numbers. Through the actions of their strong stellar winds, and eventual disruption as supernovae, they provide much of the energy input into the interstellar medium (Abbott 1982). Their short lives (< 8 Myr) and high mass-loss rates ($> 10^{-6}\mathcal{M}_\odot$/yr) result in their being the primary source of CNO enrichment in the Galaxy (Maeder 1992). Furthermore, their high effective temperatures and luminosities result in their providing nearly all of the UV flux, while also powering the far-infrared luminosities of galaxies through the heating of dust (Maeder & Conti 1994).

Unfortunately, the lives of massive stars are hard to model. Radiatively-driven stellar winds result in significant mass loss even on the main sequence: a $100\mathcal{M}_\odot$ O-type star might lose half its mass during the core-H burning phase. As the star evolves to the He-burning phase, mass-loss rates may increase 10-fold or more as the atmospheric opacity increases with decreasing effective temperatures to about 10,000°K (A0 I). The highest luminosity stars exceed their Eddington limits at this point, resulting in episodic mass loss as the star becomes a Luminous Blue Variable (LBV). (Well-known examples of LBVs include η Car and S Dor.) Further evolution and mass loss lead to Wolf-Rayet stars (WRs) and/or red supergiants (RSGs).

This mass loss depends upon the initial metallicity, scaling in an uncertain manner (see Kudritzki 2002 and discussion in Massey 2003). Thus the evolution of massive stars will depend upon the metallicity of the host galaxy. We can expect that the effect that metallicity has on the evolution of massive stars will affect the integrated colors of star-forming regions, and thus be important in efforts to understand the colors of galaxies at early look-back times, as well as the interpretation of the resolved massive stellar population closer to home. Indeed, gross differences are seen in the relative number of RSGs/WRs as a function of metallicity (Fig. 1). This trend is not well reproduced by evolutionary models.

Here we are proposing to use a sensitive, direct method to determine the progenitor masses of evolved massive stars; the results will be of crucial importance in evaluating and improving the new generation of stellar evolutionary models now becoming available (e.g., Maeder 1999). If an OB association or young cluster is coeval, then the "turn-off mass" (the mass of the highest mass star still on the main-sequence) can be used to set the lower limit on the mass of any evolved massive stars in the same cluster. This is a classic tool of stellar astrophysics, first used by Sandage (1956) to determine the mass of RR Lyrae stars in globular clusters, and subsequently used by Anthony-Twarog (1982) to find the progenitor masses of white dwarfs in intermediate-age clusters. To apply it to massive stars requires a much higher degree of coevality, but by constructing an H-R diagram we can *measure* the degree of coevality directly. In our previous studies in the Magellanic Clouds and Milky Way (Massey et al. 2000, 2001) we found that young associations met our stringent coevality criterion in about half the cases. We were able to establish that WRs in the low-metallicity SMC must come from stars with masses $> 80\mathcal{M}_\odot$, while in the Milky Way stars as low in mass as $25\mathcal{M}_\odot$ can evolve to Wolf-Rayets (Fig 2).

We now wish to extend this work to the Andromeda Galaxy, M31, which has the highest metallicity of any galaxy with a resolved massive star population. 4-m CCD *UBV* imaging has selected candidate massive stars in OB associations containing evolved massive stars (WRs and RSGs), *HST* WFPC2 images have been obtained to check for crowding, and STIS spectra have been obtained for the stars too crowded to do from the ground. We began this project in the mid-90s with the old MMT, but need the larger aperture of the new MMT to obtain spectra of the visually fainter (but intrinsically bluer and hotter) stars in our sample. We expect these stars to be the more bolometrically luminous and massive members of the Andromeda Galaxy.

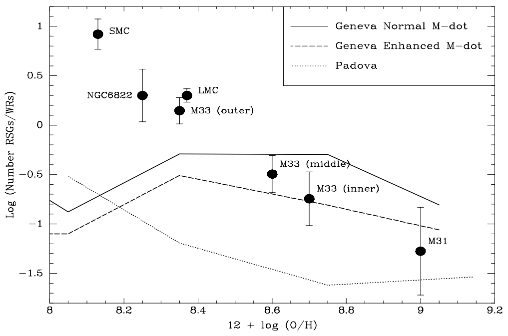

Figure 1: The relative number of red supergiants (RSGs) and Wolf-Rayet (WRs) changes by 2 orders of magnitudes over just a 0.8 dex change in metallicity. Yet these trends are not reproduced by any of the evolutionary models (solid lines) to date. From Massey (2003).

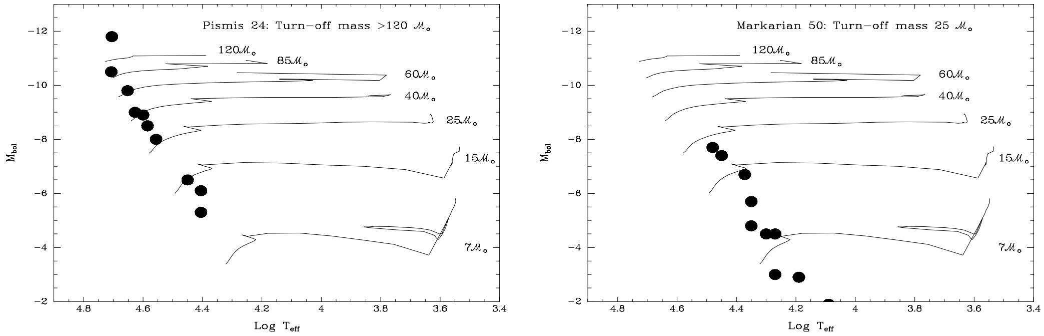

Figure 2: The H-R diagram of two young Galactic clusters demonstrate that at Milky Way metallicities Wolf-Rayet stars come from a large range of masses. Pismis 24 (left) contains a Wolf-Rayet star of type WC7, and Markarian 50 (right) contains a Wolf-Rayet star of type WN4.5. The clusters are sufficiently coeval for the turn-off mass of the cluster to set a lower bound on the progenitor masses of the WRs. We find that at Galactic metallicities some WC star progenitors are of very high mass ($> 120\mathcal{M}_\odot$), while some WN stars must come from stars as low in mass as $25\mathcal{M}_\odot$. What will we find in the higher metallicity galaxy M31?

- Abbott 1982, ApJ, 263, 723
- Anthony-Twarog 1982, ApJ, 255, 245
- Kudritzki 2002, ApJ, 577, 389
- Kudritzki & Puls 2000, Annual Reviews Astron & Astrophys, 38, 613
- Maeder 1992, A&A, 264, 105
- Maeder 1999, in Wolf-Rayet Phenomena in Massive stars and Starburst Galaxies, 177
- Maeder & Conti 1994, Annual Reviews Astron & Astrophy, 32, 227
- Massey 1998 in The Stellar Initial Mass Function, ed. Gilmore & Howell, 17.
- Massey 2003 Annual Rev Astron & Astrophys, 41, 15
- Massey, Armandroff, Pyke, Patel, & Wilson 1995, AJ, 110, 2714
- Massey, Bianchi, Hutchings, & Stecher 1996, ApJ, 469, 629
- Massey, DeGioia-Eastwood, & Waterhouse 2001, AJ, 121, 1050
- Massey, Waterhouse, & DeGioia-Eastwood 2000, AJ, 119, 2214
- Sandage 1956, ApJ, 123, 278
- Zaritsky, Kennicutt, & Huchra 1994, ApJ, 420, 87

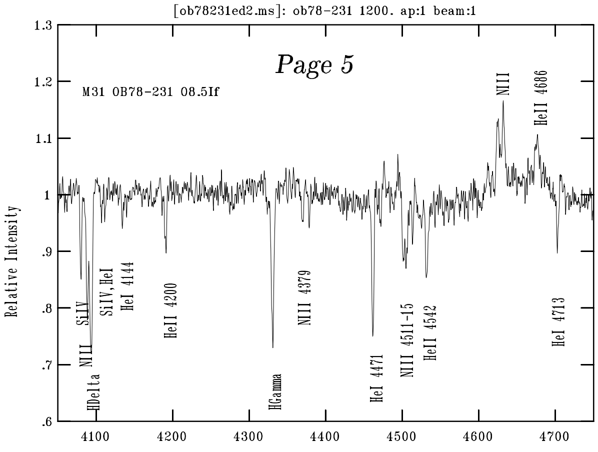

Figure 3: During our half night of clear weather last year at the MMT, we obtained this spectrum of a $B = 19.0$ magnitude O-type star in M31 (a 2 hr integration). The resulting S/N is 100 per 1Å resolution element, and shows what can be done with the 6.5-m MMT! The relative strengths of He I $\lambda4471$ and He II $\lambda4542$ establish that this is of spectral type O8.5, while the NIII $\lambda\lambda4634, 42$ and He II $\lambda4686$ emission (along with strong Si IV $\lambda4089$ *absorption*) make it an "If" supergiant.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

We will obtain high S/N data in the blue (S/N$\sim$ 100) and at Hα (S/N$\sim$ 75). Such high S/N is needed as the key diagnostic lines are quite weak in O-type stars, while the Hα profile needs to be well determined for accurate assement of the mass-loss rates. For the detailed modeling we will use Rolf Kudritzki's stellar atmosphere code, which we have implemented at Lowell. These models are spherically extended, include the hydrodynamics of stellar winds, and provide the full non-LTE treatment of metal lines (Kudritzki & Puls 2000). These models will yield values for the mass-loss rates, effective temperatures, and bolometric luminosities. The model fits will also provide a check on the metallicity we adopt, based upon the HII region abundance studies of Zaritsky et al. (1994). With the stellar parameters thus determined, we will use the Geneva evolutionary tracks to assign masses and ages to our stars, following the procedures of Massey et al. (2000, 2001), where we imposed an objective, rigorous measure of coevality, and ignored the clusters that failed to qualify.

Two remaining points that we wish to emphasize: (1) This study is not possible to carry out using photometry alone; spectroscopy is critical. As shown unequivocally in Massey (1998), the colors of hot stars are essentially degenerate with effective temperatures above 30,000°K, while the bolometric corrections are a very steep function of effective temperature. Good photometry is necessary for this study but by itself is not sufficient. (2) This spectroscopy can be best carried out with the MMT and blue channel. The blue observations will be made with the 832 grating in 2nd order (3800Å-5000Å) with 1.0 Å resolution using a $CuSO_4$ blocking filter, a setup which we have used many times with good success (e.g, Massey et al. 1995, 1996). For the Hα observations, we will simply remove the blocking filter and change grating tilts, obtaining 1.9Å resolution. With the MMT last September we obtained a count rate of 1.5 e/sec/Å at B=19, and thus 2 hours/star is needed to achieve a S/N$\sim$100 under dark skies in the blue; 1 hr/star is needed at Hα. We can, however, observe 2 stars at each slit position by aligning the slit with judicious concern for the paralactic angle and crowding considerations. Our sample includes 4 OB associations with evolved massive stars, a bare minimum to draw meaningful conclusions, and we will observe 3-4 stars per region to assure that we've found the most massive unevolved stars in each region and to check for coevality. Thus (2 hr [blue] + 1 hr [red]) x 2 slit positions x 4 OB associatiosn = 24 hr, and we are asking for 3 nights.

Previous Use of Steward Facilities *List allocations of telescope time on facilities available through Steward to the investigators during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal.*

In the mid-1990s the Steward TAC generously gave us blue channel time on the (old) MMT; these data appeared in Massey et al. (1995, 1996) and help “fill in” the H-R diagrams we plan to complete as part of the present proposal. However, visually fainter (but bolometrically more luminous) stars had to await the larger aperture of the refurbished MMT. Last year, while Eastwood was on leave from NAU (rotating at the NSF), we applied for, and were granted, 3.5 nights on the MMT through the NOAO TAC. Unfortunately, the late monsoons during the first week of September wiped out all but half a night. Nevertheless, we obtained a few excellent spectra during that time. These data appeared in 2002, ApJ, 580, L35.

Note that the *HST* TAC generously gave us 1 night of MMT time in the upcoming semester (through the NOAO/HST coordinated program time) in support of a successful Cycle 12 proposal to study the structure of the stellar winds at high metallicity using 4 O-type stars in M31. The targets in that proposal have previously been observed with the MMT in the blue, and we require only Hα data to complement our pending STIS/FUV data. Those targets are not the same as the ones here, and they are being observed for different scientific purposes. If convenient, however, the programs can be scheduled back to back.