NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: April 1, 2002 **Category:** Resolved Galaxies

The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andromeda Galaxy

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We are proposing to obtain spectra of hot, massive O-type stars in M31 in order to determine the fundamental properties (effective temperature, luminosity, mass-loss rates) of these stars at high metallicity. Using extensive ground-based and *HST* data we have selected stars in young clusters and associations that contain evolved massive stars of various types (Wolf-Rayet, red supergiant). Our data will allow us to determine how coeval these regions are, and for the ones that show no detectable age spread, we can use the cluster turn-off masses to set lower limits on the progenitors of these evolved stars. This will provide a sensitive test of massive star evolution at high metallicities, where the mass-loss rates should be 1.5× greater for stars of the same luminosity than in the Milky Way. The observations we propose of O-type stars in M31 require the large aperture of the MMT and high spectral resolution of the Blue Channel spectrograph.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	MMT	BCHAN	2.5	dark	Sep - Oct	Sep - Nov
2						
3						
4						
5						
6						

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

None.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

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 number. 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).

The physics of massive stars is complicated, and reliable stellar models cannot be constructed from first principles; instead, observations must be used to "close the loop" with these models. Many of these stars are near their Eddington limit, with gravity delicately balanced by radiation pressure, requiring spherically extended atmosphere models. Strong stellar winds may remove half of a star's mass during its main-sequence evolution, and the functional dependence of mass-loss on stellar parameters greatly influences the theoretical evolutionary tracks (Maeder & Conti 1994). Mixing of fresh hydrogen back into the core, and the removal of highly processed material from the core, can have a large effect on the expected evolution of a star, but there is little agreement among the pundits on how to treat the relevant processes of semi-convection and convective overshooting (Maeder & Conti 1994; Langer & Maeder 1995), while the most recent work has emphasized the significant role that rotation may play in this regard (Maeder 1997, 1999).

The PI is engaged in an NSF-funded study to understand the evolution and physical parameters of massive stars by using the galaxies of the Local Group as our laboratories. Since mass-loss occurs through radiation pressure in highly ionized metal lines, stars of a given luminosity should have a lower mass-loss rate in the low-metallicity SMC than in a high-metallicity galaxy such as M31. Indeed, we find extreme differences in the relative population of evolved massive stars (Fig. 1) over this $10\times$ change in metallicity. By using this and other "global" measures (such as the blue-to-red supergiant ratio) we obtain something useful against which the stellar models can be compared.

However, a much more sensitive test is possible, and it is for this that we are proposing here. 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 now need the larger aperture of the MMT to obtain spectra of the visually fainter stars, which we expect to be the more bolometrically luminous and massive members of the Andromeda Galaxy.

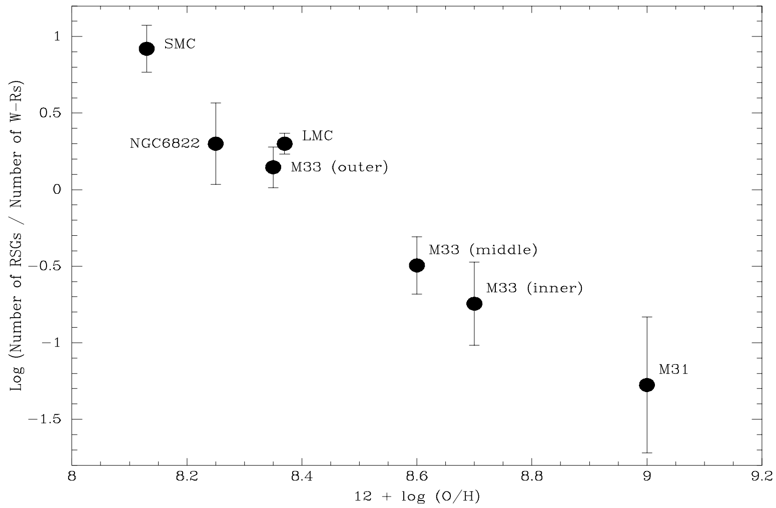

Figure 1: The relative number of red supergaints (RSGs) and Wolf-Rayet (WR) stars change as a function of metallicity among the Local Group galaxies. This *global measure* relies upon the assumption that we are observing samples which are totally heterogeneous in ages. This figure is from Massey (2002).

REFERENCES—Science Justification and Experimental Design

Abbott 1982, ApJ, 263, 723

Anthony-Twarog 1982, ApJ, 255, 245

Kudritzki & Puls 2000, Annual Reviews Astron & Astrophys, 38, 613

Langer & Maeder 1995, A&A, 295, 685

Maeder 1992, A&A, 264, 105

Maeder 1997, A&A, 321, 134

Maeder 1999, in Wolf-Rayet Phenomena in Massive stars and Starburst Galaxies, 177

Maeder & Conti 1994, Annual Reviews Astron & Astrophy, 32, 227

Massey 1998a, ApJ, 501, 153

Massey 1998b in The Stellar Initial Mass Function, ed. Gilmore & Howell, 17.

Massey 2002, ApJS, in press

Massey, Armandroff & Conti 1986, AJ, 92, 1303

Massey & Johnson 1998, ApJ, 505, 793

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

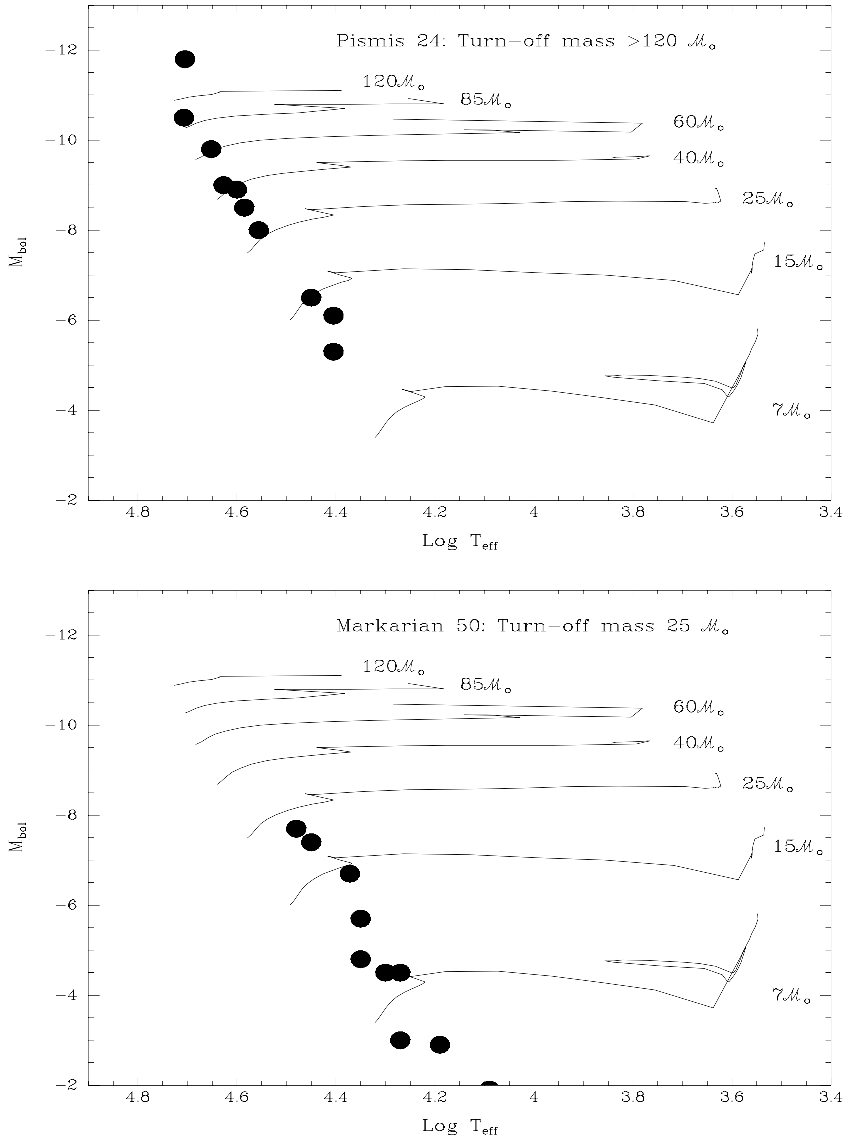

Figure 2: The H-R diagram of two young Galactic clusters demonstrate that at Milky Way metallicities Wolf-Rayet stars come from a large range of masses. Pismis 24 (top) contains a Wolf-Rayet star of type WC7, and Markarian 50 (bottom) contains a Wolf-Rayet star of type WN4.5. The clusters are sufficiently 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?

Experimental Design *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)*

Our sample of stars consists of the bluest and more luminous members of five OB associations in M31 known to contain Wolf-Rayet and red supergiants (Massey & Johnson 1998; Massey 1998a). We have used KPNO 4-m CCD *UBV* images (Massey, Armandroff, & Conti 1986) as our starting point, supplemented by WFPC2 data to ascertain that stars that appear to be single from the ground-based data aren't unresolved tight clusters. Our spectroscopy of the brighter OB stars was carried out mostly with Hydra on the 4-m and the MMT blue channel (Massey et al. 1995, 1996), with *HST* STIS time used to observe the handful of stars too crowded to do from the ground. The spectroscopy we propose here is the culmination of these efforts, as the larger aperture has been needed to obtain data on the (visually fainter) stars which—owing to the steep dependence of the bolometric correction on effective temperature (see Massey 1998b)—may in fact be the most luminous and hence massive stars in these associations.

Our plan is as follows. For the brighter stars on our list ($B = 18 - 19$) we will obtain high S/N (100) data in the blue ($\lambda\lambda 4000-4700$) and at Hα for detailed modeling. Through our collaboration with Rolf Kudritzki, we have implemented his stellar atmosphere code at Lowell. These models are spherically extended, include the hydrodynamics of stellar winds in the entire sub- and supersonic atmospheric structure (Kudritzki & Puls 2000) and provide the full non-LTE treatment of metal lines needed for the spectral synthesis of O-stars. These models will yield values for the mass-loss rates, effective temperatures, and bolometric luminosities of these stars, providing the calibration between effective temperature and spectral types. These model fits will also provide a check on the metallicity we adopt, based upon the HII region abundance studies of Zaritsky et al. (1994). For the fainter stars ($B = 19 - 20$) we will obtain more modest S/N (40) and simply classify the stars, using our newly improved calibration to then derive effective temperatures and stellar luminosities.

With parameters of effective temperature and bolometric luminosity thus determined, we will use the Geneva evolutionary models to assign masses and ages to our stars, following the procedures of Massey et al. 2000, 2001. As in those two studies, we will impose an objective, rigorous measure of coevality, and ignore the clusters that fail to meet our stringent tests.

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 unequivocably in Massey (1998b), 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 study can best be carried out with the MMT and blue channel. Neither the 4-m nor WIYN has the necessary aperture; GMOS on GEMINI can achieve the necessary resolution only with very narrow slits ($<$ 0.5-arcsec), requiring exceptional seeing conditions, and HET lacks the needed spatial resolution, even if its moderate-resolution spectrograph were available.

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

As described above, the sample of stars we are proposing to observe with the MMT were selected through the best ground-based imaging, complemented with *HST* WFPC2 imaging and STIS spectroscopy.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI 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. Please include original proposal semesters and ID numbers when available.*

Recent (2000-2002) allocation of time:

⋆ **2001A-062:** A *UBVR* Survey of the Magellanic Clouds, 6 nights CTIO Curtis Schmidt April 2001: Massey 2002, ApJS 141, in press.

⋆ **2001B-002:** The Wolf-Rayet Content of IC10, 2 nights Mayall 4-m Sept 2001; results of that analysis forms the basis for a complementary proposal submitted concurrently.

⋆ **2000B-010:** A Survey of Local Group Galaxies Currently Forming Stars, on-going survey project. We are current with all of our data reductions, and have begun the photometric analysis.

⋆ **2001B-227:** The Red Supergiant Content of the Magellanic Clouds, 3 nights CTIO 4-m Hydra, October 2001, data reduced and undergoing analysis.

⋆ **1999B-099; 2000B-070:** Where Do Wolf-Rayet Stars Come From? CTIO 1.5-m 5 nights October 2000; 6 nights October 1999: Massey & Duffy 2001, ApJ 550, 713; Niemela et al. 2002, MNRAS, in press.

Recent papers (2000-2002) based upon NOAO data:

Massey, P. 2002, "A UBVR CCD Survey of the Magellanic Clouds," ApJS, 141, in press.

Slesnick, C. L., Hillenbrand, L. A., & Massey, P. 2002, "The Star Formation History and Mass Function in the Double Cluster h and Chi Persei", ApJ, submitted.

Niemela, V. S., Massey, P., Testor, G., & Benitez, S. G. 2002, "The Massive Wolf-Rayet Binary WR7 in the SMC", MNRAS, in press.

Walborn et al. 2002, "A Giant O2-O4 Spectral Classification Study", AJ, in press.

Bianchi et al. 2001,"The Massive Star Content of NGC 6822. Ground-based and *HST* photometry, AJ, 121, 2020.

Massey, P. & Duffy, A. S. 2001, "A Deep Search for Wolf-Rayet Stars in the Small Magellanic Cloud", ApJ, 550, 713.

Massey, P., DeGioia-Eastwood, K., & Waterhouse, E. 2001, "The Progenitor Masses of Wolf-Rayet Stars and Luminous Blue Variables Determined from Cluster Turn-offs. II. Results from 12 Clusters in the Milky Way", AJ, 121, 1050.

Massey, P., Waterhouse, E., & DeGioia-Eastwood 2000, "...I. Results from 19 OB Associations in the Magellanic Clouds", AJ, 119, 2214.

Massey, P., & Foltz, C. 2000, "The Spectrum of the Nigh Sky Over Mount Hopkins and Kitt Peak: Changes After a Decade", PASP, 112, 566.

Massey, P., 2000, "An Unprecedented Change in the Spectrum of S Doradus: As Cool As It Gets", PASP, 112, 144.

Observing Run Details for Run 1: MMT/BCHAN

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

We will use the MMT's high-throughput Blue Channel for our observations of B=18-20 O-type stars in M31. The blue observations will be made with the 832 grating in 2nd order (3800Å-5000Å) with 1.0Å 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 (an operation which takes a minute or so), obtaining 1.9Å resolution.

Our goal is to achieve a S/N of 100 per spectral resolution element for the brighter stars (B=18-19) to allow modeling, while a S/N of 40 will suffice for the fainter stars (B=19-20) to allow classification using the weak helium lines.

The count-rate with the old (4.5-m) MMT was about 2.4 e/sec/Å at B=17.5 in the blue (λ4500); with the larger mirror (and two fewer reflections) we expect about a 1.0 mag increase; i.e., 2.4 e/sec/Å at B=18.5. Thus to achieve a S/N of 100 per 1Å spectral resolution element we will need to expose for about 4000 seconds (65 min) in the absence of sky for our modeling work. For the fainter stars (B=19.5) we expect a around rate of 1 e/sec/Å, and thus will achieve a S/N of 40 in about 1600 sec. We have 5 stars that we want to model (a bare minimum, if we are to include both early and late O-type dwarfs and supergaints), and another 10 stars for classification purposes. This will require 1.5 nights (assuming 8-hr nights, typical of September), including calibration and spectral standards. For the 5 stars with high S/N we will also need Hα observations, and expect a count rate about 1.0 e/sec/Å at $V = 18.5$. To obtain a S/N of 100 per 1.9Å spectral resolution element, we require 5000 sec (85 minutes). Thus 5 stars will require another 8 hours. We are therefore requesting 2.5 nights in total.

During prime dark time the sky brightness will be about 22.5 mag/arcsec^2 (see Massey & Foltz 2000, PASP), and during "dark" (First or Last quarter moon) about 21 mag/arcsec^2. Brighter than this the sky becomes comparable to or greater than than our objects, making the exposure times prohibitively long. In practice, we will do the Hα observations when the moon is up, and the blue observations when the moon is down.

Instrument Configuration

Filters: $CuSO_4$	Slit: 1.0-arcsec	Fiber cable:
Grating/grism: 832	Multislit: no	Corrector:
Order: 2 (blue) and 1 (Halpha)	$\lambda_{\rm start}$: See above	Collimator:
Cross disperser:	$\lambda_{\rm end}$: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 1 to 1

Dec. range of principal targets (degrees): 40 to 40

M31 is located at 00:40 +40:00

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.6.