NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: March 26, 2004 **Category:** Massive Stars

The Physical Parameters of Red Supergiants: When Massive Stars Are as Cool as They Get

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:

Red supergiants (RSGs) are an important but poorly characterized stage in the evolution of massive stars. Evolutionary models do not reproduce the "observed" location of RSGs in the H-R diagram, but in reality the conversion from the observable quantities (spectral type, photometry) to the theoretical quantities (effective temperature, bolometric luminosity) is quite uncertain. With time generously granted by the TAC last semester, we are in the process of collecting high quality relative spectrophotometry on a sample of Galactic RSGs to re-examine the effective temperature scale using new stellar atmosphere models. We are now proposing to extend this work to the lower-metallicity Magellanic Clouds, and particularly the SMC. Our previous work has found that the average spectral type of RSGs found in the SMC is much earlier than in the Milky Way (K5 vs M2), an effect which *may* simply be due to the effect that the lower TiO has on the appearance of the spectrum; the average spectral types of RSGs in the LMC are intermediate between these two, consistent with metallicity being the explanation. Modeling of a Magellanic Cloud sample will allow us to determine the effective temperature scale of RSGs as a function of metallicity, either confirming or rejecting this hypothesis. This new calibration will provide the observational constraints against which future evolution models may be compared.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	RCSP + BAS	5	bright	Nov - Dec	Oct - Dec
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.*

We tend to equate "massive stars" with "hot stars", owing to the fact that while on the main-sequence these are OB stars with effective temperatures of 30,000°K or more. Among the evolved stages of massive stars, most attention has been given to the spectacular Luminous Blue Variables, which are hot stars near their Eddington limit shedding mass at a prodigious rate (η Car, S Dor), and the enigmatic Wolf-Rayet stars, with high effective temperatures and optically thick winds. We sometimes overlook the fact that the majority of massive stars spend a significant fraction of their lives as red supergiants (RSGs) with extremely cool effective temperatures and gigantic radii.

The stellar evolution of a massive star is hard to model owing to the complications of mass-loss; in addition, the tracks are sensitive to the treatment of convection and mixing (Maeder & Meynet 1987, Maeder & Conti 1994). Recent emphasis has been on the role that rotation plays in mixing in massive stars (Maeder & Meynet 2000, 2002). An excellent observational database has been growing which allows critical comparison between theory and observation. An example is shown in Fig. 1, where we see that the relative fraction of RSGs and WRs is a very strong function of metallicity (Massey 2003). This is in the sense predicted by Maeder et al. (1980): at low metallicities there is less mass-loss and hence it is harder to produce a WR, as this requires stripping off the outer layers of the star until processed material is revealed at the surface. But we also see in Fig. 1 that quantitatively none of the models fit the observed trend very well (Massey 2003).

This comes about from the fact that the evolutionary models do not *seem* to produce RSGs that are as cool and luminous as those observed, as shown in Fig. 2. There are two explanations. (1) RSGs present a tremendous challenge to evolutionary calculations. In addition to possible deficiencies in the molecular opacities, these stars produce dust in their outer atmospheres, and this additional opacity complicates the definition of the photosphere. Furthermore, the velocities of the convective layers are nearly sonic, which invalidates most assumptions about mixing length. The latter provides an adjustable parameter that influences how far to the right the evolutionary tracks extend. (2) The basic "observational data" are themselves suspect owing to uncertainties in the effective temperature scale of RSGs. Although interferometric data provide a fundamental calibration of red *giants*, there are simply not enough nearby red *super*giants (Dyck et al. 1996, 1998). The data shown in Fig. 2 are based on "adjusting" the red giant scale, but there is at least a 10% uncertainty in $T_{\rm eff}$ as a result, which leads to a 1.0 mag error in the bolometric correction.

A far better approach is to use stellar atmosphere models, but until now there has not been a sufficiently good treatment of molecules. This problem has been corrected by the new generation of MARCS models (Plez 2003; Gustafsson et al. 2003; Josselin & Plez 2003), and we have begun a program in semester 2004A to obtain good spectrophotometry of a sample of Galactic stars for which we can determine a more reliable effective temperature scale.

We now seek to extend this work to the Magellanic Clouds. Our recent study (Massey & Olsen 2003) shows there is a shift in the distribution of spectral types with metallicity (seen by Elias et al. 1985 on the basis of few data), with the average type in the Milky Way M2 I, in the LMC M0-1 I, and in the SMC K5 I (Fig. 3). This may simply be due to the fact that the spectral types are based upon the strengths of TiO, which is less abundant in the Clouds. This would require RSGs in the SMC to be 300°K cooler than their Galactic counterparts of the same spectral type. To test this assertion we need good spectrophotometry to compare to these new stellar atmosphere models. When we are done, we will have an effective temperature scale for RSGs that is known as a function of metallicity, and will have a solid observational data base against which the stellar evolutionary models can be compared. Until that time, this important phase in the life of a massive star remains shrouded by the many physical complications that compromise the stellar models.

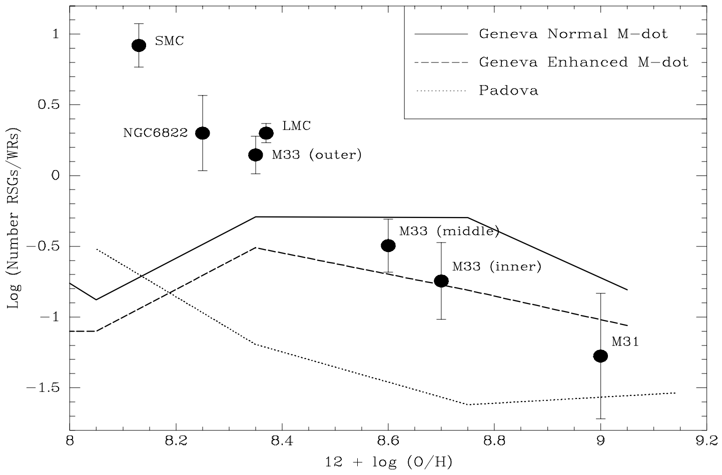

Figure 1: The relative number of RSGs and WRs changes by 2 orders of magnitude over just 0.8 dex in oxygen abundance. This is easy to understand in the sense that at lower metallicities a massive star will spend a greater fraction of its He-burning lifetime as a RSG than a WR as the mass-loss rates will be lower, and hence it will be harder to "peel down" the outer layers of the star to reveal the nuclear-processed material that characterizes a WR. None of the current evolutionary models (solid and dashed lines) reproduce this trend, however. From Massey (2003).

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Schaller, G., Schaerer, D., Meynet, G., & Maeder A. 1992, A&AS, 96, 269

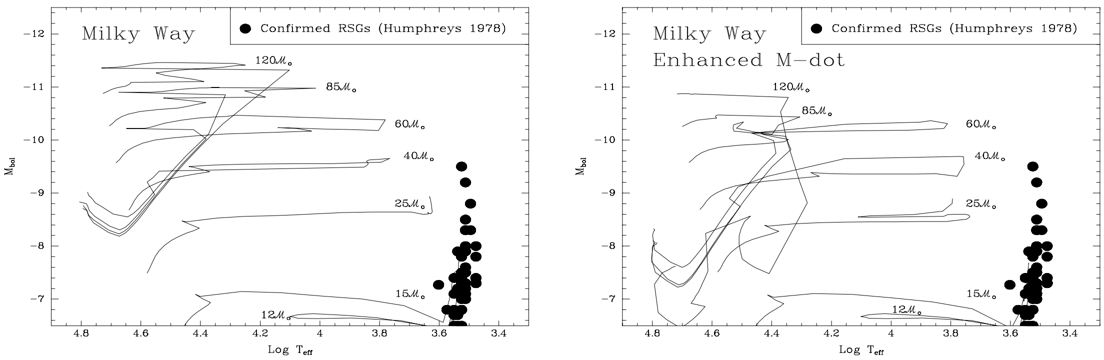

Figure 2: The location of the Milky Way RSGs in the HRD is compared to two sets of $Z = 0.02$ evolutionary tracks of Schaller et al. (1992) and Meynet et al. (1994). Although there are plenty of RSGs of initial masses $\geq 25\mathcal{M}_\odot$ present (judging from the luminosities), none of the tracks produce RSGs as cool and luminous as these—the tracks stop well to the blue side of the observed sequence. From Massey (2003).

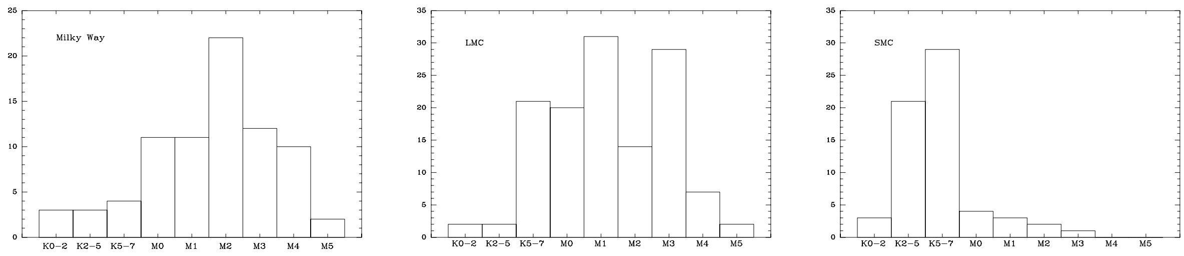

Figure 3: Histograms of the spectral types found in the Milky Way (Elias et al. 1985, Table 20) and the LMC and SMC (Massey & Olsen 2003, Tables 1 and 2). There is a progression towards earlier type with decreasing metallicity (i.e., Milky Way to LMC to SMC). The spectral classification scheme is based purely on the *strengths* of the TiO bands, and hence a lower metallicity will make a star of a given effective temperature appear earlier. Put another way, RSGs in the SMC and LMC should be cooler (and hence more bolometrically luminous) than Galactic stars of the same spectral type. From Massey & Olsen (2003, AJ, 126, 2867.

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)*

Previous comparisons between RSG models and observational data have been based primarily on broad-band photometry, with $V-R$ generally recognized as a good effective temperature indicator, while $B-V$ is sensitive to both effective temperature and surface gravity (Massey 1998, ApJ, 501, 153). However, the new generation of MARCS models allows us to perform a far more sensitive comparison, using both the relative spectral energy distribution *and* the strengths of the TiO lines. The latter, after all, form the basis for the spectral types in the first place. A similar study has been attempted by Oestreicher & Schmidt-Kaler (1998, MNRAS 299, 625) who used a preliminary form of the models and found better agreement than that produced by the Kurucz ATLAS9 models, but the data we are proposing to obtain here will be of much higher quality (better resolution, greater wavelength coverage) and will be compared to an improved (and final?) version of the MARCS models.

We have selected a sample of Magellanic Cloud RSGs with known spectral types (Massey & Olsen 2003). These stars all have modest reddenings (particularly in the SMC), and well-known distances. The dereddened intrinsic fluxes provide us with a much more sensitive test than just the broad-band colors, although the latter can readily be synthesized from our data. Observations with two different gratings will provide complete coverage from 3600Å to 9200Å. Our spectral resolution will be 5Å more than adequate for comparing the line strengths of the numerous TiO bands to that predicted by the models. With a comprehensive grid of T (3,000°K to 4,000°K at 100°K intervals) and surface gravities appropriate to supergiants ($\log g$=0.0, -0.5, and -1.0) we will be able to determine an accurate (50°K) effective temperature scale for these stars. This data set will be comparable to that we are currently obtaining for Galactic stars. Our sample includes 40 SMC RSGs and 20 LMC RSGs, allowing for a few examples of each spectral subtype (K0 I to M5 I). Such a sample size is needed to distinguish the intrinsic dispersion in such a relationship from the actual trend.

The new generation of MARCS models computed by collaborator Plez are derived from the original Gustafsson et al. (1975, A&A, 42, 407) plane-parallel, LTE, line-blanketed models, which included convective and radiative flux conservation. Subsequent improvements included the introduction of spherical symmetry, the technique of opacity sampling, and vast improvements to both the continuum and line opacities. The current version of the MARCS code is a final merging of all these changes, along with an update of the opacities and chemical equilibriums. About 600 molecular species are included. Further details can be found in Plez (2003) and Gustafsson et al. (2003).

Proprietary Period: 18 months

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.*

This program is based upon observations we obtained at CTIO in October 2001, and is complementary to a program being carried out in the current semester using Galactic RSGs.

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 (2000-2003) allocation of time:

$\boxed{\star}$ **2004A-200:** The Physical Parameters of Red Supergiants: When Massive Stars Are as Cool as They Get, 10 nights KPNO 2.1-m (5 successfully carried out in March, 5 more scheduled in late May), plus 5 nights CTIO 1.5-m scheduled for April. This is the Galactic side of the current project.

Target of Opportunity: Spectroscopy of a Newly Found Dwarf Irregular, 2 hrs kindly granted by Richard Green on the 2.1-m with GoldCam, April 2003. The data appear in Massey, Henning, & Kraan-Korteweg, 2003, AJ, 126, 2362

2002B-218: The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andromeda Galaxy", 3.5 nights MMT Sept 2002. We obtained only 0.5 nights out of 3.5 nights scheduled, due to weather, but published what we were able to get in a nice ApJ Letters paper Massey & Holmes 2002, ApJ, 580, L35

$\boxed{\star}$ **2001A-062:** A *UBVR* Survey of the Magellanic Clouds, 6 nights CTIO Curtis Schmidt April 2001: Massey 2002, ApJS 141, 81

2001B-002: The Wolf-Rayet Content of IC10, 2 nights Mayall 4-m Sept 2001: Massey & Holmes 2002, ApJ, 580, L35

$\boxed{\star}$ **2001B-227:** The Red Supergiant Content of the Magellanic Clouds, 3 nights CTIO 4-m Hydra, October 2001. This work forms the basis for the current project. Massey & Olsen 2003, AJ, 126, 2867

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 are completing the photometric analysis. Some data appear in Di Stefano et al. 2004, ApJ, in press (astroph-0306440)

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, 333, 347

Recent papers (2002-2004) based upon NOAO data:

Massey, P., Bresolin, F., Kudritzki, R. P., Puls, J., & Pauldrach. A. W. A. "The Effective Temperature Scale of O-type Stars as a Function of Metallicity. I. A Sample of 20 Stars in the Magellanic Clouds", ApJ, in press (June 20 issue, astroph/0402633)

Walborn et al. 2004, "A CNO Dicomotomy Among O2 Giant Spectra in the Magellanic Clouds", ApJ, in press (June 20 issue)

Bianchi, L., Bohlin, R., & Massey, P. 2003, "The Ofpe/WN9 Stars in M33", ApJ, 601, 228

Massey, P. 2003, "The Massive Star Content of the Local Group: Implications for Star Formation and Stellar Evolution", ARA&A, 41, 15

Di Stefano et al. 2003, "Supersoft X-Ray Sources in M31", ApJ, submitted, astro-ph/0306440

Massey, P., Olsen, K. A. G., & Parker, J. W. 2003, "The Discovery of a 12th Wolf-Rayet Star in the Small Magellanic Cloud", PASP, 115, 1265 astro-ph/0308237

Massey, P., Henning, P. A., & Kraan-Korteweg, R. C. 2003, "A Neighboring Dwarf Irregular Galaxy Hidden By the Milky Way", AJ 126, in press (Nov issue), astro-ph/0308080

Massey, P., & Olsen, K. A. G. 2003, "The Evolution of Massive Stars. I. Red Supergiants in the Magellanic Clouds", AJ, 126, 2867 astro-ph/0309272

Morrell, N. I., Ostrov, P. G., Massey, P., & Gamen, R. 2003, "Hodge 53-47: An Early O-type Double-lined Binary in the SMC", MNRAS, 341, 583

Massey, P., & Holmes, S. 2002 "Wolf-Rayet Stars in IC10: Probing the Nearest Starburst", ApJ 580, L35

Massey, P. 2002, "A UBVR CCD Survey of the Magellanic Clouds," ApJS, 141, 81

Massey, P. 2002, "Observational Constraints on Massive Star Evolution" (invited review), in *A Massive Star Odyssey, from Main Sequence to Supernova, IAU 212*, ed. van der Hucht, Herrero, & Esteban, 316.

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, 576, 880

Snow, T. P., Zukowski, D., & Massey, P. 2002, "The Intrinsic Profile of the 4428Å Diffuse Interstellar Band", ApJ 578, 877

Niemela, V. S., Massey, P., Testor, G., & Benitez, S. G. 2002, "The Massive Wolf-Rayet Binary WR7 in the SMC", MNRAS, 333, 347

Walborn et al. 2002, "A Giant O2-O4 Spectral Classification Study", AJ, 123, 2754

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.

Observing Run Details for Run 1: CT-4m/RCSP + BAS

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 observe a subsample of Magellanic Cloud red supergiants taken from Tables 1 and 2 of Massey & Olsen 2003 AJ 126, 2867. Our goal is to achieve 1% spectrophotometry (per 5Å spectral resolution element) from 3600Å to 9200Å, which will match the type of data we are currently acquiring with the KPNO 2.1-m and CTIO 1.5-m on Galactic red supergiants. In order to maintain good relative fluxes we will observe each star at the parallactic angle.

We require two gratings for complete wavelength coverage: grating KPGL1 (3600-6400Å) with a GG-345 blocking filter, plus grating KPGLF (6300-9200Å) with a GG-495 blocking filter. With the slit open to 2.5-arcsec (to allow good spectrophotometry) we expect 5Å resolution (5 pixels).

These stars typically have $V \sim 13$, with $U-B=2.0$, $B-V$=2.0 and $V-R=1$. Assuming a 15% system throughput we expect to detect 15 photons/sec/Å at 4500Å, and about one-tenth this at 3600Å. Thus to achieve a S/N of 100 per 5Å resolution element will require about 20 minutes per star for the blue spectra; the observations will be just a couple of minutes per star in the red. With overhead, we can thus expect to do about 20 stars per night in the blue, and in 3 nights we can do a 60 stars, with our plans to split our time to about 40 SMC RSGs and 20 LMC RSGs. This gives us a good coverage of spectral types, from K0 to M5, with a few stars of each type—a bare minimum. The red observations should require an additional 1.5 nights, given overhead.

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: KPGL1,KPGLF	Multislit:	Corrector:
Order: 1st, 1st	λ_{start}: See above	Collimator:
Cross disperser:	λ_{end}: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 00 to 06

Dec. range of principal targets (degrees): -60 to -70

Note that the greatest science resturn is from the SMC sample (lower metallicity) and hence October/November is preferable to December.

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

NOAO observing proposal LaTeX macros v2.9.