Resubmission of 09B-0034

NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: March 19, 2010 **Category:** Massive Stars

A Census of Yellow Supergiants in the Magellanic Clouds: Testing Massive Star Evolutionary Models

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We are proposing to continue our program to determine an accurate census of the yellow (F- and G-type) supergiants in the SMC and LMC in order to carry out a new and stringent test of the latest stellar evolutionary models. This region of the H-R diagram is heavily contaminated (80-90%) by foreground dwarfs and halo giants, but our study will use radial velocities to establish membership. Our recent study of the yellow supergiants in M31 demonstrated a serious disagreement between the evolutionary time scales for stars in this very short-lived phase. This might be connected to M31's high metallicity ($\sim 2\times$ solar) and its result on mass-loss during the red supergiant phase, or it may be a more generic problem with the models. We therefore propose to conduct similar tests at low metallicity. The Magellanic Clouds are ideal to further these studies, due both to their proximity and low reddening, plus our knowledge of their unevolved (O-type) and evolved (red supergiants, Wolf-Rayet star) populations. The TAC generously assigned us 5 nights for this project last October. Despite poor weather, we were able to obtain useful data on 74% of our SMC sample, but now need to finish our SMC sample and extend the work to the LMC. When our study is complete, the SMC and LMC will be the first galaxies to have their massive population characterized from one side of the HRD to the other, providing the observational database against which both current and future evolutionary models can be compared.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	HYDRA	8	bright	Nov - Dec	Oct - Jan
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.*

When we look at color-magnitude diagrams of nearby galaxies, we can readily pick out the blue and red supergiants (Fig. 1). However, the yellow supergiants (spectral types F0-G9 I) are lost among a sea of foreground dwarfs in the Milky Way. Such contamination is typically 80% or higher, even for galaxies at very modest Galactic latitudes (Massey et al. 2007). This is a shame, because accurate censuses of these stars at various metallicities are important for testing, and refining, stellar evolutionary models for massive stars. The lifetimes of the F- and G- supergiants stage are very short (3,000-300,000 years, depending upon the mass and metallicity), and their expected numbers and locations in the H-R diagram (HRD) are very sensitive to the uncertain values of the mass-loss rates for massive stars, and how convection and other mixing processes are treated (Maeder & Meynet 2000). As Kippenhahn & Weigert (1990) put it, "[The yellow supergiant] phase is a sort of magnifying glass, revealing relentlessly the faults of calculations of earlier phases."

Our recent study of yellow supergiants in M31 (where the metallicity is 2× solar) found a 1000× discrepancy in the relative number of lower (15-20$M_\odot$) and higher ($25 - 40M_\odot$) mass yellow supergiants compared to that predicted by evolutionary theory (Drout et al. 2009). One possible explanation is that the mass-loss rates in the red supergiant (RSG) stage are higher than usually assumed; if so, then even stars of $15 - 20M_\odot$ would evolve back to the blue after the RSG stage, and spend more time in the yellow region than the evolutionary models predict. Since only the *dust production rates* in RSGs can be measured, the actual mass-loss rates depend upon uncertain assumptions of gas-to-dust ratios in the atmospheres of these stars. But, it could also be that something more generic is awry in the models. We therefore propose to redo the experiment using the SMC and LMC, where the metallicities are ∼1/4 and ∼1/2 solar, respectively, and where the population of progenitor stars is relatively well known, unlike the case for M31, providing additional constraints on where any problems may lie with the models.

Having trustworthy evolutionary models for massive stars is key not only to understanding how massive stars themselves evolve, but also for a host of other problems of astrophysical interest, i.e.

- Determining the star formation processes in rich clusters and associations, where we find ourselves asking such questions as whether the pre-main-sequence 3-5$\mathcal{M}_\odot$ objects formed before or after the high mass stars formed (see, for example, Hillenbrand et al. 1993).
- Determining the initial mass function (IMF) in mixed-age populations, where the models are needed both to convert luminosities to masses, and to correct for the ages of stars at each point in the HRD (see e.g., Massey et al. 1995). Knowing how the IMF varies, or doesn't, with physical environment provides important constraints for models of star formation (e.g., Elmegreen 2002).
- Interpreting the integrated spectral energy distributions (SEDs) of distant starburst galaxies. The way this game is usually played is to match the observed SED using some synthesis code, such as STARBURST99 (Leitherer at al. 1999; Vazquez & Leitherer 2005). This is a wonderful, powerful tool, but is no better, and no worse, than the evolutionary models on which it is based.

Observational tests of massive star evolution provide constructive feedback to the model builders, and allow us to know what to trust, and what not to. The Magellanic Clouds are excellent testbeds for addressing where the yellow supergiant problem lies, as the evolutionary models *do* correctly predict the relative number of Wolf-Rayet stars (WRs) and RSGs in these galaxies (Massey 2003), unlike the situation for M31. The Magellanic Clouds also have the advantage that the number of blue supergiants (which are, after all, the unevolved progenitors of both the yellow and red supergiants) are known (Massey et al. 1995, Massey 2002), thanks to their proximity and low reddening. When our study is complete, the SMC and LMC will be the first galaxies to have their massive star population characterized from one side of the HRD to the other, providing the observational database against which both current and future evolutionary models can be compared.

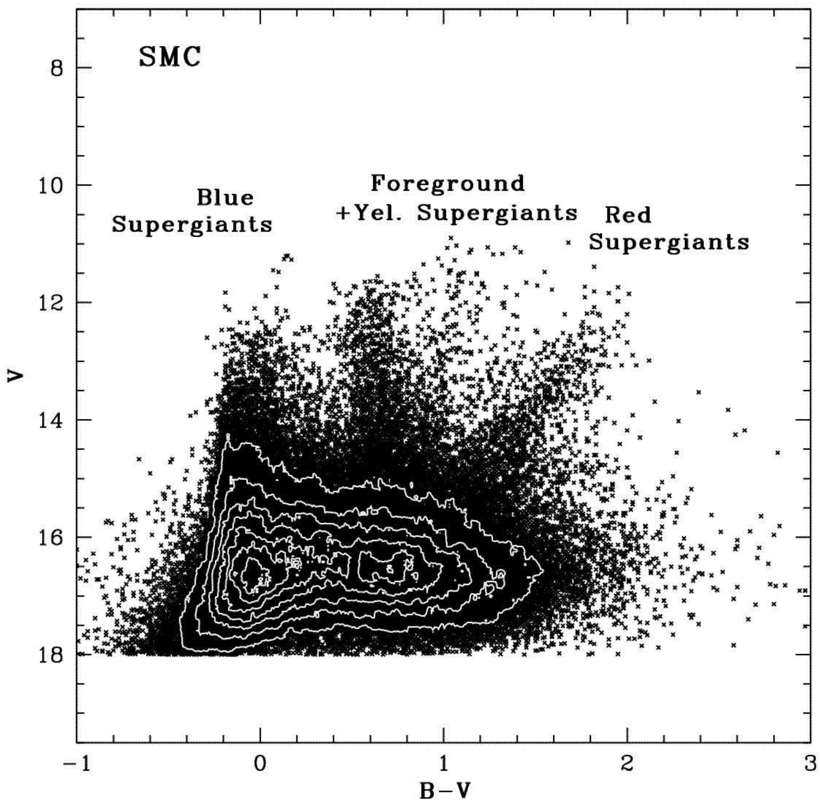

Figure 1: Color-magnitude diagram of the SMC. The blue and red supergiants are readily identified, but the yellow supergiants in the middle top of the diagram are lost among a sea of foreground dwarfs in the Milky Way. From Massey et al. (2007).

References

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Vazquez, G. A., & Leitherer, C. 2005, ApJ, 621, 695

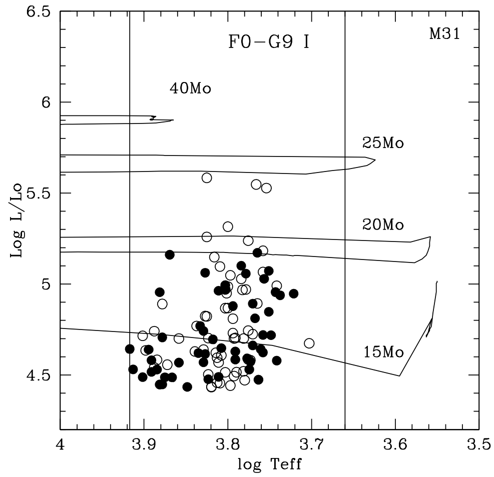

Figure 2: HRD showing M31's F- and G-type supergiants. The filled circles have been kinematically confirmed, while the open circles are the "possible" yellow supergiants. The evolutionary models predict far longer lifetimes for 25-40$M_\odot$ yellow supergiants than those of 15-20$M_\odot$, but nearly none are seen. This discrepancy between the observations and the models is a factor of 1000 (Drout et al. 2009).

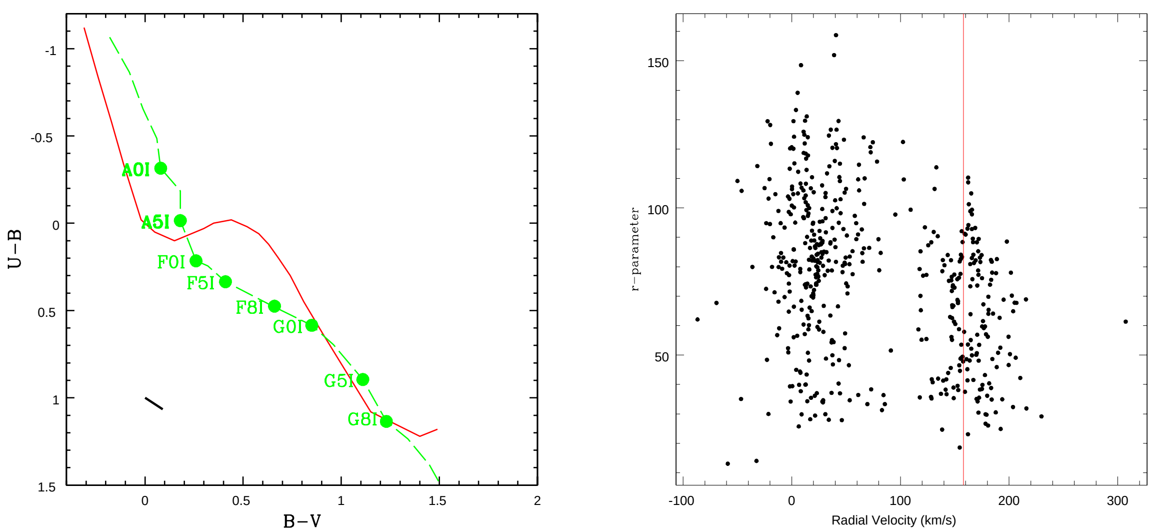

Figure 3: Identifying yellow supergiants. *Left.* This two-color diagram shows the expected colors of supergiants as a dashed (green) line, while the solid (red) line shows the expected colors of giants. It is easy enough to distinguish early (Magellanic Cloud) A-type and mid F-type supergiants from (foreground) A-type dwarfs from such data, but impossible to distinguish the G-type supergiants from foreground dwarfs. *Right.* This plot shows what radial velocities can do instead. The Tonry-Davis (1979) "r-parameter " (a measure of how good the cross-correlations are) is plotted against the radial velocity measured for each star in our SMC sample from our October Hydra run. The solid red line at a radial velocity of 158 km/sec is the nominal value of the SMC. It is easy to distinguish foreground stars (with velocities near 0) from SMC members. In the LMC this separation will be even stronger, as the systemic velocity of the LMC is 258 km/sec.

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)*

It's been our experience in talking to our colleagues about this project that *everyone* knows that you can tell the difference between supergiants and dwarfs just from a two-color $U-B$, $B-V$ diagram (or its Strömgren equivalent, [c_1], β). And, we see in Fig. 3 (left) that this is sort of true, over limited color ranges. Early A-type supergiants have more negative $U-B$ than dwarf stars of the same $B-V$, while the trend reverses itself around late-A. An F5 I star will have a $U-B$ that is several tenths of a magnitude more positive than dwarfs of the same color. But, the lack of color separation for the G supergiants is apparent, and in addition, there is no suitable catalog of $U-B$ (or [c_1] photometry) that covers the right magnitude range ($9 < V < 14$).

Instead, we will obtain spectra of F and G supergiant candidates, and use the radial velocities measured from the strong Ca triplet ($\lambda\lambda$ 8498, 8542, 8662) to determine membership. In October 2009 we obtained such data on most of our SMC fields (despite poor weather) and demonstrated that the separation is quite clean, as shown in Fig. 3 (right), as the nominal radial velocity of the SMC is 158 km/sec, shown by the solid red line, while the expected radial velocity of the primary foreground contaminant, foreground F and G dwarfs, is nearly 0 km/sec. Examination of the Besancon (Robin et al. 2003) Milky Way model suggests that the contamination for stars with radial velocities >100 km/sec is <5%, mostly due to disk and halo giants. For the LMC we expect an even cleaner separation, as the LMC's radial velocity is roughly 278 km/sec.

The wavelength coverage also includes OI λ7774 and the upper Paschen lines, which proved useful luminosity indicators among the hotter SMC stars. Our supplemental blue observations last October confirmed that the low metallicity of the SMC precludes using the standard luminosity indicators (e.g., CN λ4180). Thus radial velocities are crucial for determining membership.

We have selected candidate F- and G-type supergiants from the UCAC3 catalog, removed stars with measurable proper motions, and relied upon the 2MASS J-K colors to defined our sample, as our own SMC/LMC BVR photometry (Massey 2002) saturates slightly fainter ($V \sim 13$) than the brightest yellow supergiants predicted by the models. For the SMC there were 677 stars, of which we now have observations for 498 (74%). For the LMC, there are 2187 stars that meet our color and proper motion criteria. Observing a comparable fraction of these LMC stars is readily achievable in the requested time, as we show in the observing run section. Once membership is established, we will use existing photometry to accurately place these stars in the HRD, determining their numbers as a function of luminosity (mass), and comparing these to the known population of other massive stars (e.g., O-type, RSGs, WRs) as a check against the predictions of evolutionary theory.

We're compelled to include the LMC primarily in that it provides a second metallicity (one that is twice as high as for the SMC) for our comparison of the yellow supergiant population with the number of WRs and O-type stars. Such a comparison was not possible in our M31 study as neither the O-type nor WR populations are yet completely known (although we are certainly working on it!). Also, as the names imply, the LMC is, well, much larger than the SMC, and contains a correspondingly greater massive star population.

Finally we note that it is necessary to observe relatively complete samples in each galaxy, rather than sampling just a few fields, as our tests rely upon the assumption of a relatively constant star formation rate over an evolutionary time-scale ($\sim$10 Myr). This is a good approximation when the sample is averaged over an entire galaxy, but would be violated if we included only a few individual associations, each of which is itself coeval.

Proprietary Period: 18 months

Use of Other Facilities or Resources *(1) 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. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

(1) Our interest in the F- and G-type supergiants of the Magellanic Clouds stems from our interesting results from M31, using data that was obtained with the Hectospec fiber positioner on the MMT.

(2) This work has so far been supported through the National Science Foundation grant AST-0604569 and supplement AST-0844315. We have applied for a new 5-year grant to cover costs associated with the stellar content of the Local Group galaxies, and the LMC F- and G-type project is an integral component of that proposal.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), 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.*

Survey Project: The Stellar Content of Local Group Galaxies Currently Forming Stars, October 2000-Sept 2002 ($\sim$ 10 nights Mayall 4-m, 2 nights Blanco 4-m, all with the Mosaic cameras). The final processed images were released in early 2005, and were among the first to populate the fledgling NOAO Science Archive. The photometry and analysis were published in three major papers (listed below) and have used in many other papers and PhD theses (Ben Williams, Univ. of Washington; Alceste Bonanos, Harvard; Henry Lee, Univ. Minnesota).

- Massey, P., Olsen, K. A. G., Hodge, P. W., Strong, S. B., Jacoby, G. H., Schlingman, W., & Smith, R. C. 2006, "A Survey of Local Group Galaxies Currently Forming Stars. I. UBVRI Photometry of Stars in M31 and M33," *AJ*, **131**, 2478.
- Massey, P., Olsen, K. A. G., Hodge, P. W., Jacoby, G. H., McNeil, R. T., Smith, R. C., & Shay, S. B. 2007, "A Survey of Local Group Galaxies Currently Forming Stars. II. UBVRI Photometry of Stars in Seven Dwarfs and a Comparison of the Entire Sample", *AJ*, **133**, 2393.
- Massey, P., McNeil, R. T., Olsen, K. A. G., Hodge, P. W., Blaha, C., Jacoby, G. H., Smith, R. C., & Strong, S. B. 2007, "A Survey of Local Group Galaxies Currently Forming Stars. III. A Search for Luminous Blue Variables and Other Hα Emission-Line Stars", *AJ*, **134**, 2474.

Other Time (2008-present):

- 2010A-0067: Massive Binaries in the Local Group's Most Massive Young Cluster (M. Hanson, PI), 6 nights SOAR scheduled for June 2010.
- 2009B-0149: Massive Star Evolution as a Function of Metallicity: Closing the Loop in the Local Group", 2.5 nights MMT with Hectospec. The Hectospec queue produced useable data for most of our M31 fields but nothing for M33 due to bad weather in Nov/Dec. We will be resubmitting the proposal for the remainder. In the meanwhile the data we did obtained are fully reduced and form the basis of our summer student's project this summer.
- $\boxed{\star}$ 2009B-0034: A Census of Yellow Supergiants in the SMC: Testing Massive Star Evolutionary Models, 5 nights CTIO 4-m Hydra. Data fully reduced, and form the basis of the present proposal.

Publications by the PI based on NOAO data (2007–present):

- Levesque*, E. M., Massey, P., Olsen, K. A. G., & Plez, B. 2009, "The Coolest Stars in the Clouds: Unusual Red Supergiants in the Magellanic Clouds", invited keynote address, in The Biggest, Baddest, Coolest Stars, ASP Conf. Ser. 412, ed. Luttermoser, Smith, & Stencil, 33.
- Massey, P., Plez, B., Levesque*, E. M., Olsen, K. A. G., Silva, D. R., & Clayton, G. C. 2009, invited keynote address, Ibid, 3.
- Drout*, M. R., Massey, P., Meynet, G., Tokarz, S., & Caldwell, N. 2009, "Yellow Supergiants in the Andromeda Galaxy (M31)", ApJ, 703, 420.

- Massey, P., Silva, D. R., Levesque*, E. M., Plez, B., Olsen, K. A. G., Clayton, G. C., Meynet, G., & Maeder, A. 2009, "Red Supergiants in the Andromeda Galaxy (M31)", ApJ, 703, 420.
- Massey, P., 2009, "A Census of Massive Stars Across the Hertzprung-Russell Diagram of Nearby Galaxies: What We Know and What We Don't", invited review talk to appear in Hot and Cool: Bridging the Gaps in Massive Star Evolution, ed. Leitherer, Bennett, Morris, & van Loon), in press, arXiv:0903.0155
- Massey, P., Zangari*, A. M., Morrell, N. I., Puls, J., DeGioia-Eastwood, K., Bresolin, F., & Kudritzki, R. P. 2009, "The Physical Properties and Effective Temperature Scale of O-type Stars as a Function of Metallicity. III. More Results from the Magellanic Clouds", ApJ, 692, 618.
- Morrell, N. I., Massey, P., Eastwood, K., Penny, L. R., Gies, D. R., Tsitkin*, Y., & Darnell*, E. 2008, "Massive Binaries in the R136 Cluster", in Massive Stars: Fundamental Parameters and Circumstellar Interactions, ed. Benaglia, Bosch, & Cappa, RevMexAA, 33, 113

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- Levesque*, E. M., Massey, P., Olsen, K. A. G., Plez, B. 2007, "Late-Type Red Supergiants: Too Cool for the Magellanic Clouds?", ApJ, 667, 202.
- Massey, P., Levesque*, E. M., Olsen, K. A. G., Plez, B., & Skiff, B. A. 2007, "HV 11423: The Coolest Supergiant in the SMC", ApJ, 660, 301.
- Olsen, K. A. G., & Massey, P. 2007, "Evidence for Tidal Effects in the Stellar Dynamics of the Large Magellanic Cloud", ApJ, 656, L61

*Denotes undergraduate or graduate student author.

Observing Run Details for Run 1: CT-4m/HYDRA

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 queue and Gemini runs).*

We plan to use the same setup as last October, namely grating KPGL-D in 1st order, covering 7300-9050Å at 3Å spectral resolution. This wavelength region will include the Ca II triplet lines ($\lambda\lambda$ 8498, 8542, 8662) as well as the O I λ7774 line and upper Paschen Balmer line P10 at λ9010, which have proven useful luminosity indicators for the higher temperature stars in our SMC sample. This gives us adequate velocity resolution (1/10th of a resolution element is 10 km/sec); in practice, in cross-correlation against radial velocity standards, our actual repeatability from observations on separate nights is about 3 km/sec, more than adequate for the job.

Our LMC sample consists of 2187 stars ranging from V=9.5 to 13.5, with fairly neutral colors. The exposure times are short; we found that 15 minute exposures achieved excellent radial velocities and adequate OI λ7774 measurements Each field then requires about 45 minutes to complete, including moving to zenith, configuring the instrument, acquiring the field, running the in-place calibration (flat-field and comparison arcs), plus actually exposing on the objects.

We have completed the assignments, and settled on 70 fields, which include about 80% of these 2187 stars. (Even though there are 138 fibers, on average the surface density is low enough that we average only 25 "new" stars per field.) Thus 70 fields times 45 minutes per field requires about 53 hours of observing. During Oct-Jan the LMC is at acceptable airmasses (<2) for 6-7 hours per night, and so we are asking for 8 nights.

Note that full moon has little or no impact on observing in the far red. Observing time in late November (during the bright of the moon) will allow us to also squeeze in the remaining SMC fields at the start of each night. We will also observe radial velocity standards during twilight.

Instrument Configuration

Filters: OG515	Slit:	Fiber cable:
Grating/grism: KPGL-D	Multislit:	Corrector:
Order: I	λ_{start}: 7300	Collimator:
Cross disperser:	λ_{end}: 9050	Atmos. disp. corr.:

R.A. range of principal targets (hours): 5 to 6

Dec. range of principal targets (degrees): -69 to -68

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

NOAO observing proposal LaTeX macros v2.14.