**NOAO Observing Proposal** *Standard proposal* **Panel:** *For office use.*
*Date:* March 28, 2003 **Category:** Massive Stars

# Spectroscopy of Hot, Massive Stars in the Magellanic Clouds: Getting the Numbers Right!

**PI:** Phil Massey **Status:** P **Affil.:** Lowell Observatory
1400 W. Mars Hill Road, Flagstaff, AZ 86001 USA
Email: Phil.Massey@lowell.edu Phone: 928-774-3358x264 FAX: (928) 774-6296

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**CoI:** Knut Olsen **Status:** P **Affil.:** CTIO
**CoI:** Joel W. Parker **Status:** P **Affil.:** Southwest Institute

**Abstract of Scientific Justification** *(will be made publicly available for accepted proposals)*:
The SMC and LMC are both nearby and rich in massive stars, permitting studies which are simply not possible elsewhere. For many years we have been involved in characterizing the massive star content of these galaxies, in order to study star-formation processes and stellar evolution. A recent run with Hydra produced spectra of $\sim$ 800 stars with the goal of characterizing the IMF of relatively isolated O stars. The run identified a number of interesting objects: we found a new Luminous Blue Variable in the SMC, as well as a new Wolf-Rayet star; we identified several new double-lined spectroscopic binaries; and we found many new early-type O stars. About half of our sample was unclassifiable due to nebular emission (not unexpected with a fiber instrument). We now need the long-slit, good through-put capabilities of the RC Spectrograph for important followup work: determinations of stellar parameters by adding data at H$\alpha$ for the early-type stars with excellent blue data, and well sky-subtracted spectra for the most interesting objects with nebular contamination, better signal-to-noise data for the WR star, and nightly coverage of the double-lined spectroscopic binaries so we can determine masses. These data will be used to find the IMF of massive stars in the field, and to determine the fundamental parameters (effective temperatures, luminosities, masses) of massive stars in these low-metallicity environments.

**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 | Oct - Nov | Oct - Dec |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |

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

If possible, please avoid potential conflicts with WIYN time (N042)

**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.*

The richness and relative proximity of the Magellanic Clouds (MCs) have provided some of the most fertile grounds for improving our knowledge of star formation and stellar evolution. In recent years these studies have included characterizing the stellar content of numerous OB associations using CCD photometry and spectroscopy (e.g., Testor & Lortet 1987; Heydari-Malayeri et al. 1987, Massey et al. 1989ab, Parker 1993, Garmany et al. 1994, Oey & Massey 1996; see Massey 2003 for a recent review). These studies established that the initial mass function (IMF) of the SMC and LMC associations are Salpeter, at least for the massive stars ($> 20\mathcal{M}_\odot$), and indistinguishable from that of their counterparts in the Milky Way, despite the factor of 3 difference in metallicities between these systems. In addition, these studies have helped determine some of the *physical* properties of massive stars as a function of metallicity, such as mass-loss rates (Puls et al. 1996).

Still, much fundamental work remains to be done. (1) Massey et al. (1995) found that there was a considerable population of "field" OB stars. These stars are found far from any obvious associations. Some are of spectral type O3, the hotest, most luminous, and *youngest* of any known stars. With ages less than 1 Myr, these stars are disturbingly isolated, as very high peculiar motions (hundreds of km/sec) would be needed to explain their locations. The present day mass function (PDMF) of these stars imply a very pecular IMF if they actually formed as part of relatively isolated star-forming events (Massey et al. 1995, Massey 1998). (2) We don't know yet to what extent the effective temperature scale for O-type stars differs in the MCs compared to that of the Milky Way. What is the $T_{\rm eff}$ of an O7 V star in the SMC compared to a Galactic star of the same type? The answer to this matters if we are to trust our interpretation of the upper-end of the H-R diagram, as a small difference in $T_{\rm eff}$ affects the bolometric correction, which in turn affects the mass assigned to a star via stellar evolutionary tracks and isochrones.

Accordingly we have started a comprehensive observing program to characterize the massive star population of the Clouds. Carefully calibrated *UBV* CCD photometry covering most of the Clouds were obtaind by Massey (2002) with the CTIO Schmidt to address completeness problems with other catalogs. (The old photoelectric work didn't go deep enough; the new generation of deep CCD studies saturated too quickly.) The CTIO TAC kindly granted us 4-m time with Hydra for the followup spectroscopy, and we obtained spectra of about 800 stars this past December.

Followup work is needed to meet these scientific goals. First, we have found a number of very early-type O-type stars. We have beautiful blue spectra, and these allow us to construct H-R diagrams by adopting the "standard" [Galactic] relation between $T_{\rm eff}$ and spectral types. However, we can do much more than this. These data have the resolution and signal-to-noise to allow detailed modeling using a modern stellar atmospheres code to help define this relation for the MCs. Recent work has called into the question the standard calibration, as the inclusion of full non-LTE line-blanketing may change the scale by as much as 10-20% (Puls 2002). We are using FASTWIND as part of a collaborative effort with Puls and Kudritzki. These new spectra are ideal for such modeling, *but we require observations at Hα to determine the mass-loss rates* as part of the procedure. Second, our work identified very peculiar objects (a He-rich O3 star, and an LBV-candidate in the SMC), which beg for followup studies to search for spectral variability that might explain where they fit in the evolutionary scheme of thing. Third, we identified several double-lined spectroscopic binaries. O-type double-lined binaries typically have periods of a few days, and provide the best way of determing a mass in a model-free way, (e.g., Gies 2002, Massey et al 2002). Finally, about 30% of our stars were unclassifiable due to nebular contamination. Long-slit spectroscopy (with its attendent good sky subtraction) provides the only means of including these in our IMF determinations.

## References: Scientific Justification and Experimental Design


Bohannan 1997, in Luminous Blue Varaibles: Massive Stars in Transition, ed. Nota & Lamers, 3

Garmany, Massey, & Parker 1994, AJ, 108, 1256

Gies 2002, in A Massive Star Odyssey, ed. van der Hucht et al., in press.

Heydari-Malayeri, Niemla, & Testor 1987, A&A 184, 300

Lamers 1997, in Luminous Blue Variables: Massive Stars in Transition, ed. Nota & Lamers, p 76

Massey 1998, in The Sellar Initial Mass Function, ed. Gilmore & Howell, p. 17

Massey 2000, PASP, 112, 144

Massey 2002, ApJS, 141, 81

Massey 2003, Ann. Rev Astron. Astrophys. 41, in press

Massey & Duffy 2001, ApJ, 550, 713

Massey, Garmany, Silkey, & DeGioia-Eastwood 1989a, AJ, 97, 107

Massey, Lang, DeGioia-Eastwood, & Garmany 1995, ApJ, 438, 188

Massey, Parker, & Garmany 1989b, AJ, 98, 1305

Massey, Penny, & Vukovich 2002, ApJ, 565, 982

Oey & Massey 1995, ApJ 452, 210

Parker 1993, AJ 106, 560

Parker 1997, in Luminous Blue Variables: Masssive Stars in Transition, ed. Nota & Lamers, 368

Puls et al. 1996, 305, 171

Puls 2002, in A Massive Star Odyssey, ed. van der Hucht et al., in press.

Testor & Lortet 1987, A&A 178, 25


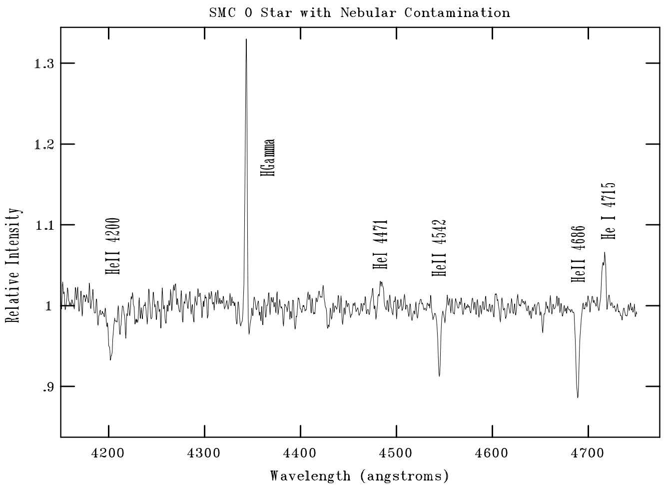


Figure 1: This SMC star has strong He II, demonstrating that it is one of the earliest O-type stars in the SMC, and hence one of the most luminous and massive. But the He I lines are contaminated by nebular emission. A long-slit spectrum with the RC spectrograph will allow accurate nebular subtraction, as we've demonstrated numerous times in the past (e.g., Massey et al. 1995).

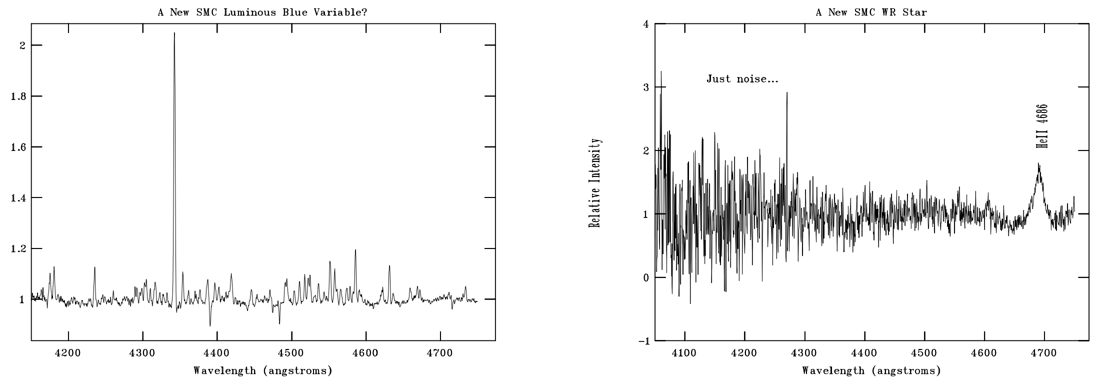


Figure 2: On the left, we show the spectrum of a newly found emission-lined star in the SMC. It resembles the classic "quiescent" phase of a luminous blue variable, such as S Doradus, with strong emission lines of hydrogen and singly ionized metals dominating the spectrum (Massey 2000). If variability is confirmed, this would be only the third LBV found in the SMC, and by far the most "normal" of the three. On the right, we show the spectrum of a newly found Wolf-Rayet star. Only the characteristic broad He II $\lambda4686$ feature is visible; better S/N is needed to reach the "classification" lines of N III, N IV, and N V, and to look for absorption features.

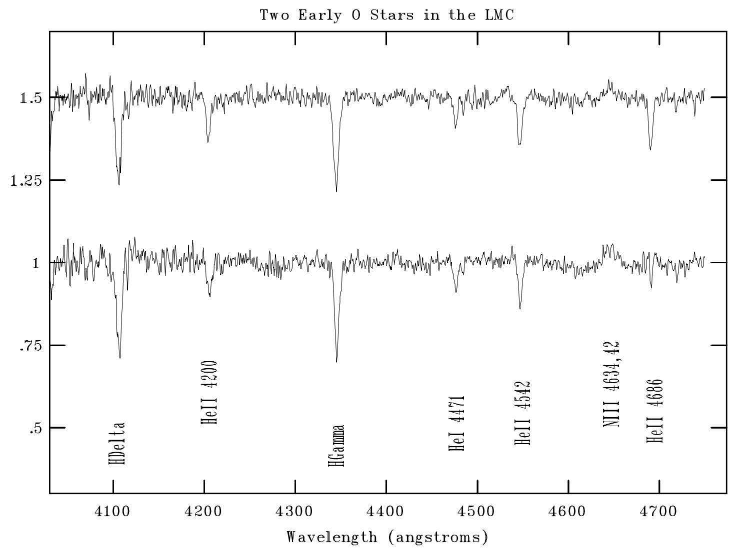


Figure 3: The spectra of two early-type O stars in the LMC are shown, both of spectral type O5 as judged by the relative strengths of HeI$\lambda4471$ to HeII$\lambda4542$. The presence of NIII $\lambda4534, 42$ emission is typical for such luminous, hot stars, while the fact that HeII $\lambda4686$ shows slight emission in the lower star is indicative of large mass-loss rates. By the standard Galactic calibration, both of these stars would be assigned effective temperatures of 43,000°K, although others would suggest much lower temperatures. Detailed modeling, including the H$\alpha$ profile, can help establish an effective temperature scale for Magellanic Cloud O stars.

**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)*

Hydra is a *wonderful* survey instrument, allowing 130 objects to be observed simultaneously within a 40-arcminute field of view. Without it, we would never have been able to obtain spectra of 800 or so stars in a single 4-night run. However, this multiplexing advantage comes at some cost: (a) the through-put is about one-third of the RC Spectrograph (due to slit losses) limiting the signal-to-noise one can obtain in a 2-hr exposure, and (b) sky subtraction is not local, so nebular contamination can easily compromise one's ability to classify stars embedded in H II regions. We have used our four nights with Hydra to the best advantage, and identified many interesting objects; we now need the greater through-put and versitility of the long-slit RC spectrograph. Here's how:

- **Getting rid of nebular lines so we can measure the IMF of the "field" stars.** About one-third of our sample has been contaminated by nebular emission. A good example is shown in our Hydra spectrum of an SMC star in Fig. 1. This star shows strong He II absorption, making it an early-type O star, and hence one of the most luminous and massive stars known in the SMC. But how luminous and massive? H$\gamma$ shows strong nebular emission; weak nebular emission is present at He I$\lambda$4715, and He I $\lambda$4471 is missing. The latter line is crucial for classifying the star. Hydra was necessary for finding this star, but we now need the sky-subtraction capabilities of the long-slit RC spectrograph to classify it.
- **Rare evolved massive stars.** We don't know as much as we'd like about how massive stars evolve as a function of metallicity. One of the big uncertainities concern Luminous Blue Variables (LBV), stars like Eta Carina and S Doradus that are near or beyond their Eddington Limits (Lamers 1997). In particular, a better knowledge of the statistics of these stars is crucial. In Fig. 2 we show the spectrum on a peculiar emission-line star we discovered as part of our survey. This spectrum resembles that of S Doradus during quiescence, with strong emission lines of hydrogen and singly ionized metals, primarily Fe II (Massey 2000). However, spectral *similarity* is not sufficient to call a star an LBV—one needs to demonstrate spectral variability (Bohannan 1997). If confirmed, this would be only the third LBV to be found in the SMC (Parker 1997). On the right of Fig. 2 we show the spectrum of a newly found Wolf-Rayet star. The broadness and strength of the He II $\lambda$4686 establishes this as a WR. Only 12 of these were previously known in the SMC (Massey & Duffy 2002). Higher signal to noise is needed to classify the star (from N III $\lambda\lambda$4634, 42, N IV $\lambda$4058, and N V $\lambda$4603, none of which are visible in this spectrum.
- **Double-lined binaries.** The most fundamental way of determining a star's mass is from its Kepleran motion in a binary system. Only a handful of double-lined systems are known (see Gies 2003 for a recent review), and the masses produce a direct confrontation with stellar evolutionary theory (Massey et al. 2002). We discovered several new double-lined systems as part of our Hydra spectroscopy but now observations over several nights are needed to confirm radial velocity motion and get a rough idea of the period. Follow-up observations will then be carried out by collaborators Morrell (Carnegie) and Niemla (CASLEO).
- **Revised effective temperature scale.** We obtained some high signal to noise data at good resolution of some early O-type stars, as shown in Fig. 3. Modern atmosphere models include full line-blanketing, non-LTE, and the significant effects of mass loss (Puls 2002). We have great data in the blue, but require H$\alpha$ observations. By doing our blue observations in second order, we can switch to the H$\alpha$ region easily within a night by simply changing the blocking filter and retilting the grating.

**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.*

**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:**

$\boxed{\star}$ **2002B-218:**

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

$\boxed{\star}$ **2001B-002:** The Wolf-Rayet Content of IC10, 2 nights Mayall 4-m Sept 2001: Massey & Holmes 2002, ApJ, 580, L35

$\boxed{\star}$ **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.

$\boxed{\star}$ **2001B-227:** The Red Supergiant Content of the Magellanic Clouds, 3 nights CTIO 4-m Hydra, October 2001. The data are reduced and the paper about 90% written; (Massey & Olsen 2003, ApJ, "on the verge" of being submitted.)

$\boxed{\star}$ **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 (2000-2003) based upon NOAO data:**

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, submitted.

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.

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: 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 use the same setup we used so successfully with the RC Spec and blue air schmidt in January 1999. For the nights we work in the blue, we will use KPGLD (790 l/mm) in second order with a $CuSO_4$ blocking filter for observations from 3850Å to 5000Å. This gives us 0.37Å per pixel dispersion, for a very nice 4-pixel 1.6Å resolution with a 200$\mu$m wide slit. For the "red" night, we will stay with the same grating and simply re-tilt it to center at $\lambda$6552, replacing the blocking filter with a GG420. This requires no extra support once we have established both setups on the first afternoon.

Why 5 nights? We want to reobserve a reasonable fraction of the 300 or so stars whose nebular contamination precluded classification; our "favorites" list includes about 100 stars, with brightness ranging from $B = 14$ to $B = 16$. A S/N of 80 per spectral resolution element is needed to classify early-type stars (weak lines!). Our experience shows that we obtain a good classification spectrum in 10 minutes at $B = 14$; at $B = 16$ we thus require an hour. We can thus do about 20 stars a night, and in 4 nights do 80-100 stars. A fifth night is needed for the H$\alpha$ observations.

### Instrument Configuration

| | | |
|---|---|---|
| Filters: | Slit: | Fiber cable: |
| Grating/grism: KPGLD | Multislit: | Corrector: |
| Order: 2 | $\lambda_{\mathrm{start}}$: 3800 | Collimator: |
| Cross disperser: | $\lambda_{\mathrm{end}}$: 4900 | Atmos. disp. corr.: |

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

**Dec. range of principal targets (degrees):** -65 to -70

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

Note that MOST of our objects are in the SMC, so time in Oct-Nov is preferred to time in Nov-Dec.

NOAO observing proposal LaTeX macros v2.7.