NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: March 31, 2004 **Category:** Massive Stars

Spectroscopy of Hot, Massive Stars in the Magellanic Clouds: Getting the IMF Right

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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. Our 2002 CTIO 4-m Hydra run yielded spectra of ~ 300 stars with the goal of investigating the initial mass function (IMF) of relatively isolated massive stars. Previous studies have suggested that these "field" stars comprise a separate and unique population, with an IMF that differs considerably from those stars found in OB associations. Unfortunately, completeness problems have plagued those earlier studies, bringing their results into question. Our project is designed to correct those problems. The new data we obtain will confirm or refute those controversial results, allowing us to definitively determine the field IMF and map its changes as a function of stellar density. Because nebular contamination of about a third of the sample precludes classification (an expected limitation of the multi-fiber observations), long-slit observations, with a larger aperture, is now needed to complete this work. We can accomplish this goal with the Magellan observations we propose here.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	Magellan-II	BCSpec	2	grey	Oct - Dec	Oct - Jan
2						
3						
4						
5						
6						

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

Please avoid conflicts with any scheduled NOAO time, if possible.

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.*

Due to their richness and proximity, 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 the determination of 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. Specifically we are proposing to address the issue of the initial mass function of isolated O-type stars in the Clouds.

Massey et al. (1995) found that there is a considerable population of "field" OB stars in both the SMC and LMC. These stars are far from any obvious associations, and comprise about 30% of all known massive stars in the MCs. Some are of spectral type O3, the hottest, most luminous, and *youngest* 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 if they were born in associations. The present-day mass function (PDMF) of these field stars implies a very steep IMF, if we assume these were formed in isolated star-forming events (Massey et al. 1995, Massey 1998). If this result is confirmed, and not due to completeness problems, it has drastic implications for interpreting the integrated properties of other galaxies.

This result is as intriguing as it is controversial, as it provides important clues to how massive stars form under different conditions. Elmegreen (1997) suggests that these field stars may have formed in "non-fractal" clouds (like the Taurus clouds), filaments whose lack of hierarchical structure should result in stars of a single mass forming preferentially, making the IMF particularly steep. Alternatively it may be that *most* massive stars formed in clusters do so by stellar collisions and subsequent coalescence (Stahler, Palla, & Ho 1999), resulting in a different IMF. Besides the unexpectness of the result, however, this steep IMF slope is at variance with that found by Hunter & Massey(1990) in their survey of the stellar content of the smallest Galactic H II regions. Furthermore, a study of a UV-flux selected sample of isolated Magellanic Clouds stars also failed to reproduce this result (Parker et al. 1998).

Thus we've started a comprehensive observing program to better characterize this population of isolated O-type stars in the Clouds. Carefully calibrated *UBV* CCD photometry covering most of the Clouds were obtained 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 NOAO TAC kindly granted us 4-m time with Hydra for the followup spectroscopy, and we obtained spectra of about 300 stars in December 2002.

However, long-slit work with a larger aperture is now needed to achieve our goal. About a third of our sample of massive stars cannot be classified, due to the contamination of nebular emission (Fig. 1) and poor S/N. This is to be expected since sky subtraction with fiber instruments is not local. Long-slit spectroscopy with the B&C spectrograph on Magellan will neatly solve this problem, allowing us to classify these stars, and assign masses, in order to complete our study of the field IMF. In addition, our work identified objects crucial to our understanding the statistics of evolved massive stars in the Clouds (such as new Luminous Blue Variable candidates and Wolf-Rayet stars; see Fig. 2) that require confirmation.

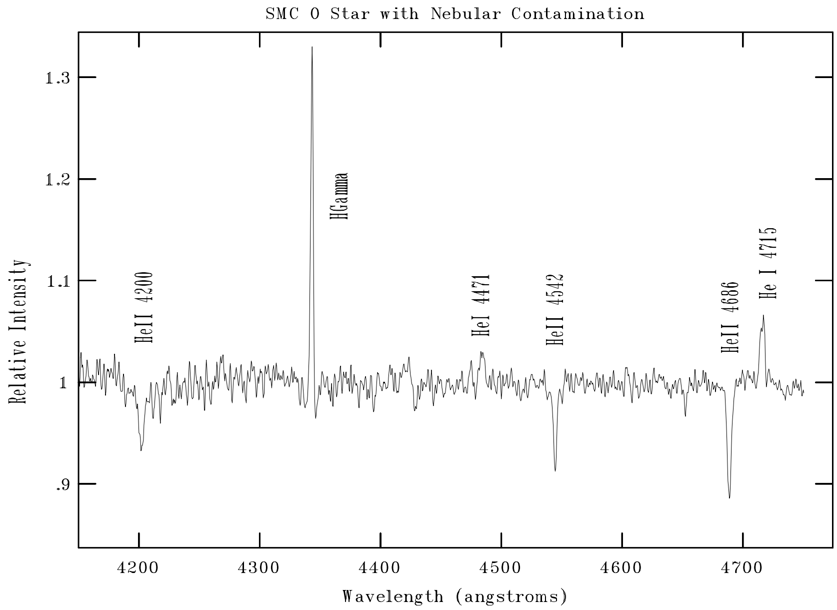

Figure 1: This SMC star has strong He II, demonstrating that it is one of the earliest O-type stars in the SMC, and hence one of the most luminous and massive. But the He I lines are contaminated by nebular emission. A long-slit spectrum with the B&C spectrograph will allow accurate nebular subtraction.

References: Scientific Justification and Experimental Design

Elmegreen 1997, ApJ, 486, 944

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

Hunter & Massey 1990, AJ, 99, 846

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

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, 15

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

Oey & Massey 1995, ApJ 452, 210

Parker 1993, AJ 106, 560

Parker et al. 1998, AJ, 116, 180

Puls et al. 1996, A&A, 305, 171

Testor & Lortet 1987, A&A 178, 25

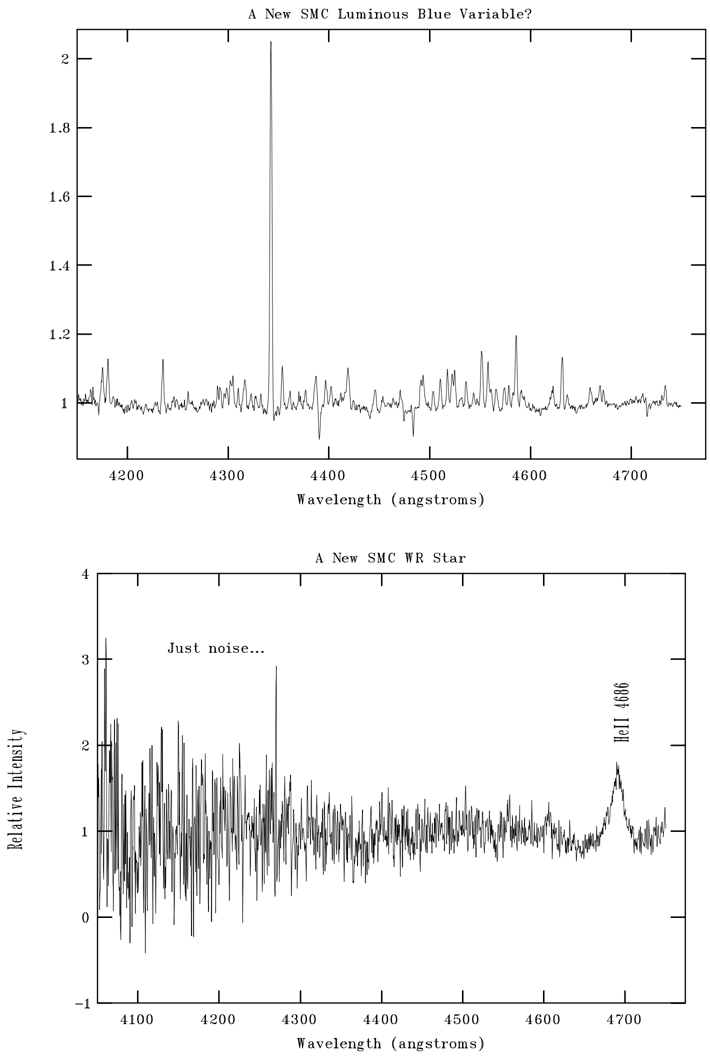

Figure 2: At the top, we show the spectrum of a newly found emission-lined star in the SMC. It resembles the classic "quiescent" phase of a luminous blue variable, such as S Doradus, with strong emission lines of hydrogen and singly ionized metals dominating the spectrum (Massey 2000). If variability is confirmed, this would be only the third LBV found in the SMC, and by far the most "normal" of the three. At the bottom, 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.

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 many objects to be observed simultaneously within a 40-arcminute field of view. Without it, we would never have been able to obtain spectra of 300+ stars in a single 4-night run. However, this multiplexing advantage comes at some cost: (a) the through-put is lower than in a conventional long-slit spectrograph (due to fiber end losses) limiting the signal-to-noise one can obtain in anexposure, 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 larger aperture offered by Magellan, and the good sky-subtraction capability of the B&C, as 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.

Why the B&C? We were tempted by IMACS on the Magellan-I, and were there several targets within any 15'x15' field of view, we would have succumbed. But there aren't, and it is certain that the observing overhead will be worse with IMACs than with the B&C (20 min vs. 5 min is our informed guess). In addition to the overhead, the spectral resolution we can achieve with the B&C is somewhat better, given the limited selection of gratings available for IMACS. MIKES would provide considerably higher resolution, but would provide less robust sky (nebular) subtraction given its short slit.

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.*

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:

The Physical Parameters of Red Supergiants: When Massive Stars Are as Cool as They Get, 10 nights KPNO 2.1-m (5 successfullycarried out in March, 5 more scheduled in late May), plus 5 nights CTIO 1.5-m scheduled for April.

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: Magellan-II/BCSpec

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 1200 line/mm grating blazed at 4000Å to provide good resolution (1.5Å) from 3900Å to 5000Å, ideal for our classification needs. The B&C web page (and our own experience) suggests a total system through-put of 10%. Our count-rate at $B = 16$ will thus be about 15 e/sec/Å, and thus to achieve a S/N of 100 will require about 900 15 minutes/star. With overhead, we hope to do about 3 stars/hour, and thus in two nights about 50 stars—a reasonable subsample of our 4-m Hydra data from two years ago, but yielding much better S/N and vastly superior sky subtraction. The latter is critical, as nebular contamination of the important He I λ4471 compromised our spectral classification.

Grey time is acceptable, although full moon would increase the exposure times unacceptably.

Instrument Configuration

Filters: None	Slit: 1.0	Fiber cable:
Grating/grism: 1200	Multislit:	Corrector:
Order: 1	$\lambda_{\rm start}$: 3900	Collimator:
Cross disperser:	$\lambda_{\rm end}$: 5000	Atmos. disp. corr.:

R.A. range of principal targets (hours): 0 to 7

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

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

NOAO observing proposal LaTeX macros v2.9.