NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: March 30, 2004 **Category:** Massive Stars

Wolf-Rayet Stars in IC10: Probing the Massive Star Content of the Nearest Starburst

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

IC 10 is a Local Group galaxy currently undergoing a galaxy-wide starburst (Massey & Armandroff 1995). Starburst galaxies have often been suspected of having a top-heavy IMF, although the evidence in general has been indirect (i.e., M82 according to Rieke et al. 1980). Previous work on the evolved massive star population of IC 10 suggested that it too might have a top-heavy IMF as evidenced by the relatively large ratio of WC-type to WN-type Wolf-Rayet stars. However, a newly completed survey has detected a wealth of new Wolf-Rayet candidates (Massey & Holmes 2003). If these are spectroscopically confirmed as predominately of WN-type, the IMF of this starburst system may be normal, although the massive star population (and hence the amount of "burst") may be factors of 5 higher than the already large value previously thought. IC 10 is the only starburst system sufficiently close to determine the massive star population *directly*, but it requires spectroscopy with Gemini-N and GMOS to take advantage of this unique opportunity.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	GEM-NQ	GMOSN	0.6	dark	Aug - Nov	Aug - 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.*

Starburst galaxies are undergoing intense star formation at a rate that is unsustainable on a Hubble time (e.g., Searle & Sargent 1972). The nearest such object is the small irregular Local Group galaxy IC 10. Van den Bergh (2000) kindly credits the recognition of IC10's starburst nature to Massey & Armandroff (1995), who identified $\sim$ 20 Wolf-Rayet stars (WRs). WRs are the He-burning descendents of the most massive O-type stars, and this high number in such a small galaxy was considered quite remarkable; for comparison, NGC 6822, another Local Group irregular of comparable absolute visual magnitude contains only 4 WRs (Massey & Johnson 1998). Other lines of evidence, such as the Hα luminosity, also argue for a starburst nature (Hodge & Lee 1990; Youngblood & Hunter 1999; Hunter 2001). The galaxy is embedded in an extended H I envelope (Huchtmeier 1979); presumably infalling gas fuels the burst.

The proximity of IC 10 gives us a unique opportunity to study the effects that an intense burst has on the *process* of star formation, and in particular the slope of the stellar initial mass function (IMF). There has long been the theoretical expectation that the IMF would be be top-heavy in regions of intense star formation (Larson 1986). And, indeed such a claim has been made for the starburst galaxy M 82 (Rieke et al. 1980), based admittedly on fairly indirect evidence (see Scalo 1990 and Leitherer 1998). However, direct measurement of the IMF in the energetic central cluster (R136) of the 30 Dor giant HII region by Massey & Hunter (1998) found a perfectly normal IMF.

However, there is evidence to suggest that IC 10 may in fact have a top-heavy IMF. Wolf-Rayet stars occur as two distinct types: those of the WN class, which show the products of H-burning at their surfaces, and those of the WC class, which show the products of He-burning at their surfaces. The mass range that is expected to evolve to WCs or WNs should be a function of metallicity (due to the effect that radiatively-driven stellar winds have on the evolution of massive stars) but at a given metallicity the WCs will *on average* be descended from more massive stars than are the WNs. (See discussion in Massey & Johnson 1998 and Massey 2003). The WR stars found by Massey & Armandroff (1995) were predominantly of WC type, unexpected in a galaxy of IC 10's low metallicity (Fig. 1). One explanation is that the IMF is more weighted in favor of massive stars in IC 10 due to its current starburst (Massey & Armandroff 1995; Massey & Johnson 1998).

However, another possibility exists: WNs are more difficult to detect than WCs as their strongest emission lines are about a factor of 4 weaker than those of WCs, and thus completeness for WNs is much harder to achieve in any sort of survey. (That is why the point for the Milky Way is also a bit high in Fig. 1—the sample there is probably not complete for WNs, as discussed in Massey 2003). IC10's low galactic latitude (-3.3°) results in a large galactic foreground reddening ($E(B-V) = 0.75 - 0.80$, according to Massey & Armandroff 1995) further complicating detection. Accordingly, two years ago we proposed and were granted time on the 4-m Mayall to conduct a deeper imaging survey for WR stars using Mosaic and our "optimized" interference filters centered on WR emission lines.

Our survey has uncovered a wealth of additional candidates (Massey & Holmes 2003). By comparing the number of positive detections with those of a nearby control field, we conclude that the total number of Wolf-Rayet stars in IC10 might be as great as 100. If the majority of the new candidates are of WN-type (which might be expected if the stronger-lined WCs have mostly all been previously detected), then these new candidates could even lower the WC to WN ratio to normal—with the implication that the IMF is also normal. Of course, this would also imply that IC 10 is an even more extreme starburst than previously thought! So far, only two of these new candidates have been observed spectroscopically—both confirmed as WNs. To obtain a reasonably complete sample requires the large aperture of Gemini and the multiplexing capabilities of GMOS.

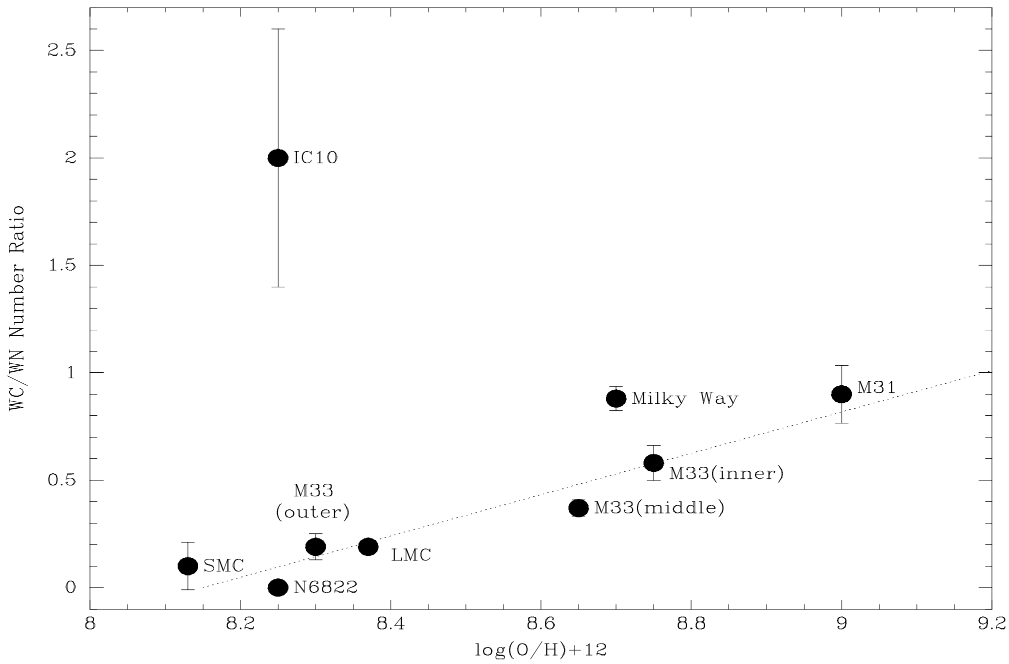

Figure 1: The relative number of WC and WN stars is well correlated with metallicity as we would expect; the exceptions are the Milky Way, and IC 10. The fact that the Milky Way ratio is high is easy to understand: the sample within 2.5 kpc is probably not complete for WNs. This figure has been adopted from Massey & Johnson 1998, with the errors bars showing the effects of $\sqrt{N}$ statistics on the ratios.

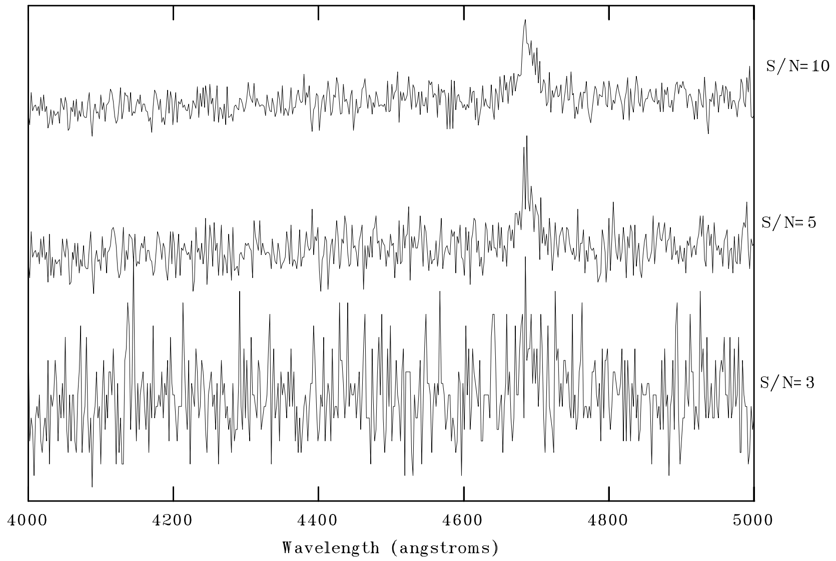

Figure 2: This plot shows a simulation of the detection of He II λ4686 with parameters typical of a weak-lined WN stars; e.g., a line width of 20Å and a equivalent width of -10Å. The S/N per 0.9Å(binned) pixel is indicated.

Armandroff, T. E., & Massey, P. 1995, AJ, 109, 2470

Crowther et al. 2003, A&A, 404, 483

Hodge, P., & Lee, M. G. 1990, PASP, 102, 1245

Huchtmeier, W. K. 1979, A&A, 75, 170

Hunter 2001, ApJ, 559, 225

Larson 1986, MNRAS, 218, 409

Leitherer, C. 1998, in The Stellar Initial Mass Function, ed. G. Gilmore & D. Howell, 61

Massey, P. 2003, *ARA&A*, 15, 41

Massey, P. & Holmes, S. 2002, ApJ, 580, L35

Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180

Massey, P., & Johnson, O. 1998, ApJ, 505, 793

Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., & Tokunaga, A. T. 1980, ApJ, 238, 24

Scalo, J. M. 1990, in Windows on Galaxies, ed. A. Renzini, G. Gabbiano, & J. S. Gallagher, 125

Searle, L., & Sargent, W. L. W. 1972, ApJ, 173, 25

van den Bergh, S. 2000, The Galaxies of the Local Group

Youngblood, A. J., & Hunter, D. A. 1999, ApJ, 519, 55

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)*

With Gemini-N, we will obtain GMOS multi-slit observations of $\sim$ 30 of our weaker-lined Wolf-Rayet candidates. The size of IC10 is a good match to the 5.5 arcmin diameter masks, and we can use a single slit mask. **Time assigned for this project in 2003B resulted in obtaining a suitable image from which we designed a slit mask, but the spectroscopic data was never obtained.**

For the spectroscopy we need reasonable resolution and S/N for a solid detection/non-detection: our WR candidates are faint ($B \sim 22 - 23$) and the expected emission of the strongest line (He II λ4686) weak (EWs of -10Å; see Table 3 of Massey & Johnson 1998 ApJ, 505, 793). The B600 grating offers 6Å resolution (with a 1-arcsec slit), which is a good match to the width of the spectral lines (10-20Å). We can bin by 2 pixels both spatially and spectrally, and as our simulation shows (Fig. 3), we require at least a S/N of 5 per 0.9Å(binned) pixel for a convincing detection of such a line. According to the GEMINI GMOS exposure time calculator tool, we will achieve this S/N for a $B \sim 23$ object in a 5 hr exposure (20 x 900 sec) assuming dark skies (20 percentile) and mediocre seeing (80 percentile), using 1-arcsec wide slits. We will do the observation in two sets of 10x900 seconds, moving the central wavelength of the grating by 3nm to provide continuous wavelength coverage.

As part of our survey of Local Group galaxies we also obtained imaging through our WR filters of *all* the Local Group galaxies currently active in forming stars: ten fields covering M31, 3 fields covering M33, plus single fields covering other Local Group galaxies. We view this IC 10 half-night as a test run for a more extensive proposal that will help identify the evolved massive star population (both red supergiants and WRs) in these nearby systems.

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:

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.

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

$\boxed{\star}$ **2002B-218:** The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andromeda Galaxy", 3 nights MMT Sept 2002. We obtained only 0.5 nights out of 3 nights scheduled, due to weather, but published what we were able to get in Massey & Holmes 2002, ApJ, 580, L35

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

2001B-227: The Red Supergiant Content of the Magellanic Clouds, 3 nights CTIO 4-m Hydra, October 2001. 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: GEM-NQ/GMOSN

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).*

Dark time is needed as our objects are faint ($B \sim 23$) and the emission weak. The B600 grating provides good spectral coverage and adequate resolution, and the observations can be obtained in "mediocre" (for Gemini!) seeing. As a 900-sec exposure will be photon-noise limited, we will combine 20 of these to obtain the equivalent of a 5-hr exposure. In the experimental design section we argue that a S/N of 5 per 0.9Å spectral resolution element is needed for certain detection of emission in our weakest-lined cases (Fig. 2), and the GMOS ETC assures us we will achieve this with a 5-hr exposure under dark skies and 80-percentile seeing.

We were granted Gemini-N time for this project in semester 2003B, and we obtained excellent imaging data under good seeing conditions that went quite deep enough to design a slitlet mask. But the spectroscopic observations were never made. The mask has been cut and is ready to go; we require only a half night (5-hr plus overhead) to complete this project.

Principal Contact: Philip Massey

Instrument Resources

Filters: None
Dispersers: B600
Focal Plane Units: Slitlet mask (already made)

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

Dec. range of principal targets (degrees): 59 to 59

Target Table for Run 1: GEM-NQ/GMOSN

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
1001	IC10	00:20:24.5	+59:17:30	J2000	23	300	PPO	80	20	any	70	MOS

NOAO observing proposal LaTeX macros v2.9.