NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: February 3, 2003 **Category:** Resolved Galaxies

Completing the Survey of Local Group Galaxies Currently Forming Stars: The Key to Understanding Massive Star Evolution

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
The galaxies of the Local Group can serve as our astrophysical laboratories, where we can investigate the formation and evolution of massive stars as a function of metallicity. The galaxies which are currently forming stars cover a range of 20× in metal abundance, far greater than the modest factor of 3 we obtain by comparative studies of the Magellanic Cloud with the Milky Way. Utilizing these galaxies will allow us to conduct sensitive tests of metallicity-depenence of the initial mass function, massive star evolution, and radiatively-driven stellar winds. Using NOAO survey time over the last two years we have obtained deep *UBVRI* as well as Hα, [OIII], and [SII] images of most of our Local Group galaxy fields. There were among the first data to be supplied to the fledgling NOAO Science Archive, and all of our pain-stakingly reduced images are now publically available, both through that archive and through our own web site, enable others to use these images for their own purposes. We are now requesting a modest amount of addition time to complete our survey, by obtaining images of the remaining fields (IC1613, Pegasus), and to repeat a few fields where the seeing was gross ($>$ 1.5-arcsecond).

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	KP-4m	MOSA	4	dark	Sep - Oct	Sep - Nov
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.*

The star-forming galaxies of the Local Group serve as our astrophysical laboratories for understanding the formation and evolution of massive stars. These galaxies cover a range of 20× in chemical abundances, from one-tenth solar (WLM) to twice solar (M31), allowing us to perform critical tests of the effects of metallicity (Z) on the initial mass function (IMF), massive star evolution, and radiatively-driven stellar winds. Such studies have been carried out only the SMC, LMC, and Milky Way, where the change in Z is a factor of 3.

Star Formation and the IMF. Studies of massive stars (Massey 1998a) have so far shown that the IMF slope is essentially Salpeter in the OB associations of the SMC, LMC, and Milky Way (Fig. 1). The variations which are seen are purely statistical (Kroupa 2001). However, Larson (1998) has argued on theoretical grounds that metal-poor systems should show a systematically different IMF, as low metallicity gas should have a lower cooling rate, and hence higher temperatures, affecting the Jeans-mass. Attempts to demonstrate this from comparing the IMF of open and globular clusters suffer from the systematic "evaporation" of low-mass stars in the latter system (Kroupa 2001); a far cleaner approch is to use the high mass stars that populate the bright OB associations of low- and high-metallicity galaxies. This is important for interpreting the star-formation histories of galaxies at large look-back times, where claims have been made for a top-heavy IMF.

Massive Star evolution. As a massive star evolves, it loses mass at rates as high as $3\times10^{-5}\mathcal{M}_\odot$ yr^{-1} (Puls et al. 1996). Thus a very massive star (100 $\mathcal{M}_\odot$) might lose half of its mass during its short 3 Myr lifetime. This mass-loss has a profound effect on the star's evolution, but it also makes it very hard to make reliable stellar evolutionary models (Maeder & Conti 1994). Observationally we see evidence of such effects from the relative number of Wolf-Rayet stars (WRs) and red supergiants (RSGs) as a function of metallicity in the Local Group (Fig. 2). Both WRs and RSGs are He-burning objects, with the WRs more evolved in the sense that they've suffered so much mass-loss that the nuclear burning products are revealed at the stellar surface. The trend we see is in the sense that we expect: at higher metallicities mass-loss rates should be higher and hence there should be more WRs than RSGs. This was predicted b Maeder et al. (1980), but we can see that the current stellar evolutionary models do not match the relation well. We would like to extend this to lower metallicties systems where the number of WRs is know but the number of RSGs requires BVR photometry for a good census (Massey 1998b).

Mass-Loss Rates and the Theory of Radiatively-Driven Winds. It's necessary to know how mass-loss rates scale with metallicity if we are to include the effects in our stellar evolutionary models. Radiatively-driven wind theory predicts that mass-loss rates will scale as $\dot{M} \sim L^{1/\alpha} M_{\rm eff}^{(\alpha-1)/\alpha}$,where $M_{\rm eff}$ is the "effective mass" (the mass modified by radiation pressure), and α is the power-law exponent of the line-strength distribution function for the thousands of lines driving the wind (Puls et al. 1996). However, there are practical difficulties in incorporating this elegant relationship in the models, as α will be a function of the effective temperature as well as Z, and $M_{\rm eff}$ depend upon the luminosity. We do have an empirical relation between the mass-loss rates and luminosity for Galactic stars (such as de Jager et al. 1988). Theory suggests that this can be extended to other metallicities using a power-law in Z, but there are uncertainities in the exponent, with estimates ranging from $(Z/Z_\odot)^{0.5}$ to $(Z/Z_\odot)^{1.0}$ (Puls et al. 2000; Vink et al. 2001, Kudritzki 2002). Here are again limited by the quality of the observational database, as all of the *measured* mass-loss rates come from O-type stars in the SMC, LMC, and the Milky Way, with their limited range in metallities. Measuring mass-loss rates in the more distant galaxies of the Local Group is within our reach, with 8-m optical spectroscopy and HST/STIS FUV spectroscopy. **But first we have to know what stars to take spectra of, and that requires imaging.**

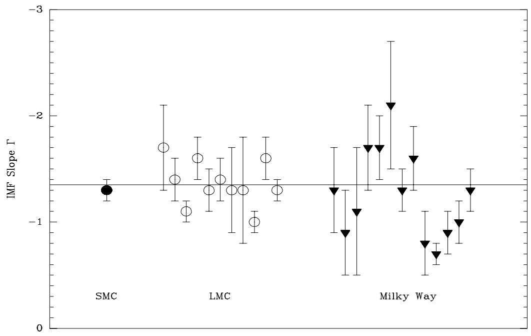

Figure 1: The initial mass function slope Γ is shown for OB associations in the SMC, LMC, and the Milky Way. The data are from Massey (1998), and the figure is from Massey (2003). A Salpeter $\Gamma = -1.35$ slope is shown for comparision.

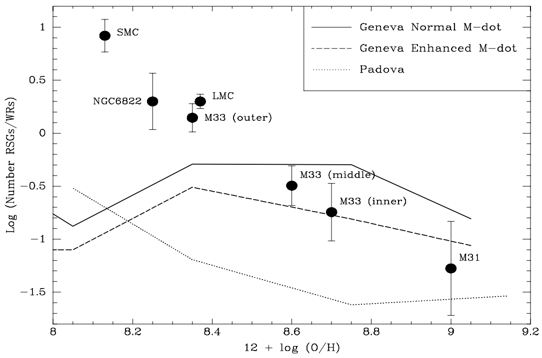

Figure 2: The relative number of red supergiants (RSGs) and Wolf-Rayet (WRs) changes by two orders of magnitudes in just 0.8 dex of metallicity. Note that none of the current crop of stellar evolutionary models do a very good job of modeling this trend. From Massey (2003).

de Jager et al. 1988 A&AS 72, 259

Kroupa 2001 MNRAS 322, 231

Kudritzki 2002 ApJ 577, 389

Larson 1998, MNRAS 301, 569

Maeder & Conti 1994 ARA&A 32, 227

Maeder, Lequeux, Azzopardi 1980, A&A 90, L17

Massey 1998a, in The Stellar Initial Mass Function, 17

Massey 1998b, ApJ, 501, 153

Massey 2003, ARAA 41, in press

Puls et al 1996, A&A 305, 171

Puls et al. 2000, A&AS 141, 23

Vink et al. 2001, A&A 369, 574

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)*

In September 2000 we began a project to survey all of the Local Group galaxies currently forming stars using the Mosaic imagers on the 4-m telescopes both at Kitt Peak and CTIO. Our project was to run for two years, and obtain deep *UBVRI* (S/N of 3 at U=B=V=R=I=25) as well as Hα, [OIII], and [SII] images of 10 fields of M31, 3 fields in M33, and single fields of the other systems: Phoenix, WLM, NGC6822, Pegasus, Phoenix, Sextans A and B, IC1613, and IC10. We've been remarkably successfully, and obtained beautiful images of *most* of our galaxies. **What we're missing are IC1613 and the Pegasus Dwarf; we also have a few fields where the images through one or more filters are vastly inferior to the 1-arcseconds images we've typically achieved.** We've been told to make our best science case to the regular TAC for the modest amount of additional time we need to complete the project. We're hoping you're agree that this is an easy sell.

IC1613. This is a low-luminosity dwarf with low metallicity (0.14$\times$ solar; Talent 1980, PhD Thesis); as such, it is the lowest metallicity Local Group galaxy that is known to contain a substantial massive star population as evidenced by the its many H II regions (Sandage 1971 ApJ 166, 13) and the presence of a lone Wolf-Rayet star (Armandroff & Massey 1985 ApJ 291, 685). The latter is of WC-type, making IC1613's WC/WN ratio very peculiar—for comparision, the SMC has 10 WNs and just 1 WC. This could just be a statistical fluke, or it could be saying something profound about the IMF of massive stars. Our new data will identify both the red supergiants and blue unevolved massive stars for comparison.

Pegasus. We obtained what we thought was good data on the Pegasus dwarf on the first night we observed as part of the survey, but found that the imfamous Mosaic corrector "ghost pupil" would not subtract properly on the interference filter or broad-band *U* and *I*. The only previous study of its resolved stellar population has been by Lee (1995, IAU 164, p. 413), and the data have never been published. We do know that it has some young massive stars as well as a few red supergiants. Thus ours would be the first systematic survey of this system.

Bad seeing. Our third goal for this run is to replace the bad seeing frames with better ones. How much does a difference this make for our studies of the IMF and the massive star population? We think it makes the difference between the data being usable and not. Judge for yourself from Fig. 3. Here we propose to obtain replacement images of only the worst data, cases where $>$ 1.5-arcsecond.

NOAO has sold the concept of its survey programs, with their generous allocation of observing resources, on the basis of the science they enables for others. After obtaining our survey data, we spent several person-years in refining the data reduction and calibration procedures; full details, include copies of our software, can be found on our survey web page **http://www.lowell.edu/ massey/lgsurvey**. We were among the first to provide data to the fledgling NOAO Science Archive, and *all* of our reduced images—both stacked and those suitable for photometry–are now available. **However, for this database to be of full benefit to others, it has to be both complete, and of reasonably uniform quality.** At the beginning of this process we made a good estimate of the clear number of nights needed to succeed in this project, and our only difficulty has been poor weather. With a very modest allocation of additional observing time we can now complete this project, and achieve our science goals.

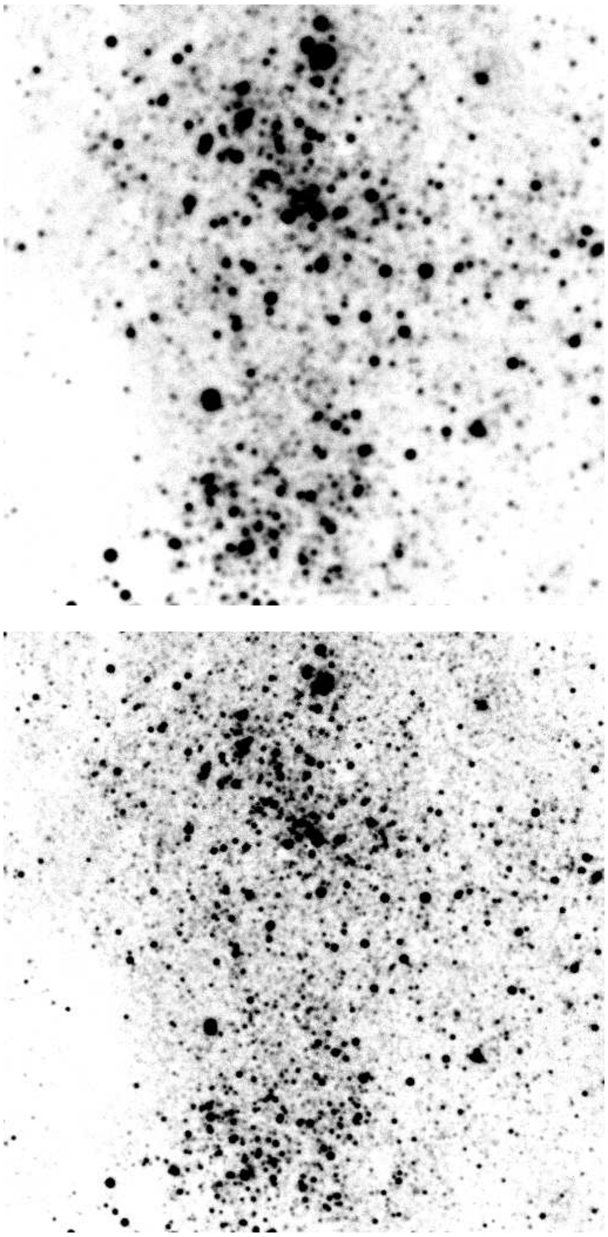

Figure 3: Two images of the same field in M 31 (B-band), obtained under very different seeing conditions. The seeing on the upper figure is 1.3-arcseconds; that on the lower is 0.79-arcseconds. This demonstrates the significant gain that can be had by reimaging the handful of poor seeing field/filter combinations under better conditions.

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.*

We are doing all of the broadband calibration of the Local Group Survey project using Lowell Observatory's 1.2-m Hall telescope at the dark-sky site at Anderson Mesa. This has saved tremendously in the amount of time for standard star observations at the 4-m, where simply the read-out time with Mosaic equals 100 minutes for 8 chips x 5 broadband filters. Instead we have been able to make use of good but non-photometric nights on the 4-meter by doing our calibration externally at Lowell, where we can use only the most pristine photometric nights to observe dozens of standards along with our Local Group galaxy fields. Our final photometric catalog is on track to come out next January.

In addition, we are using the existing set of HST images (most of which we've taken ourselves in parallel mode while doing spectroscopy of individual stars) to completement this data set with high resolution images, allowing us to estimate the effects of crowding on our IMF work.

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:** The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andomeda Galaxy", 3.5 nights MMT Sept 2002. We obtained only 0.5 nights out of 3.5 nights scheduled, due to weather. Some of the data we obtained appeared in: 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

$\boxed{\star}$ **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, data reduced and undergoing analysis.

$\boxed{\star}$ **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: KP-4m/MOSA

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).*

Instrument Configuration

Filters: $CuSO_4$	Slit: 1.0-arcsec	Fiber cable:
Grating/grism: 832	Multislit: no	Corrector:
Order: 2 (blue) and 1 (Halpha)	$\lambda_{\rm start}$: See above	Collimator:
Cross disperser:	$\lambda_{\rm end}$: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 1 to 1

Dec. range of principal targets (degrees): 40 to 40

M31 is located at 00:40 +40:00

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

NOAO observing proposal LaTeX macros v2.6.