OBSERVING REQUEST
University of Arizona Observatories

Year: *2004* **Term:** *Jul - Dec* **Proposal Number:**

The Effective Temperatures and Lyman Fluxes of Massive Stars at Low Metallicities

PI: Kathy Eastwood, NAU

CoI(s): Phil Massey (Lowell Obs), Nidia Morrell (LCO)

Proposal Type: short-term

Abstract of Scientific Justification

A knowledge of the effective temperatures of main-sequence massive stars is crucial for a variety of astrophysical applications, from understanding the reionization of the early universe to determining the initial mass function in nearby young clusters. We are proposing to obtain optical spectroscopy of 35 O-type dwarfs in the metal-poor Magellanic Clouds for the purposes of determining their effective temperatures and other physical properties using a new generation of model atmospheres. Recent studies have shown that that the effective temperatures of Galactic O stars are about 10% lower than previously assumed (Martins et al. 2002; Bianchi & Garcia 2002; Repolust et al. 2004). This has broad implications, as a 10% decrease in the effective temperatures results in 40% fewer Lyman photons, and 15% smaller inferred masses. However, the effects of wind-blanketing and metal-line blanketing will be less in the relatively metal-poor SMC and LMC, and hence we expect that O stars located in the Magellanic Clouds will be significantly hotter than their Galactic counterparts. We have identified a suitable sample using spectroscopy with the CTIO 4-m, but now need the greater S/N data that we can obtain with Magellan in order to do the detailed modeling.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Cage	Optimal months	Accept. months
1	MAG2	B&C	3	bright		Oct	Oct-Dec
2							
3							
4							

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

DuPont time has been assigned to Co-I Morrell through CIW for a complementary radial velocity study.

Is sharing nights possible and/or advisable?

Possible but not preferred.

Approval for Instrument Use from PI? N/A

For MMT requests only: Percentage of time to be assigned to UAO and CfA N/A,

For Magellan requests only: % of time to be assigned to UAO and others 100, 0

Observing List (attach list if longer than 10 objects)

Object	RA	DEC	Magniude
SMC-007622 [O5V]	00:46:50.06	-73:23:36.5	13.72
SMC-029527 [O6V]	00:54:14.96	-72:22:14.1	14.06
SMC-043724 [O7V((f))]	00:58:33.20	-71:55:46.8	14.25
SMC-051373 [O2-3V:]	01:01:29.57	-72:23:19.6	13.76
SMC-053668 [O7V((f))]	01:02:26.61	-71:50:55.3	14.36
SMC-059319 [O2-3V]	01:04:27.87	-72:04:52.0	14.32
LMC-054383 [O3V]	05:02:09.94	-70:32:58.1	13.91
LMC-054383 [He-rich O2-3]	05:02:10.94	-70:32:58.1	14.10
LMC-142450 [O7V]	05:28:51.05	-69:15:53.0	14.10
LMC-147521 [O4-5V]	05:29:33.30	-67:39:06.8	13.82

All of the other targets are also located in the SMC and LMC, with similar magnitudes.

CONTACT INFORMATION:

Observer(s) Institution: Kathy Eastwood, NAU; Philip Massey, Lowell; Nidia Morrell, LCO

Email(s): Kathy.Eastwood@nau.edu; Phil.Massey@lowell.edu; nmorrell@lco.cl

Phone Number(s) : KE: 928-523-7159; PM: 928-233-3264

GRADUATE STUDENTS:

Whose second year project is this? ______________________

Whose thesis is this? ______________________________

For **each** graduate student named on the front page, provide the following information:

Student's Name	Advisor's Name	Advisor's Signature

Scientific Justification

Knowledge of the physical properties of hot massive stars is necessary for a number of broad astrophysical applications. For instance, when we characterize the star-formation process of a young cluster containing massive stars, our ability to measure the initial mass function and star-formation history of the region is limited by how well we can determine the effective temperatures and bolometric luminosities of the member stars in order to compare to theoretical isochrones and stellar evolutionary tracks. (See, for example, Massey 2003.) Additionally, we need to know the ionizing flux and amount of mechanical energy (via stellar winds) being supplied to the surrounding gas if we are to successfully model the expanding shells, superbubbles, and normal H II regions that make up the ionized ISM of the Milky Way and other late-type galaxies (Hunter & Massey 1990, Oey & Kennicutt 1997). Without an accurate knowledge of the Lyman continuum flux, we don't know if such regions are typically density-bounded or radiation-bounded, a question which is important for understanding the ionizion of the diffuse, warm ionized interstellar medium, and the escape of ionizing radiation from galaxies (Oey 2004). Finally, such knowledge is important in terms of understanding the evolution of massive stars. If we want to know the mass range that evolve to red supergiants and Wolf-Rayet stars in galaxies of differing metallicities, then we need to understand the number and distribution of unevolved massive stars in the H-R diagram (Maeder & Conti 1994; Massey, DeGioia-Eastwood, & Waterhouse 2001). For all of these studies (and more!) we begin with photometry and spectroscopy, but what we need are the effective temperatures, bolometric luminosities, stellar masses, radii, and mass-loss rates in order to do the physics.

Translating the observed characteristics of O-type stars into physical parameters has historically proven to be very challenging. Because of the high effective temperatures, most of their flux is in the far UV, where even spacecraft such as *FUSE* and *HST* cannot observe, as the peak of the flux distribution F_λ will be below the Lyman limit for stars hotter than about 32,000°. When we observe an O-type star from the ground or from space, we are always observing on the tail of the Rayleigh-Jeans distribution, and as a result spectrophotometry (or broad-band colors) cannot give us useful knowledge of the effective temperature for O-type stars (see Massey et al. 1995), although such analyses work well for B-type stars (Fitzpatrick & Massa 1999). Instead, we depend upon comparing the line strengths predicted by stellar atmospheres with what we observe.

These stellar models are by necessity quite sophisticated, as the physics of O-star atmospheres is complex. Their strong lines are all formed under non-LTE conditions, as first shown by Auer & Mihalas (1972), and in addition stellar winds provide a significant source of heating for their photospheres through the backscattering of radiation (Hummer 1982; Abbott & Hummer 1985). Modern O-star models have included not only the full non-LTE treatment of spectral lines, but also the spherical extension and the hydrodynamics of stellar winds in the entire sub- and supersonic regions (Puls et al. 1996; Santolaya-Rey, Puls, & Herrero 1997; Kudritzki & Puls 2000).

These models have recently been improved by the inclusion of metal lines, which introduces line blanketing in the extreme UV. The result has been a lowering of the effective temperature scale for Galactic O stars by some 10% (Martins, Schaerer& Hillier 2002; Bianchi & Garcia 2002; Crowther et al. 2002; Repolust et al. 2004). This lowering of the effective temperature scale has broad implications: a 10% effect would result in 40% fewer Lyman photons, and a significant change in the deduced luminosities (0.3 mag) and masses (15%).

However, such a drastic decrease is not expected for low-metallicity O stars, such as those found in the Magellanic Clouds. Furthermore, because the stellar winds are weaker at low metallicities, the temperatures of SMC and LMC O stars should be hotter than that of their Galactic counterparts due to the lessened importance of wind-blanketing (Abbott & Hummer 1985). The net effect is that SMC and LMC stars might be significantly hotter than their Galactic counterparts. Preliminary data on a sample of SMC and LMC stars confirms the trend (see, for example, Massey et al. 2004), but detailed modeling of a large sample of normal O and early B-type dwarfs are needed, as the handful of studies of Magellanic Cloud stars have been restricted to the most luminous supergiants (e.g., Crowther et al. 2002, Hillier et al. 2003, and Bouret et al. 2003).

We have identified a suitable sample of stars in the SMC and LMC by obtaining $R \sim 3000$ blue spectra with Hydra on the CTIO 4-m telescope of 800+ stars drawn from the UBV survey of Massey (2002). We have selected a sample of 15 stars for which we have good blue (3500-4800Å) spectra, but require accurate Hα profiles. Hα observations are a crucial component of our modeling, as this line is highly sensitive to the mass-loss rates $\dot{M}$ (see Fig. 1), which in turn is needed for determining the other physical parameters (effective temperature, surface gravity, stellar radius, bolometric luminosity). We have an additional sample of 10 stars in which the blue spectrum is good enough to classify the star (S/N =80 per 1.5Å resolution element) but for which we need much higher S/N data for the modeling (typically 350 per Å), as well as Hα. These follow-up observations require the large collecting area of Magellan in order to achieve the necessary S/N, as described in more detail in the next section. These observations also require the good seeing that is typically found on Campanas, as this will allow us to use a narrow slit (0.7 arcsec), decreasing the amount of nebular Hα contamination in such spectra.

Included in this sample are some of the hottest and most luminous stars known—stars of spectral type "O2-3". Our previous study with spectra obtained from long-slit observations with the CTIO 4-m (Massey et al. 2004) was unable to detect any He I in the spectrum, and hence set only a lower limit on the effective temperature using the He II lines. This in turn meant that we could determine only a lower limit on the stellar luminosity and mass. The higher S/N spectra that we can obtain with Magellan should allow us to break this degeneracy, and determine actual physical parameters for what may be the highest mass stars ever seen.

In addition, we include a few stars in our sample that challenge the prevailing paradigm of how massive stars evolve. Our work over the past several years has found several O2-3 stars which show highly processed chemical abundances at their surfaces. Now, this makes no sense: the earliest spectral type is a short-lived phase in the lives of the most massive star, and such objects should not show He/H number ratios of ≥ 1 at their surfaces! Time has been granted to obtain UV spectra with HST of these stars, but what is also needed are high S/N optical data for better modeling. An example of such a star is shown in Fig. 2. Co-I Morrell has also been granted time on the Campanas Dupont 100-inch to monitor the radial velocities of these stars to see if they are binaries. If no motion is detected, and the high chemical abundances are confirmed by better spectra, then we are left with suspecting that these stars are in this part of the H-R diagram for the second time in their lives. From an evolutionary point of view, these stars might be thought of as Wolf-Rayet stars—but ones that have no stellar wind.

REFERENCES

Abbott & Hummer 1985, ApJ, 294, 286
Auer & Mihalas 1972, ApJS, 24, 193
Bianchi & Garcia 2002, ApJ, 581, 610
Bouret et al. 2003, ApJ, 595, 1182
Crowther et al. 2002, ApJ, 579, 774
Fitzpatrick & Massa 1999, ApJ, 525, 1011
Hillier et al. 2003, ApJ, 588, 1039
Hummer 1982, ApJ, 257, 724
Hunter & Massey 1990, AJ, 99, 846
Kudritzki & Puls 2000 ARA&A, 38, 613

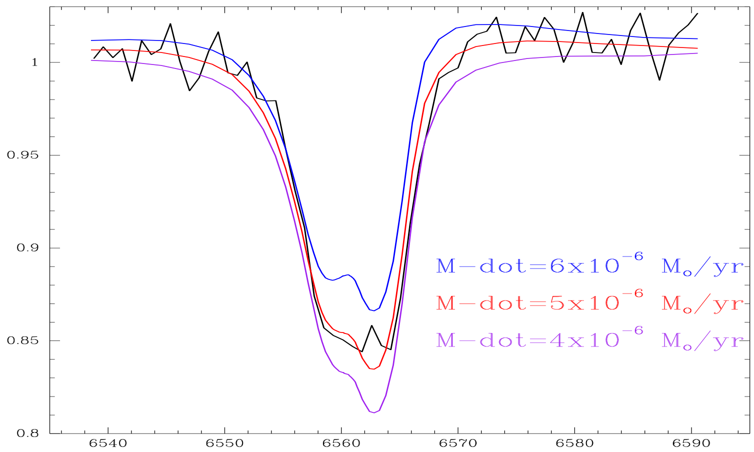

Figure 1: The effects of differing mass-loss rates on the Hα profile is shown. From Massey et al. (2004).

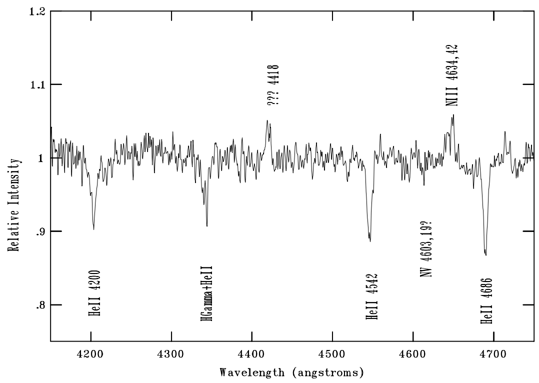

Figure 2: Most of the "hydrogen Balmer lines" in the spectrum of this O2-O3 star, LMC-054303, appear to actually be due to the even-n Pickering He II transitions; i.e., the surface of this star is highly helium rich, with little (if any) hydrogen present. A higher S/N spectrum is needed in order to detect He I λ4471, necessary for any effective temperature determination. The spectrum is a 2-hr exposure with the CTIO 4-m in Dec 2002.

Martins, Schaerer, & Hillier 2002, A&A, 382, 999
Massey 2002, ApJS, 141, 81
Massey 2003, ARA&A, 41, 15
Massey, Bresolin, Kudritzki, Puls, & Pauldrach 2004, ApJ, in press (astro-ph/0402633)
Maeder & Conti 1994, ARA&A, 32, 227
Massey, DeGioia-Eastwood, & Waterhouse 2001, AJ, 121, 1050
Massey, Lang, DeGioia-Eastwood, & Garmany 1995, ApJ, 438, 188
Oey, in The Local Group as Astrophy. Laboratory, ed. Livio, in press
Oey & Kennicutt 1997, MNRAS, 291, 827
Puls et al. 1996, A&A, 305, 171
Repolust, Puls, & Herrero 2004, A&A, 415, 349
Santolaya-Rey, Puls, & Herrero 1997, A&A, 323, 488

Experimental Design & Technical Description *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)*

Using the B&C Spectrograph on Magellan we will obtain high S/N (> 350) Hα and blue spectra at a resolution of 1.5Å(comparable to the smallest $v \sin i$ values). These data will then be modeled with the stellar atmosphere code FASTWIND ("Fast Analysis of STellar atmospheres with WINDS"), which now includes line-blocking (Repolust et al. 2004). The technique is described by Massey et al. (2004): the effective temperatures are constrained primarily by the line strengths of He I ($\lambda 4387, 4471$) and He II lines ($\lambda 4200, 4542$) The surface gravity of the star is determined from fitting the wings of Hδ and Hγ. The mass-loss rate $\dot{M}$ comes from fitting of the Hα profile (Fig. 1). In practice, the determination of any one of these is dependent upon the the other two, and all three must be solved for iteratively until a good (and unique) fit is found to the observed spectrum. For stars with the highest mass-loss rates the determinations will also depend upon the value adopted for the terminal velocity of the wind, v_∞, which can be best measured from fitting the CIV $\lambda 1550$ resonance line. For some of the stars in our sample we have *HST* UV spectra either in-hand or pending; for others we will propose in Cycle 14, assuming that there is one. (Lacking UV data, we can approximate the terminal velocity using the modified mass-luminosity-momentum relation $v_\infty \dot{M} R^{0.5} \sim L$, where R is the stellar radius and L the luminosity, determined by the models.)

Why Magellan? We have pursued these studies as far as we can go with 4-m apertures (e.g., Massey et al. 2004). The CTIO 4-m has provided good spectra of the brighter supergiants and giants, but the larger aperture of Magellan is needed for the dwarfs, which of course are the most numerous type of O-star, and which dominate the ionization of any HII region. Assuming a total throughput of 20%, we expect about 120 photons/sec/Å for our typical $V \sim 14$ star observed at an airmass of 1.3, and so for a S/N of 350 requires about 20 minutes per star. With overhead, we expect to be able to do 2.2 stars/hour, and so in an 8-hr night we should be able to 18 stars. Thus two nights are needed for the Hα observations (35 stars), and a third night is needed for the blue/optical observations (15 stars). The large sample (35 stars in all) is needed to cover the full range of spectral types (O2-O9), with 2-3 examples at each subtype.

Why the B&C? We were tempted by IMACS on the MAG1, and were there multiple targets within any 15'x15' field of view, we would have succumbed. But we don'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 about 30% better at Hα, as the only IMACS grating that covers Hα provides only 2.2Å resolution with a 0.7-arcsec slit. The B&C provides 1.5Å resolution, which is an ideal match to the typical $v \sin i$, and hence is optimal for detection of the weak He I lines in O2-3 stars, which is needed for determining the effective temperatures. MIKES would provide considerably higher resolution, but would provide less robust sky (nebular) subtraction given its short slit. Good nebular subtraction at Hα is crucial to the determination of the mass-loss rates (Massey et al. 2004).

Previous Use of Steward Facilities *List allocations of telescope time on facilities available through Steward to the investigators 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.*

3 1/2 night MMT time Sept 02 through NOAO TAC—3 nights wiped out by monsoons; the clear half-night led to Massey & Holmes ApJ, 580, L35.

3 nights MMT time Sept 03 through the UAO TAC—wiped out by monsoons.