Scientific Justification

The presence of P Cygni profiles in the UV spectra of OB supergiants demonstrated the existence of stellar winds in these stars (Morton 1967). Subsequent studies with the *Copernicus* satellite then established that such mass-loss was ubiquitous among hot, luminous stars (Snow & Morton 1976). Typical mass-loss rates are 0.2–20$\times10^{-6}\mathcal{M}_\odot$ yr^{-1} (Puls et al. 1996; Kudritzki & Puls 2000). Thus a very massive star (100 $\mathcal{M}_\odot$) might lose half of its mass during its 3 million year life.

These observations motivated the development of a theory to explain this mass-loss: Lucy & Solomon (1970) calculated that the radiation pressure acting on UV resonance lines of ionized metals were sufficient to drive stellar winds, and the study of radiatively-driven stellar winds was born. Work by Castor et al. (1975), Abbott (1979), and Pauldrach et al. (1985) convincingly demonstrated that the mass-loss of hot massive stars was driven and maintained by this mechanism.

This mass-loss has a very profound effect on the evolution of massive stars, as shown by the first stellar interior models that included the effects of mass-loss (de Loore et al. 1977; Chiosi et al. 1978; Brunish & Truran 1982). Since mass-loss is driven through radiation pressure through ionized metal lines, the mass-loss rates are expected to be a function of metallicity. The effects of this dependency are easily seen in Fig. 1, where we compare the evolved massive star content of nearby galaxies of differing metallicities. The relative number of red supergiants and Wolf-Rayet stars changes by two orders of magnitudes over just 0.8 dex in the metal abundance, in the same qualitative sense predicted by Maeder et al. (1980). We can expect that the effect that metallicity has on the evolution of massive stars will affect the integrated colors of star-forming regions, and thus be important in efforts to understanding the colors of galaxies at early look-back times, as well as the interpretation of the resolved massive stellar population closer to home.

Given the effects mass-loss has on the evolution of massive stars, an accurate parameterization on stellar parameters (luminosity L, effective temperature $T_{\rm eff}$, as well as metal abundance Z) is clearly of interest. This is critical, after all, in knowing how to account for mass-loss in computing the stellar evolutionary models. The theory of radiatively-driven winds predicts that the mass-loss rate $\dot{M}$ will be related to the physical parameters of a star by $\dot{M} \sim L^{1/\alpha}M_{\rm eff}^{(\alpha-1)/\alpha}$, where $M_{\rm eff}$ is the "effective mass" (the mass modified by radiation pressure on free electrons), and α represents the power-law exponent of the line-strength distribution function for the thousands of lines driving the wind (Puls et al. 1996, Kudritzki & Puls 2000). However, there are practical difficulties in incorporating this elegant relationship into stellar evolutionary models: in general, α will be a function of the effective temperature, and the "effective mass" depends additionally upon the luminosity. For hot O-type stars, the value of α is approximately 0.6 (Pauldrach, Puls, & Kudritzki 1986; Kudritzki & Puls 2000), suggesting a luminosity exponent ~ 1.7, similar to what is observed.

The parameterization of mass-loss has been attempted *empirically* by a number of authors; the relation of de Jager et al. (1988) has commonly been adopted for Galactic metallicity stars, i.e., $\dot{M} \sim L^{1.769}T_{\rm eff}^{-1.676}$. Note that the exponent on the luminosity is similar to that predicted above (ignoring the implicit dependence of L on $M_{\rm eff}$), with the $M_{\rm eff}$ replaced with a dependence upon $T_{\rm eff}$ instead. (The latter has the advantage of being observable, but hides the underlying physics.) For Galactic stars this relationship provides good agreement between theory and observations.

However, the fundamental difficulty in the use of mass-loss parameterizations arises in the extension to non-Galactic environments, where the metallicity Z differs significantly from solar. For simplicity most evolutionary models (e.g., Schaller et al. 1992; Bressan et al. 1993) adopt a scaling of the de Jager relation by $(Z/Z_{\odot})^{0.5}$ following Kudritzki et al. (1989), although others have suggested a steeper scaling (i.e., 0.8–0.9, Leitherer et al. 1992; Lamers & Cassinelli 1996).

New theoretical work has called this simple metallicity dependence into question. Puls et al. (2000) suggest a scaling with metallicity of approximately $(Z/Z_{\odot})^{(1-\alpha)/\alpha}$, where α itself is a function of Z. Kudritzki (2002) also finds that the situation is more complicated than simple power-law scaling, with a threshold effect at low Z. However, over the metallicity range usually considered (i.e., SMC to the solar neighborhood, or $Z/Z_{\odot}$ from 0.3 to 1.0), a scaling with $(Z/Z_{\odot})^{0.5}$ turns out to be a good approximation, at least for O-type stars. Vink et al. (2001) have also developed models of mass-loss at different metallicities, finding a somewhat steeper dependence $(Z/Z_{\odot})^{0.7}$. In Fig. 2 we compare the different theoretical predictions against the observational data-base, and see that they are indistinguishable over the small range of metallicity covered by stars in the Magellanic Clouds and the solar neighborhood (i.e., from one-third solar to solar in Z). The scatter in such a diagram makes it impossible to argue that any one scaling is any better than another. (Such scatter is a natural consequence of how one "observes" a mass-loss rate in the first place, which is itself somewhat model dependent; see discussion in Lamers & Leitherer 1993, Puls et al. 1996, and in particular Kudritzki & Puls 2000). **To advance radiatively-driven wind theory, and to thus better understand the evolution of massive stars in environments of differing metallicities, we must extend the database of observed mass-loss rates to a larger range of metallicities.**

We now have an unprecedented opportunity to extend our knowledge of the mass-loss rates to $2\times$ solar by using O-type stars in M31, the Andromeda Galaxy. (The H II region abundances measured by Zaritsky et al. 1994 suggest an oxygen abundance twice that of the solar neighborhood.) Early efforts to study mass-loss in Andromeda's O stars are nicely summarized by Bresolin et al. (2002), but were mainly quixotic. These included ultraviolet spectroscopy with the *IUE* satellite (Bianchi, Hutchings, & Massey 1991), as well as (primarily pre-COSTAR) FOS observations with *HST* (Bianchi, Hutchings, & Massey 1996). The *IUE* data were so poorly exposed that we were misled to the conclusion that M31's hot stars lacked stellar winds (Hutchings, Massey, & Bianchi 1987). The *HST* FOS observations produced tantalizing confirmation that there are indeed stellar winds in the hot stars of M31 (Bianchi et al. 1996, Haser et al. 1995), but were still of very marginal quality (i.e., signal-to-noise of 8 to 10 per $\sim$2Å resolution element), limiting the quantitative information that could be extracted. Optical work carried out with the 4-m class telescopes and intensified Reticons provided approximate spectral classifications (Massey et al. 1986) but were nothing to write home about either, as demonstrated by the misclassification by the present PI of a B1 I as an early O-type star (cf. Hutchings, Massey, & Bianchi 1987 and Bianchi et al. 1994).

Now a new generation of instruments has placed these stars within our reach. A single 10-orbit exposure with STIS/FUV-MAMA will result in a beautiful ultraviolet spectrum from 1150–1735Å with a signal-to-noise of 20-30 per 0.9Å resolution element, similar in quality to what we have been using routinely for similar analysis of Magellanic Cloud O-type stars. Optical spectra taken with the MMT 6.5-m telescope and its high-throughput blue channel spectrograph have resulted in high quality optical spectra (Fig. 3), suitable for detailed modeling.

We have identified four O-type stars of similar spectral type (O8-O8.5 I) in M31 which are suitable for such studies. This selection is based upon two decades of ground- and space-based studies (Massey et al. 1986, 1996) plus new MMT 6.5-m data obtained specifically for this program. We consider four to be a reasonable, minimum sample size for a single effective temperature, given the expected scattered (recall Fig. 2!) in our results. Our optical spectroscopy of this sample is nearly complete: we require only Hα data for two of the stars, and for this we are requesting 1 night on the MMT through the *HST* TAC via the coordinated observing NOAO program. (Lacking this, we will pursue other options, but one way or another, the Hα data are crucial to our study.)

Our analysis will make use of the most sophisticated and comprehensive models, which include spherical extension and the hydrodynamics of stellar winds in the entire sub- and supersonic atmospheric structure (Kudritzki and Puls 2000), as well as providing the full non-LTE treatment of metal lines needed for the spectral synthesis of O-stars. We have planned our team to include the appropriate skills, and will proceed as follows. Co-I Bresolin will measure the terminal velocities of the stellar winds using our new STIS/FUV-MAMA spectra. His modeling will produce a value for the terminal velocity, which will be used with Co-I Puls' FASTWIND atmosphere code (Santolaya-Rey et al. 1997; Puls et al. 2002) to fit the optical blue and Hα profiles to derive mass-loss rates, effective temperatures, surface gravities, and bolometric luminosities (Massey, in consultation with Co-Is Kudritzki and Puls). Co-I Bianchi will use the WM-basic atmosphere code (Pauldrach et al. 1994, 1998, 2001) to obtain an independent fit of these stellar parameters solely from the STIS/FUV-MAMA spectra themselves (i.e., following Bianchi & Garcia 2002 and Bianchi et al. 2003), consulting with Co-I Pauldrach as needed. In addition, the WM-basic modeling will provide an independent estimate of the stellar abundances, important as some recent work (Trundle et al. 2002, Bresolin et al. 2002) finds somewhat lower abundances from stellar analysis than one would expect from the H II region data. Finally, Co-I Eastwood will assist Massey in obtaining and reducing the new ground-based optical spectra from the MMT.

When we complete this analysis we will have good knowledge of the stellar wind parameters (terminal velocities and mass-loss rates) as well as the physical properties (luminosity, effective temperature, radius, surface gravity, mass, and metallicity) of four early-type stars in the Andromeda Galaxy: the first O-type stars to be analyzed in this way in an environment higher than solar. This will have the same impact in the field as the early *IUE* observations had of Magellanic Cloud stars, with its extension to lower-than-solar metallicity. It complements recent work on the wind momentum-luminosity relation being carried out for B-type supergiants in M31 and more distant galaxies (i.e., Bresolin et al. 2002). We have been working hard on this problem for the past 20 years; it is only now, though, that it is within our grasp, thanks to the improvement in UV instrumentation (i.e., STIS/FUV-MAMA) and optical telescopes (i.e., ≥ 6.5-m).

Parallel Imaging: During each STIS exposure we will carry out parallel WFPC2 and ACS imaging of two fields using UV and optical filters. The HST resolution will prove a useful complement to the ground-based M31 Local Group Survey data (Massey 2003), with the space-UV imaging providing excellent additional data on the hottest stars (Massey et al. 1995, Bianchi et al. 2001). The multi-band photometry will be fit with synthetic colors constructed from a vast grid of line-blanketed atmospheres to derive T_{eff} and extinction. These images will be the deepest look at HST resolution of the Local Group galaxy which most closely resembles our Milky Way.

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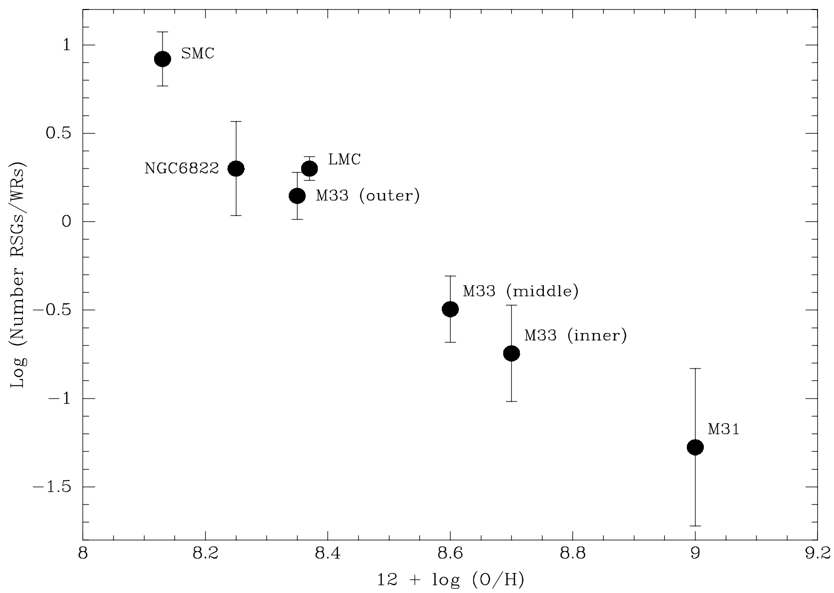

Figure 1: The relative number of red supergiants (RSGs) and Wolf-Rayet stars (WRs) is shown as a function of the oxygen abundances (Z is typically taken as proportional to O/H). Lower metallicity means lower mass-loss rates, and so an evolved massive star spends a greater proportion of its He-burning life as a RSG rather than a WR, while at higher metallicity, mass-loss rates are larger, making it easier to "peel off" the H-rich outer envelopes and reveal nuclear burning products at the stellar surface, characteristic of WRs. This figure is from Massey (2002, 2003).

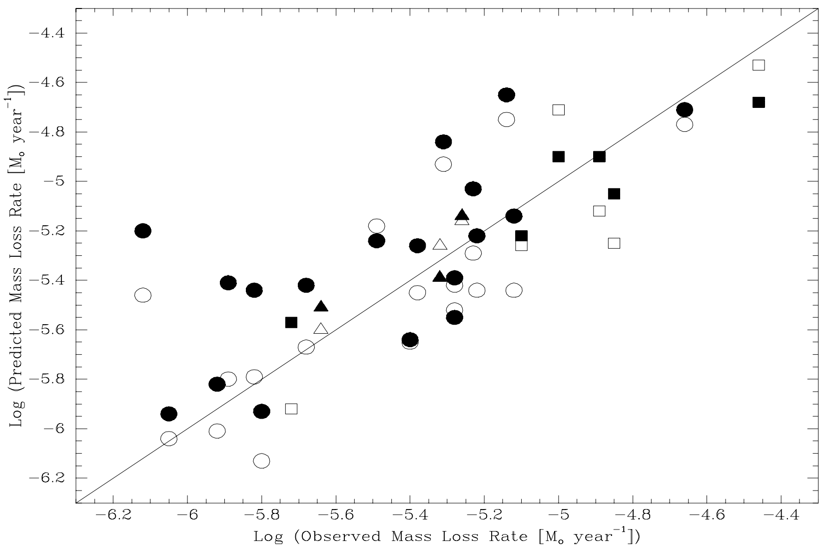

Figure 2: A comparison is shown between the observed mass-loss rates determined by Puls et al. (1996) and that predicted by the de Jager et al. (1988) using a $(Z/Z_\odot)^{0.5}$ scaling (filled symbols) and that predicted by Vink et al. (2001) using a $(Z/Z_\odot)^{0.7}$ scaling (unfilled symbols). Circles denote Galactic stars, squares denote LMC stars, and triangles denote SMC stars. The scatter in this diagram is at least partially observational, and partially deficiencies in our understanding of stellar winds. From Massey (2003).

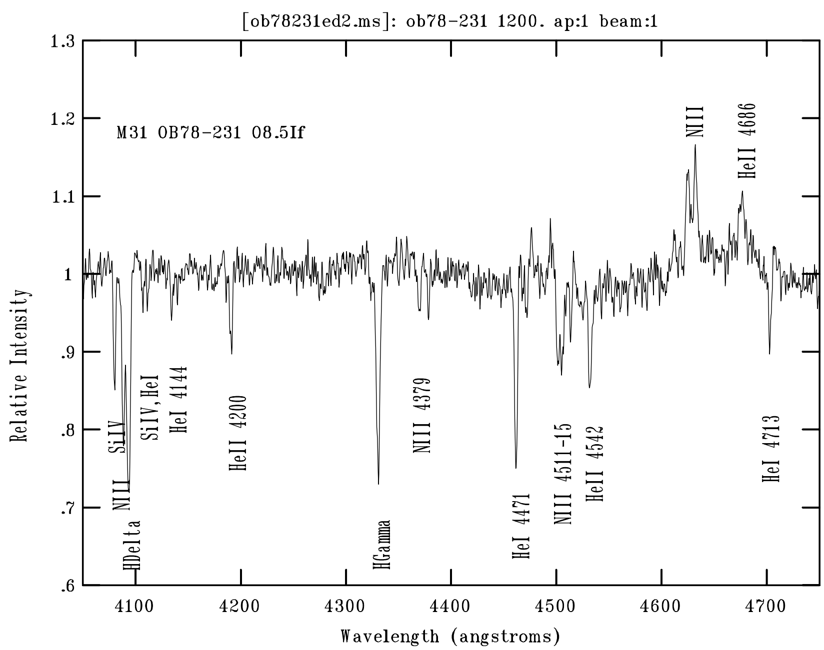

Figure 3: The normalized blue spectrum of M31's OB78-231 obtained at the MMT in September 2003 by Massey & Eastwood. The spectra have a S/N of 90 per 2Å resolution element, and shows what can now be done with large telescope apertures and high-throughput spectrographs. It is finally possible to do "galactic astronomy" even at the distance and reddening of M31!

Description of the Observations

The maximum allowed length for a single visit is 5 orbits, and we will need two such visits to observe each of our four targets in M31, or a total of 40 orbits. Each orbit has a visibility period of 54 minutes, and each visit then allows 13500 seconds of integration. Here's the basis for request:

Orbit 1:
- Guide star acquisition: 6 minutes
- STIS/ACQ for a nearby bright offset star: 6 minutes
- Small Angle Maneuver (SAM) to target: 1 minute
- Overhead for first STIS/FUV-MAMA exposure: 8 minute
- Remaining integration time in first orbit: 33 minutes.

Orbits 2-5:
- Guide star re-acquisition: 5 minutes
- Overhead for next STIS/FUV-MAMA exposure: 1 minute
- Remaining integration time for each of orbits 2-5: 48 minutes

Total integration time per 5-orbit visit: 13500 seconds

According to the STIS exposure time calculator, this will lead to a S/N of 16 at 1550Å for our typical $V = 19$, $E(B - V) = 0.25$ target; two such visits will thus allow us to reach a S/N of 22. Given the range in V and $E(B - V)$ of our targets (Massey et al. 1986 AJ, 92, 1303) we expect in practice to reach a S/N of 20-30 for each target. This is then comparable to what we have been using for our Magellanic Cloud investigations. Given the uncertainty in $E(B - V)$, we have chosen not to tailor the exposures for the slightly different Vs. WFPC2 images of each of our targets that show that they are isolated at the 0.1-0.2" level; there are no signs of companions visible in the optical spectra, giving us confidence that we are truly looking at single objects.

For the parallel observations, we plan to use **both** WFPC2 and the ACS/WFPC cameras **simultaneously** to observe two neighboring fields during each visit. Thus we will obtain deep imaging with one or the other camera for 16 fields. (Following a request from STScI's help desk, we list each of these fields separately (80 parallel orbits) in the observing summary, but include only 40 parallel orbits on the cover page.) **Since we will be using three instruments simultaneously, we will obtain the equivalent of 120 orbits worth of data for only 40 orbits of telescope time—which we view as quite a bargain!** With WFPC2 we will use F170W (1 orbit), F255W (1 orbit), F336W (1 orbit), and split F439W, F555W, F675W, and F814W for the remaining two orbits. With the ACS we will expose in the B, V, R, I, and Hα, and O[III] filters, distributed as best we can to not interfere with our primary observations.

Special Requirements

We will request permission from the Institute to once again use the "echelle" 0.2" $\times$ 0.2" aperture rather than the default first-order long slit. This alleviates any concerns about bright field stars that might accidentally fall in the long slit. We have used this aperture very successfully with our Cycle 9 and 11 HST STIS/FUV-MAMA programs.

Coordinated Observations

We are requesting 1 night of MMT time with the blue-channel spectrograph to complement our existing spectroscopy by obtaining Hα profiles of OB10-150 and OB48-444. The Hα observations are needed to compute mass-loss rates, when combined with our HST STIS/FUV data, and our already existing MMT blue spectra. We will use our usual setup, namely the 832 l/mm grating in first order with a L-495 blocking filter and standard apertures (1.5 to 0.75" wide slit, depending upon the seeing). No special timing is needed. Quarter moon (grey time) is acceptable.

Justify Duplications

Stars OB48-444 and OB78-231 have previously been observed by two of the Co-Is with the FOS in the ultraviolet, but have too poor a signal-to-noise for the quantitative spectroscopic analysis we propose here. We have already done the best that is possible with those data; we need a good quality dataset (higher S/N and better resolution) to answer the scientific questions we pose here.

Previous Related HST Programs

Massey has been PI or CoI on the following *HST* proposals which are relevant to the program described here:

- **"Stellar Winds in M31, M33 and NGC6822":** GO-1150 (Cycle 1, Hutchings PI), GO-2581 (Cycle 1, Bianchi PI), GO-3954 (Cycle 2, Hutchings, PI), GO-5179 (Cycle 4, Hutchings, PI), GO-5494 (cycle 5, Bianchi, PI), GO-6567 (cycle 6, Binachi, PI). These were are early attempts to use *HST* (both with GHRS and FOS) to obtain UV spectra of hot stars in M31 and M33 (and subsequently NGC 6822). The data and analysis were published in the following papers (excluding meeting abstracts):
  - Hutchings, Bianchi, Lamers, Massey, & Morris 1992 ,"Hubble Space Telescope Spectroscopy of OB Stars in M31", ApJ, 400, 35
  - Bianchi, Lamers, Hutchings, Massey, Kudritzki, Herrero, & Lennon 1994, "Ultraviolet and Optical Spectroscopy of a B Supergiant Star in M31", A&A, 292, 213
  - Haser, Lennon, Kudritzki, Puls, Pauldrach, Bianchi, & Hutchings 1995, "The Stellar Wind of an O8.5 I(f) Star in M31", A&A, 295, 136
  - Bianchi, Hutchings, & Massey 1996, "The Winds of Hot Stars in External Galaxies. III. UV Spectroscopy of O and B Supergiants in M31 and M33", AJ, 111, 2303
  - Bianchi, Clayton, Bohlin, Hutchings, Massey 1996, "Ultraviolet Extinction by Interstellar Dust in External Galaxies: M31", ApJ, 471, 203
  - Bianchi, Scuderi, Massey, & Romaniello 2001, "The Massive Star Content of NGC 6822: Ground-Based and Hubble Space Telescope Photometry", AJ, 121, 2020
- **"The Evolution of Massive Stars: Closing the Loop Observationally...":** GO-5998 (Cycle 5, PI Massey), GO-7464 (Cycle 7, PI Massey). These two projects were intended to

complement on-going ground-based studies of coeval regions in M31 and M33. In GO-5998 I obtained WFPC2 images of selected OB associations in these two galaxies in order to see establish whether particular high luminosity stars were single or simply blends undetected from the ground; the data were then used to improve the ground-based photometry. These data were then used to select stars for further spectroscopic observations, with the MMT and KPNO 4-m telescopes. A STIS/CCD proposal was then awarded time (GO-7464) in order to obtain spectra of the stars that had proven too difficult (crowded) to do from the crowd. The ground-based spectroscopic part of the program was delayed while the MMT underwent its conversion to 6.5-m, and the subsequent commissioning pains. Now that the telescope is functional I hope to have the total project completed next year. The data have been partially published in:

- Massey, Bianchi, Hutchings, & Stecher 1996, "The UV-brightest Stars of M33 and Its Nucleus: Discovery, Photometry, and Optical Spectroscopy", ApJ, 469, 629
- Massey, Armandroff, Pyke, Patel, & Wilson 1995, "Hot Luminous Stars in Selected Regions of NGC 6822, M31, and M33", AJ, 110, 2715
- Massey 1998, "Observations of the Most Luminous Stars in Local Group Galaxies", in Stellar Astrophysics for the Local Group, ed. A. Aparicio, A. Herrero, and F. Sanchez (invited series of lectures), 95

• **"Star Formation in the Prototype Super Star Cluster R136":** GO-6417 (Cycle 6, PI Massey). This was the first study to obtain spectra of a significant number of stars in the R136 cluster in the LMC, demonstrating that the IMF was Salpeter, and that whatever the mass is of the highest mass star, we have yet to encounter it in nature. Publications included:

- Massey & Hunter 1998, "Star Formation in R136: A Cluster of O3 Stars Revealed by Hubble Space Telescope Spectroscopy", ApJ, 493, 180
- Massey & Hunter 1998, "R136: A Cluster of O3 Stars" (invited talk), in Boulder-Munich II: Properties of Hot, Luminous Stars, ed. Howarth (ASP), 355
- Massey 1998 "The Initial Mass Function of Massive Stars in the Local Group" (invited review), in The Stellar Initial Mass Function, 38th Herstmonceux Conf., ed. Gilmore & Howell (ASP), 17
- Hunter 1999 "The Stellar Population of R136" (invited talk), in New Views of the Magellanic Clouds, IAU Symp. 190, ed. Suntzeff, Hesser, & Bohlender (ASP), p. 217
- Walborn et al. 2002 "A New Spectral Classification System for the Earliest O Stars: Definition of Type O2", AJ, 123, 2754
- The resulting papers generated a great deal of public interest: Our work was featured on the Univ. of Texas' STARDATE radio program broadcast March 13, 1998, was included in Astronomy Magazine's June 1998 "Astronews", and appears in the January 1998 Sky and Telescope ("Hubble Spies Supermassive Stars")

- **“Tests of Stellar Models Using Four Extremely Massive Spectroscopic Binaries in the R136 Cluster”:** GO-8217 (Cycle 8, PI Massey). We had previously (GO-6417) discovered four extremely early-type stars in the R136 cluster that showed double absorption lines, suggesting that they were spectroscopic binaries. In this program I went after them with STIS/CCD in order to obtain radial velocities and light-curves to produce orbits and Keplerian masses to compare these to evolutionary models. We discovered the highest mass binary yet known (57 $\mathcal{M}_\odot$), and established excellent agreement with the evolutionary models. We also discovered five new light-variables in this cluster, which form the basis of another proposal being submitted for Cycle 12 time. The study was published in:
  - Massey, Penny, & Vukovich 2002, “Orbits of Four Very Massive Binaries in the R136 Cluster”, ApJ, 565, 982
  - In addition, a press release invited by the AAS for the Jan 2001 meeting resulted in a very nice popular article in the the June 2002 Sky and Telescope (News Notes).
- **The Physical Parameters of the Hottest, Most Luminous Stars:** GO-7739 (GO-6417 “carryover” time in Cycle 7, PI Massey), GO-8633 (Cycle 9 snap, PI Massey), and GO-9412 (Cycle 11, PI Massey). We are using STIS/FUV-MAMA data to obtain data on stellar winds in the hottest and most massive stars in the Magellanic Clouds, combining this with high S/N, high resolution optical data obtained at CTIO. Our “snap” program in Cycle 9 had a very poor completion rate, and so the Cycle 11 TAC kindly assigned us sufficient time to complete the project. The data are still being taken. The “carryover” Cycle 7 time (from our Cycle 6 R136 program) obtained high S/N optical data on R136 stars, which are being combined with this for a single paper. Once the data-taking is complete this Spring, we will get to work on the paper. The anlysis is complete for the stars for which data have been obtained.
- **“The Mass-Luminosity Relationship for High Mass Stars”:** GO-9097 (Cycle 10, PI Massey). We exampled about a dozen “nearby” O-type stars (out to 2 kpc) with the FGS looking for previously unresolved binaries that would be suitable for long-term monitoring with HST/FGS to determine orbits. We’ve found several, and are submitting a proposal for the current cycle. Our preliminary results are in preparation (with Otto Franz and Larry Wassermann).