OBSERVING REQUEST
University of Arizona Observatories

Year: 2016 **Term:** Jul–Dec **Proposal type:** short-term⋆

The Masses of Wolf-Rayet Stars in M31 and M33

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CoI(s): Philip Massey (Lowell Obs./NAU)

Abstract of Scientific Justification

Wolf-Rayet stars are the evolved bare cores of massive stars. For the past 40 years we have believed that they form as a result of a massive star losing its hydrogen-rich outer envelope by strong stellar winds. However, recent work suggests that these winds are not as powerful as previously thought, and other mechanisms may be responsible for stripping down the star, such as episodic mass loss during the Luminous Blue Variable or red supergiant phases, or Roche-lobe overflow in binary systems. Single-star evolution models do a good job of predicting the relative numbers of WRs at low metallicities, such as found in the Magellanic Clouds and the outer regions of M33, but fail at high metallicities, such as in M31 or the center of M33. Using the MMT's Hectospec in Oct-Nov of 2012, we identified a large number of Wolf-Rayet binaries in M31 and M33, our nearest spiral neighbors in the Local Group. This discovery provided us with an incredible opportunity to *directly* determine the masses of these evolved, massive stars by obtaining the additional observations needed for orbits. Such data will provide unprecedented constraints on the evolutionary models of massive stars, and help answer how Wolf-Rayet stars form. We targeted the best of these systems, obtaining additional observing time in Fall 2013-2016. Although we planned on finishing this project in 2016, weather losses and the prolonged summer shut-down halted this project's progress. We are now requesting an additional observing season to obtain orbit solutions and hence masses. This opportunity is "a limited-time offer," as Hectospec is uniquely suited to this project, given its large field of view, multiplexing capability, and operation in queue mode. Now that Binospec's commissioning begins this summer, Hectospec will likely have decreased availability beginning this Fall.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/5	Hectospec			3.5	dark	Sep–Oct	Sep–Nov	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	M31	00:42:44	+41:16:10	1 configuation x 10obs
2	M33	01:33:42	+30:44:34	1 configuation x 10obs

Approval for Instrument Use from PI: ____________________

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Kathryn Neugent	Philip Massey		no	no

Scientific Justification

In the standard picture, a massive star loses mass as it evolves primarily through stellar winds, aided in some cases by episodic mass loss during a Luminous Blue Variable (LBV) phase. Further evolution can then be likened to peeling an onion layer by layer, with stellar winds doing the work. When the hydrogen-rich outer layers are gone, a Wolf-Rayet (WR) star is formed. The type of WR star, either WN (nitrogen rich) or WC (carbon rich), then depends upon which layer is visible. Mass loss first peels away enough material to reveal the star's H-burning products, helium and nitrogen (WN stage) before peeling away more to reveal the He-burning products, carbon and oxygen (WC stage). These winds also create the WR's characteristically broad emission lines. As the "Conti scenario" describes, the amount of mass lost by a massive star dictates whether a star will evolve only to the WN stage, or whether it will evolve first to a WN and then to a WC (Conti 1976; Maeder & Conti 1994). Since this mass loss is driven by radiation pressure on highly ionized metal atoms, a massive star born in a higher metallicity environment will have a higher mass-loss rate, and thus more easily peel down to the WC stage.

However, this elegant picture has been complicated by the discovery in recent years (Fullerton et al. 2006) that stellar winds are not the homogeneous entities we've long assumed, and that instead the winds are *clumped.* This means that the "measured" mass-loss rates have historically been over-estimated. The current question is by how much. Some argue it is merely a factor of 2 or 3 (e.g., Puls et al. 2008), while others maintain it is as much as a factor of 10. Smith & Owocki (2006) argue that these weaker stellar winds mean that the LBV phase of massive star evolution must be the dominant mass-loss mechanism, aided, in some cases, by mass-loss through Roche lobe overflow in binary systems (Smith 2012). The picture is further complicated by the recent argument of Haunch et al. (2014) that most WRs may have formed after going through a red supergiant (RSG) phase; mass loss during the RSG is neither well understood nor constrained (Meynet et al. 2015).

Nevertheless, single-star evolutionary models with "reasonable" mass-loss rates (i.e., down a factor of 2-3, not a factor of 10) generally do a good job of reproducing many of the observables. At low metallicities (where admittedly the mass-loss rates are expected to be low), the single-star models do a pretty good job of reproducing the relative number of WC and WN stars (see, e.g., Meynet & Maeder 2005, Neugent & Massey 2011). However, at higher metallicities we begin to see a significant problem: the models predict far fewer WC-type stars relative to the number of WN-types than what is observed in M31 or the center of M33 (Neugent & Massey 2011, Neugent et al. 2012). It is not clear if the models are predicting too few WCs or too many WNs; all we know is that the observed ratio disagrees with the models.

One possibility we looked into is that binary evolution has led to extra WCs, and that (for whatever reason) the binary fraction of massive stars is larger at high metallicities. This isn't quite as *ad hoc* as it sounds, as there have been various observational hints that the binary frequency of massive stars may depend upon the environment's metallicity (Zinnecker 2003). To investigate this, we used Hectospec in the Fall of 2012 to obtain 3-5 new epochs of observations of M31 and M33 WRs. Combined with our discovery spectra, which were also taken with Hectospec (Neugent & Massey 2011, Neugent et al. 2012), this gave us 4-6 observations of each star, allowing us to see if the binary fraction is higher in M31 and the center of M33 (where the single-star models fail) compared to the outer regions of M33 (where the single-star models work). However, our analysis of the new data fails to support this hypothesis: the binary frequencies are quite similar (Neugent & Massey 2014).

This leaves us with two explanations for why the single-star models fail to predict an accurate WC to WN ratio at high metallicities while succeeding at lower metallicities: (1) The mass-loss rates are actually underestimated in the evolutionary models at higher metallicities. (2) Or, the single-star models' success at low metallicities may be sheer coincidence, and Roche-lobe induced mass-loss in binaries and/or LBV episodic mass loss play a major role at all metallicities in the formation of WRs.

Although our comparative study of the binary frequencies of WRs in M33 and M31 has ruled out one hypothesis, it has also provided us with the identification of a large number of WR+OB binaries that may allow us to answer how WRs form once and for all. As detailed in the next section, our Hectospec radial velocity study has found 102 likely binary candidates. Of these, 31 (29%) show strong absorption typical of an OB companion. These WR+OB binaries allow us to *directly* determine stellar masses, both for the WR star and OB companions. In a WR+OB binary, the WR member evolved from what was originally the more massive component. Thus by comparing the relative masses of the WR and OB star, we know the minimum fraction of mass that the WR star has lost. We can then use the masses with the evolutionary tracks to see if this amount of mass-loss is consistent with stellar wind driven mass-loss, or if additional mechanisms need to be invoked.

We took advantage of our discoveries to obtain additional observations in the following four observing seasons (i.e., Fall 2013, 2014, 2015, and 2016) in order to obtain orbits and determine masses. (Note that our efforts for the third season in 2015 were thwarted by poor weather; no useful data were obtained). Nevertheless, the data we have obtained are beautiful and already begin to tell a story.

Consider the star J004026.23+404459.6, a WN+OB star in M31. Its spectrum is illustrated in Fig. 1. Strong He II $\lambda4686$, N III $\lambda\lambda4634, 42$, and N IV $\lambda4058$ comes from the WR star, while the He I $\lambda4471$ absorption and the Balmer absorption lines (Hγ, Hδ, Hϵ, and H8-12) all come from an OB companion. We see in Figure 2 that the emission and the absorption components both change in radial velocity in the opposite sense; these two spectra were taken around a year apart and show the maximum velocity separation we see from our 18 spectra.

Even though these data are not yet sufficient for an orbit solution (along with mass determinations), we can learn something interesting about the formation of WR stars from these data. O. C. Wilson noted that if you plot the radial velocity of one binary component against the radial velocity of the other component, the points should fall on a straight line, the slope of which is the inverse of the mass ratio of the two stars (Wilson 1941). We show such a "Wilson diagram" in Figure 3. The slope is -1.9 ± 0.1, implying that the WR star has a mass that is only about 53% as much as that of the OB star. Yet, from a stellar evolutionary point of view, we expect that the WR star must have begun as the more massive component, suggesting that it must have lost more than 47% of its mass in becoming a WR. The orbit solution will tell us the orbital separation and whether the stars are filling their Roche lobes, and whether this is possibly just a case of binary evolution, where the OB star has accreted mass from the progenitor of the WR star as the system evolved. But were we to find that these stars are relatively well separated, we would know that the WR progenitor has lost this mass by other means. Is this mass loss consistent with stellar winds? To answer this, we need the mass, as the expected mass-loss rates depend upon mass (luminosity). If the system is massive and luminous enough, it's possible. But if it's not, it would then require mass loss during the LBV phase to explain its evolution. Thus, what we have is only tantalizing. But with additional observations of this system (and the 30 others like it) we can determine actual masses (with a little additional help from the light curves we're currently obtaining with Lowell's 4.3-m Discovery Channel Telescope), not just the mass ratios, and directly answer these questions for each system.

References

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Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 1063
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Meynet, G. & Maeder, A. 2005, A&A, 429, 581
Meynet, G. et al. 2015, A&A, 575, 60
Neugent, K. F. & Massey, P. 2011, ApJ, 733, 123
Neugent, K. F. & Massey, P. 2014, ApJ, 789, 139
Neugent, K. F., Massey, P., & Georgy, C. 2012, ApJ, 759, 11
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Smith, N. 2012, in ASP Conf. Ser. 464, 290
Smith, N. & Owocki, S. P. 2006, ApJ, 645, L45
Wilson, O. C. 1941, ApJ, 93, 29
Zinnecker, H. 2003, in IAU Symp 212, p. 80

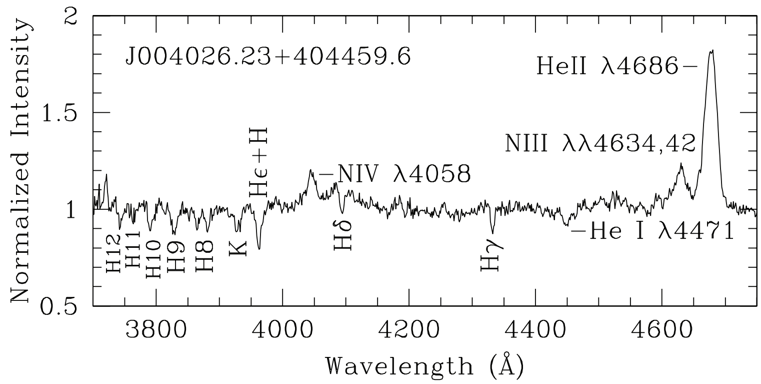

Figure 1: Spectrum of M31 star J004026.23+404459.6. The emission comes from the WR star (WN5), the absorption from an OB companion (roughly B0). Interstellar Ca II H and K lines are also evident.

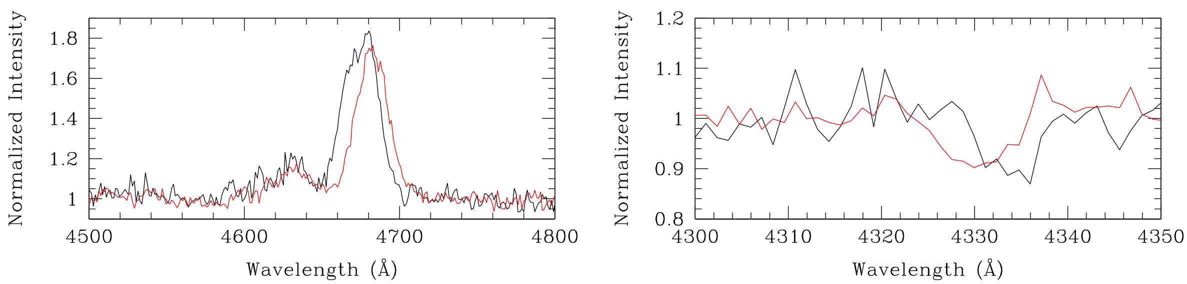

Figure 2: Radial velocity of emission (left) vs absorption (right) in J004026.23+404459.6. Black corresponds to our MMT spectrum obtained on 8 Nov 2012; red to the one on 5 Oct 2013.

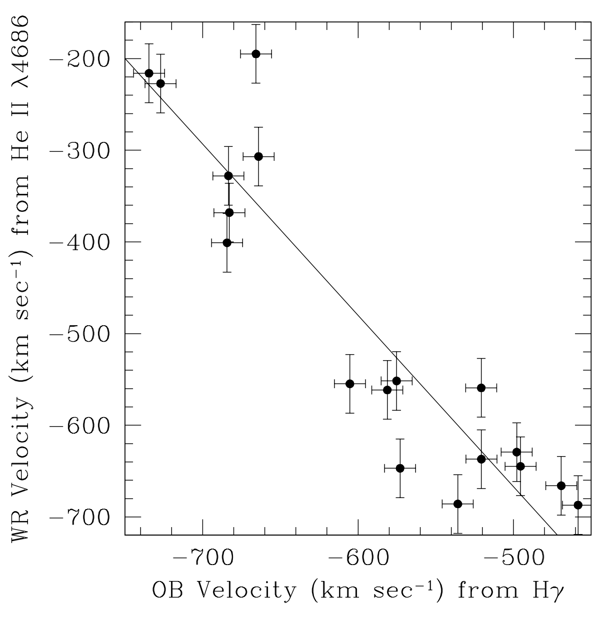

Figure 3: Updated Wilson Diagram for J004026.23+404459.6. The radial velocity of the He II $\lambda4686$ emission line (from the WR star) is plotted against the radial velocity of the Hγ absorption line (from the OB star). The least-squares linear fit is shown. Its slope, -1.9 ± 0.1, means that the WR star has a mass that is 53% of its OB companion. Yet, it must have started its life as the initially more massive star, and must therefore have lost more than 47% off its mass.

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.* ***(up to one page)***

Our goal is to use additional radial velocities from Hectospec observations to construct orbit solutions for the 31 double-lined (WR+OB) stars in our sample. These data will provide orbital semi-amplitudes, orbital eccentricities, and help with the period determinations. This will determine the *minimum* mass for each component of the binary, $m \sin^3 i$. In order to determine the orbital inclinations i's, and to nail down the periods, we are also obtaining light-curves of these systems using the Lowell Observatory's 4.3-m Discovery Channel Telescope (DCT). For the $\sim$ 70 single-lined WR binaries (where we know there are significant radial velocity variations but we can't detect absorption lines at our S/N), we include these in the assignments but at lower priority. Analysis of these systems will not directly yield masses, but will provide the mass functions, $\frac{m_{\rm OB}^3 \sin^3 i}{(m_{\rm WR}+m_{\rm OB})^2}$, which can be used to statistically constrain the masses in these remaining systems.

Justification of time requestioned. We so far have 14-19 observations of each of our binaries; these provide a solid demonstration of binarity, and a teasing look at the evolutionary process that formed these WR stars as discussed earlier. In order to determine the orbits, we need a bare minimum of 20-25 observations (depending upon our phase coverage); 25-30 would be preferable. This is around half as many as what is typically used to determine an orbit in such systems (see, e.g., Massey & Conti 1977, ApJ, 218, 431; Massey & Niemela 1981, ApJ, 245, 195; Niemela et al. 1984, PASP, 96, 549), but we are counting on the photometry to do the heavy lifting when it comes to finding the periods, and thus constrain the orbital phases, much as we did in our recent study of O-type binaries in the LMC (Massey et al. 2012, ApJ, 748, 96). We are therefore asking for 10 new observations per star (to be combined with our present 14-19 observations). If conditions are perfect for all the dark Hectospec nights on the schedule (unlikely!) it would give us 24-29 observations, a very agreeable number, but even with some weather losses we should be in good shape for the stars for which we already have the most observations. We have been very successful in obtaining nice spectra of our M31 and M33 WR stars using 90 minute exposures (3×30 min $+$ 20 minute overhead $= 110$ minutes). This provides a S/N of 45 per 5Å resolution element if the seeing is good, allowing measurements of the (relatively weak) absorption lines. Dark time is crucial as the continuum magnitudes of these objects are $V =$ 19-22. We thus calculate 2 configurations $\times$ 10 observations $\times$ 110 minutes = 36 hours, or 3.5 nights.

Why Hectospec? The discovery of this many WR binaries has given us a *unique opportunity* to answer how a massive star evolves to the WR stage, with M31 and the center of M33 providing an example of high metallicity and the outer regions of M33 providing an example of low metallicity. However, this turns out to be a *limited time offer* because Hectospec is really required for this project, and it will be replaced by Binospec in the near future. Hectospec's large field of view (1°) is needed for efficient coverage of M31 (optical disk is $>2^\circ$ across) and M33 (about $0\overset{\circ}{.}5$), while the large multiplexing advantage is well matched to our sample size and density. Finally, repeated observations throughout the semester are needed for good phase coverage, and that is well provided by the queue nature of Hectospec, as we well demonstrated with our previous program that found these binaries.

We note that most of the techniques and analysis methods we are planning to apply here were developed as part of Massey's thesis work on 7th-8th magnitude Galactic WR binaries in the late 1970s; here we are applying them to a sample of WRs 10-14 magnitudes fainter and located in neighboring spirals!

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

In the Fall of 2012, NOAO assigned us 2.5 nights with Hectospec to identify the binaries among the WR population of M31 and M33 (PI: Neugent). We followed this up with more Hectospec observations in the Fall of 2013 (3 nights) and 2014 (3.5 nights). Our efforts in 2015 failed due to the horrible weather that wiped out the entire Hectospec observing run; we obtained no useful data. The 2016 observing season suffered losses due to the prolonged summer shut-down though we still obtained another three observations of each system. At this point we have 14-19 observations of each system. With the additional 3.5 nights requested this semester, we will have enough time for 10 more observations of each system **if** the weather is good. In the event of 50% weather losses we should still have sufficient data for about half of our systems. This should finish the project.

We have begun photometric monitoring with Lowell Observatory's 4.3-m DCT; we had a moderately successful Fall in 2014 with $\sim$30 observations of each star obtained on 16 nights. In Fall 2015 we again obtained around 30 observations of each star over 19 nights. This past Fall weather losses dropped our number of observations down to $\sim$10 more for each star over 5 nights. Still, this gives us around 50 observations for each star. While the data in hand clearly show the majority of our systems do eclipse or show ellipsoidal variations (night-to-night variations are 5-20$\times$ the internal error), we don't have enough photometry to remove the observing aliases and find actual periods. We had always anticipated that we would require at least three years of perfect weather for the photometry (i.e., about 80-100 observations). This is one of the "key projects" used in funding our imager on the DCT, and we can count on continued support at the level of $\sim$ 20 half-nights on the 4.3-m per M31/M33 observing season.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

⋆ (1) Massive Stars in M31 and M33: MMT: 2.5 nights, October 2010; 1 night, September 2011; 2.5 nights, October 2012 (all awarded through NOAO); 3 nights, October 2013; 3.5 nights, November 2014; 3 nights September 2015 (no useful data); 2 nights, November 2016. This has resulted in seven ApJ/AJ papers, three conference presentations, and two AAS posters.

- Neugent, K. F., & Massey, P. 2011, "The Wolf-Rayet Content of M33," ApJ, 733, 123
- Neugent, K. F., & Massey, P. 2011, "Wolf-Rayet Stars in the Local Group," AAS #218, #125.07
- Drout, M. R., Massey, P., Meynet, G. 2012, "The Yellow and Red Supergiants of M33," ApJ, 750, 97
- Neugent, K. F., Massey, P., & Georgy, C. 2012, "The Wolf-Rayet Content of M31," ApJ, 759, 11
- Massey, P., Neugent, K. F., Drout, M., & Meynet, G. 2013, "Yellow and Red Supergiants in the Local Group," Massive Stars: From α to Ω, held 10-14 June 2013 in Rhodes, Greece
- Neugent, K. F., Massey, P., Meynet, G., & Georgy, C. 2013, "The Wolf-Rayet Content of Local Group Galaxies," Massive Stars: From α to Ω, held 10-14 June 2013 in Rhodes, Greece
- Neugent, K. F., & Massey, P. 2014, "The Close Binary Frequency of Wolf-Rayet Stars as a Function of Metallicity in M31 and M33," ApJ, 789, 139
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- Evans, K. A., & Massey, P. 2015, "A Runaway Red Supergiant in M31," AJ, 150, 149
- Evans, K. A., & Massey, P. 2016, "A Runaway Red Supergiant in M31," AAS Meeting #227, id.239.04
- Massey, P., Neugent, K. F., & Smart, B. 2016, "A Spectroscopic Survey of Massive Stars in M1 and M33, AJ, 152, 62
- Massey, P. & Evans, K. A. 2016, "The Red Supergiant Content of M31," ApJ, 826, 224

(2) A Search for Thorne-Żytkow Objects: Magellan MIKE and MagE, 2×0.5 TBS nights, Sept 2011. In 1975, Kip Thorne & Anna Żytkow suggested that massive star binary evolution could lead to the capture of a neutron star by a companion red supergiant (RSG). The core of the RSG and neutron star would quickly merge, resulting in a RSG impostor, dubbed a Thorne-Żytkow object or TŻO. These objects could be distinguished from RSGs only by very unusual lithium and other heavy element enhancements. Using our half night of Magellan time, we discovered the first (and so far only) example of these exotic objects:

- Levesque, E. M., Massey, P., Morrell, N., & Żytkow, A. 2014, AAS Meeting 223, #113.06
- Levesque, E. M., Massey, P., Żytkow, A., & Morrell, N. 2014, "A Thorne-Żytkow Object Candidate in the Small Magellanic Cloud," *MNRAS,* 433, L94
- Levesque, E. M., Massey, P., Żytkow, A., & Morrell, N. 2015, IAU Symp. 307, p. 127

(3) Wolf-Rayet Stars in the Magellanic Clouds: 1 night Clay, Dec 2013; 1 night Clay, Sept 2014; 1 night Clay, February 2015; 2 nights, Baade Nov 2015 (poor weather); 2 nights Feb 2016; 1.5 nights Baade Feb 2017. This program has resulted in the discovery of 16 new Wolf-Rayet Stars in the LMC, including an entire new class. We have produced five ApJ/AJ papers and three presentations at international conferences.

- Neugent, K. F., Massey, P., & Morrell, N. 2013, "The Discovery of a Rare WO-type Wolf-Rayet Star in the Large Magellanic Cloud," AJ, 144, 162
- Massey, P., Neugent, K. F., Morrell, N., & Hillier, D. J. 2014, "A Modern Search for Wolf-Rayet Stars in the Magellanic Clouds: First Results," ApJ, 788, 83
- Massey, P., Neugent, K. F., Morrell, N., & Hillier, D. J. 2015, "A New Class of Wolf-Rayet Stars: WN3/O3s," in IAU Symposium 306, p. 64
- Massey, P., Neugent, K. F., & Morrell, N. 2015, "A Modern Search for Wolf-Rayet Stars in the Magellanic clouds: A Second Year of Discoveries" ApJ, 807, 81
- Neugent, K. F., Massey, P., Hillier, D. J., & Morrell, N. I. 2015, "The Discovery and Physical Parameterization of a New Type of Wolf-Rayet Star," in Wolf-Rayet Stars, p. 101.
- Massey, P., Neugent, K. F., & Morrell, N. 2017, "A Modern Search for Wolf-Rayet Stars in the Magellanic Clouds. III. A Third Year of Discoveries," ApJ, 837, 122
- Neugent, K. F., Massey, P., Hillier, D. J., & Morrell, N. I. 2017, "The Evolutionary Status of WN3/O3 Wolf-Rayet Stars," in IAUS 329 proceedings, in press
- Neugent, K. F., Massey, P., Hillier, D., J., & Morrell, N. I. 2017, "The Evolution and Physical Parameters of WN3/O3s: a New Type of Wolf-Rayet Star," ApJ, submitted

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

Neugent is currently a student at Northern Arizona University as well as a research associate at Lowell Observatory. As of this Fall, she will begin a PhD program at the University of Washington but she will continue on as a research associate at Lowell Observatory.