Ryan Lau

Deciphering the Dusty “Helix” Trails from Isolated and Massive Evolved Stars

Scientific Justification

Massive stars. Massive stars above ~20 M_{Sun} play a crucial role in the metal-enrichment, dust budget, and energetics of the interstellar medium, especially during their post-main sequence phases where they undergo periods of intense mass loss. An O-type star with an initial mass between ~20 and ~60 M_{Sun} is believed to evolve to the highly unstable Luminous Blue Variable (LBV) phase (Humphreys & Davidson 1994) as hydrogen burning ceases in its core and its envelope begins to swell and eject material at a significantly enhanced rate (10^{-3} M_{Sun}/yr ; Kochanek 2011). After expelling most of its hydrogen shell, the LBV phase is followed by the hydrogen-poor Wolf-Rayet (WR) phase, which is characterized by prominent helium emission lines as well as nitrogen, carbon, and/or oxygen lines (Crowther et al. 2007). For stars with an initial mass greater than 60 M_{Sun}, a hydrogen-rich WR phase with nitrogen emission lines (WNh) precedes the LBV phase and then follows a similar evolutionary track as the lower mass counterparts (Crowther et al. 2007; Smith & Conti 2008). Stars in the WR (and in some cases the LBV) phase are in the final stage before ending as supernovae. Unfortunately, due to their short lifetimes LBV and WR stars are quite rare and therefore the details of the evolutionary track of massive stars are not well understood. The greatest uncertainties on evolutionary models arise from poor constraints on their mass-loss history and the influence of close binary companions, which are typical for a majority of massive stars (Kobulnicky et al. 2014 and references therein).

Implications of Isolation. Interestingly, Smith & Tombleson (2014) show that LBVs are statistically much more isolated than O-type stars and even more isolated than WR stars, which presents an alarming inconsistency with the traditional evolutionary picture described above that interprets LBVs simply as O-type stars in transition to becoming a WR star. Smith & Tombleson (2014) reconcile this seemingly paradoxical issue by proposing bifurcated evolutionary tracks for massive stars in close binaries where the more massive companion (the mass donor) is stripped of several solar masses of material accreted on to the lower mass companion (the mass gainer):
The Mass Donor loses its hydrogen envelope, enters the WR phase, and goes supernova, which kicks the gainer from the binary system.
The Mass Gainer has a high proper motion from the supernova kick, becomes more luminous due to mass accretion from the donor, and retains its hydrogen envelope as it transitions to more evolved phases.

The Big Question. How can we study the influence of the mass-loss history and binarity to constrain the evolutionary track of massive stars and reconcile their relative isolation?

WR102c and its Dusty “Helix” Trail. SOFIA/FORCAST (Herter et al. 2012) observations at the mid-infrared reveal a dusty ~1.5 pc long “helix”-shaped trail extending from the isolated and massive evolved star **WR102c** (Lau et al. 2014a; Fig 1), which is one of the most luminous stars in the Galaxy. WR102c is a WR-type star exhibiting prominent nitrogen and hydrogen emission lines (WNh) with a luminosity of $L_* \sim 2 \times 10^6$ L_{Sun}, effective temperature of $T_* \sim 50000$ K (Barniske et al. 2008), and is located ~3 pc in projection from the massive, young cluster known as the “Quintuplet” near the Galactic center (Liermann, Hamann, & Oskinova 2009). The Quintuplet cluster contains a population of massive, evolved stars, which suggests WR102c is a cluster member despite its relative isolation in the vicinity of the "handle" of the "Sickle" HII region (Fig. 1a). Since WR102c exhibits prominent hydrogen lines and an extremely high luminosity, it is likely in a "pre-LBV" phase where it has just evolved off the main sequence. In the Smith & Tombleson (2014) interpretation of the evolutionary track, WR102c would be the mass gainer that was ejected by its companion that went supernova.

The helix appears to trail WR102c in the direction of the Quintuplet clusters, which would substantiate the claim that it is a cluster member if the helix is indeed associated with the star. An identical Paschen-α (λ = 1.87 μm; Wang et al. 2010; Dong et al. 2011), ionized gas counterpart of the helix is observed by HST/NICMOS (Fig. 1c). The orientation of the helix in the vicinity of WR102c also appears consistent with the alignment of bipolar lobes that are centered on WR102c. If the helix and bipolar lobes are indeed associated with outflows from the massive, evolved star, they can provide a diagnostic of the star's age/mass-loss history and the orbital/rotational dynamics as well as indicate the location of the star's initial birth site. **We therefore propose a kinematic study of the helix and bipolar lobes to determine their association with WR102c. If confirmed, we will have identified a new class of massive, evolved stars that exhibit helix trails.** The H and K magnitudes of WR102c are 13.4 and 11.6, respectively.

Interpretation of the Helix. We interpret the helix as a dusty, collimated outflows from a precessing, supernova-kicked, massive evolved star (i.e. the mass gainer in the Smith & Tombleson 2014 evolutionary interpretation). The dynamics of the outflow creating the helix would therefore be analogous to that of water shooting from a spinning fire hose that is moving in the direction of its rotational axis. The helix only appears on the trailing side of the star because the leading outflow is plowed up against the approaching interstellar medium. Wind outflow velocities from WR102c are estimated to be 1300 km/s (Barniske et al. 2008). Based on the apparent opening angle of the helix (~45°), we therefore predict maximum line-of-sight velocities of ~900 km/s. These velocities will be resolvable by the TripleSpec instrument, which has a resolving power of ~3000 ($\Delta v \sim 100$ km/s).

Another Helix – WMD 54. Wachter et al. (2010) identified circumstellar shells surrounding massive, evolved stars from 24 μm imaging in the MIPSGAL Legacy project (Carey et al. 2009) taken by Spitzer/MIPS (Rieke et al. 2004). One of the newly revealed Wachter sources, hereafter referred to as **WMD 54**, exhibits a helix-shaped outflow that is symmetric about the star (Fig. 2). WMD 54 is particularly interesting since it exhibits spectral features similar to both Wolf-Rayet and LBV-type stars (Wachter et al. 2011), which suggests it may currently be in a stage transitioning from a hydrogen-rich WR star to an LBV. We estimate a distance of ~4.5 kpc to WMD 54 by using observed and estimated intrinsic $J - K$ colors and M_K values assuming WMD 54 is a late-type nitrogen emission line star based on its near-IR emission lines (Crowther et al. 2006). The size scale of the helix is ~1.5 pc on each side of WMD 54, consistent with the WR102c helix. The symmetry of the helix about WMD 54 suggests that the outflow is not interacting with a particularly dense surrounding medium. **As a secondary objective, we propose a kinematic study of the WMD 54 helix as well as near-IR spectroscopic follow-up of WMD 54 to check for any spectroscopic or photometric variability (initial near-IR spectra were taken in 2010 by Wachter et al. 2011).** The J, H, and K magnitudes of WMD 54 are 11.88, 10.14, and 9.13, respectively.

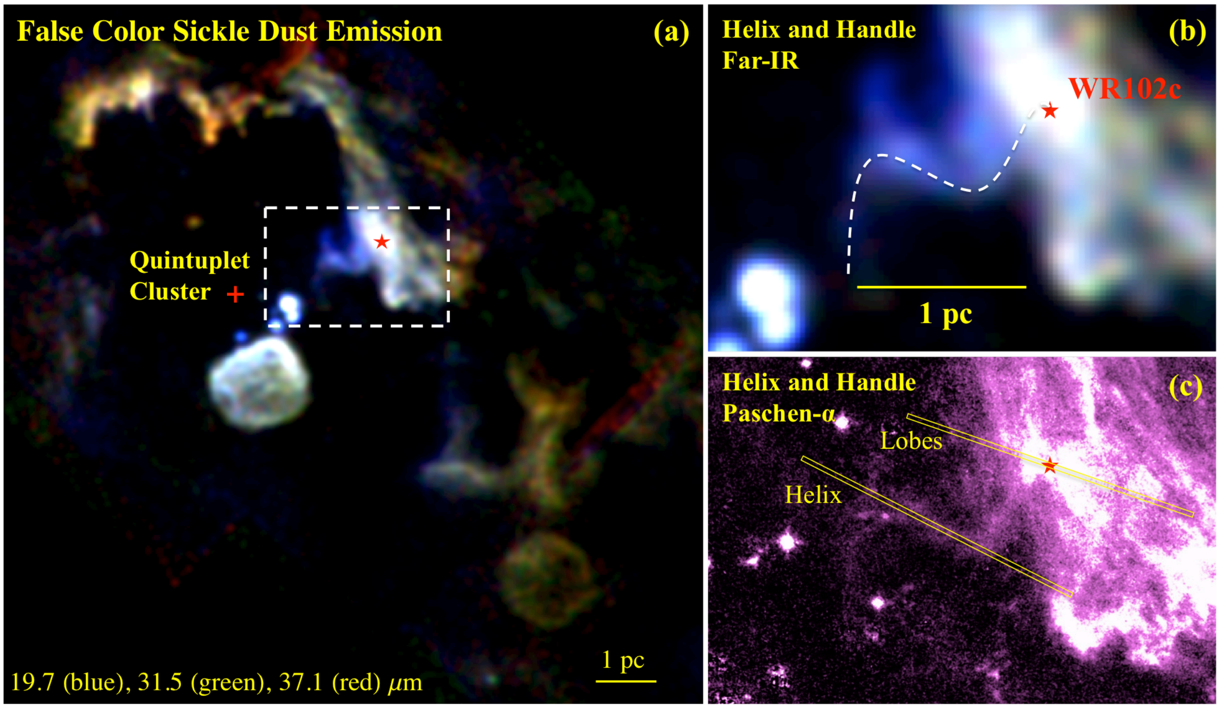

Fig. 1: (a) False color image of the Sickle, the illuminated inner-edge of a dense molecular cloud heated by the Quintuplet cluster. The cross and star correspond to the approximate center of the Quintuplet cluster and WR102c, respectively. The bright, asymmetric nebula, and the dim, circular nebula are composed of ejecta from the Pistol star and LBV3, which are both LBV-type stars (Lau et al. 2014a). (b) Zoomed false color far-IR image of the helix and handle. The overlaid dashed line traces the curvature of the helix. (c) Zoomed Paschen-α (Dong et al. 2011) image of the same region as (b) with the proposed slit positions overlaid. North is up and east is to the left.

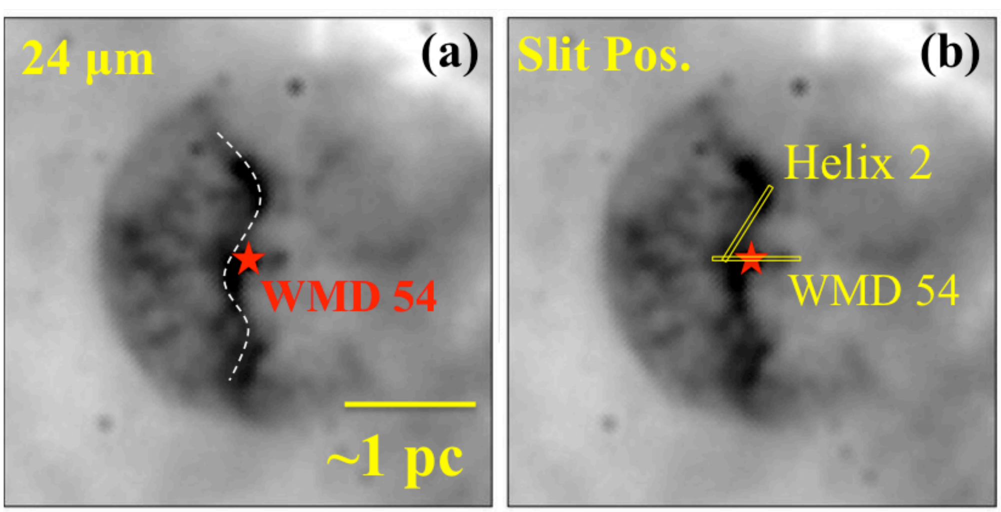

Fig. 2: (a) 24 μm image of WMD 54 and the surrounding helix/nebula. The star corresponds to the location of WMD 54 and the dashed line traces the curvature of the helix. (b) The same image as (a) with the proposed slit positions overlaid. North is up and east is to the left. (From Fig. 1 in Wachter et al. 2010).

Observations and Technical Justification

Near-IR Spectroscopy. TripleSpec is an ideal instrument to perform the observations required for this investigation and to complement the mid-IR imaging data by FORCAST and MIPS and the optical by HST. We intend to study the kinematics of the ionized gas composing the helix and lobes by measuring the velocity shifts of the Brackett-γ (λ = 2.16 μm) hydrogen emission line. Based on the Paschen-α fluxes from the NICMOS observations of the WR102c helix and the ratio of the resolving powers between the NICMOS F187N band and TripleSpec in its primary configuration (~100 vs ~3000), we estimate the Brackett-γ flux detected by TripleSpec to be ~1.25 mJy for the helix and ~5 mJy for the lobes. In its primary configuration with the 1 arcsec-wide slit, TripleSpec is able to make a 5-σ detection in 1-hr of total exposure time for a ~3 mJy source per resolution element (roughly 3 × 3 pixels; TripleSpec User's Guide). Assuming WMD 54 is a late-type nitrogen emission line WR star, its effective temperature and luminosity will be similar to that of WR102c and we expect the WMD 54 helix to exhibit similar Brackett-γ as the WR102c helix. **We therefore propose 7.5 hr of exposure time with the slit aligned across the WR102c helix, 7 hr of exposure time with the slit across the WMD 54 helix, 0.5 hr of exposure time with the slit aligned along WR102c and its lobes, and several minutes of exposure time on WMD 54.** WR102c and WMD 54 exhibit K magnitudes of 11.6 and 9.1, respectively, and will be sufficiently bright to be used as a guide stars.

Slit Position and Observing Time. The position of the slits for both helix observations (see Fig. 1c and 2b) are aligned such that we can confirm if the dynamics of the outflow is identical to that of a "spinning fire hose." Another option is that charged particles are following a spiral trail along magnetic field lines. This distinction can be made by selecting slit positions that reveal the maximum and minimum line of sight velocities: if the velocities peak at the outer edges of the helix (e.g. northeast and southwest areas of the WR102c helix slit; see Fig. 1c) then the ionized gas moves along a spiral trail, and if the velocities peak along the central axis of the helix (e.g. middle of the WR102c helix slit) the outflow is similar to that the "spinning fire hose." With an exposure time of ~7 hr we expect to obtain a ~6-σ detection of the Brackett-γ emission line from both helices.

We request a slit position across the bipolar lobes surrounding WR102c that appear consistent with the orientation of the helix (pos. Lobes). Measurements of opposing velocities of the two lobes will confirm of they are indeed outflows from WR102c, and the amplitude of the velocities may provide a dynamical link to the helix. Since the lobes are brighter than the helix, we only request 0.5 hr of exposure time for this slit position and expect to obtain a ~6-σ detection of the Brackett-γ emission line from the lobes. At this position, we also include WR102c, which will provide the highest resolution near-IR spectrum of the star and allow for refined estimates of the wind velocities and its luminosity as well as reveal any spectral variation that might indicate an evolutionary transition since the last observations several decades ago (Figer, McLean, & Morris 1999). Lastly, we propose a slit position on WMD 54 (Fig. 2b) to check for spectroscopic or photometric variability from near-IR observations taken ~5 years ago.

Scheduling Constraints. Given its location at the Galactic center, the first week of August will be the ideal time to observe the WR102c lobes and helix. In early August, WR102c will be best observed between 800 PM and 1200 AM PDT, where the airmass will be below 3 (we note that WR102c does not get below an airmass of 2). WMD 54 will be higher in the sky and can be observed between 1200 AM and ~330 AM PDT at an airmass below 3. **We therefore propose 2 nights of observing with 4 hr on WR102c and 3.5 hr on WMD 54 (~15 hr total)**.

Object/Slit Position List

Source	R.A. (2000)	Dec. (2000)	Night 1 Exp. Time	Night 2 Exp. Time	Slit Pos. Angle
WR 102c Helix	17 46 12.30	-28 49 14.28	3.5 hr	4 hr	117°
WR102c & Lobes	17 46 11.14	-28 49 05.9	0.5 hr	-	109°
WMD 54 Helix (2)	18 51 02.95	-00 58 10.46	3.5 hr	3.5 hr	25°
WMD 54	18 51 02.95	-00 58 24.21	~2 min	-	90°

References

Barniske A., Oskinova L. M., & Hamann W.-R. 2008, A&A 486, 971
Carey, S. J., Noriega-Crespo, A., Mizuno, D. R., *et al.* 2009, PASP, 121, 76
Crowther, P. A., Hadfield, L. J., Clark, J. S., Negueruela, I., & Vacca, W. D. 2006, MNRAS, 372, 1407
Crowther P. A., 2007, ARA&A, 45, 177
Dong, H., Wang, Q. D., Cotera, A., *et al.* 2011, MNRAS, 417, 114
Figer D. F., McLean, I. S., & Morris M., 1999a ApJ, 514, 202
Herter, T. L., Adams, J. D., De Buizer, J. M., *et al.* 2012, ApJL, 749, L18
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Kobulnicky H. A. *et al.,* 2014, ApJS, 213, 34
Kochanek, C. S. 2011, ApJ, 741, 37
Lau, R. M., Herter, T.L., Morris, M. R., Adams, J. D. 2014a, ApJ, 785, 120
Liermann, A., Hamann, W.-R., & Oskinova, L. M. 2009, A&A, 494, 1137
Rieke, G. H., Young, E. T., Engelbracht, C. W., *et al.* 2004, ApJS, 154, 25
Smith N., Conti P. S., 2008, ApJ, 679, 1467
Smith, N., & Tombleson, R., 2015, MNRAS, 447, 598
Wachter, S., Mauerhan, J. C., Van Dyk, S. D., *et al.* 2010, AJ, 139, 2330
Wachter, S., Mauerhan, J., Van Dyk, S., Hoard, D. W., & Morris, P. 2011, Bulletin de la Societe Royale des Sciences de Liege, 80, 291
Wang, Q. D., Dong, H., Cotera, A., *et al.* 2010, MNRAS, 402, 895