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The isolation of luminous blue variables: on subdividing the sample

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ABSTRACT

A debate has arisen concerning the fundamental nature of luminous blue variables (LBVs) and their role in stellar evolution. While Smith & Tombleson proposed that their isolated environments indicate that LBVs must be largely the product of binary evolution, Humphreys et al. have recently expressed the view that the traditional single-star view still holds if one appropriately selects a subsample of LBVs. This paper finds the claim of Humphreys et al. to be quantitatively unjustified. A statistical test of 'candidate' as opposed to 'confirmed' LBVs shows no significant difference ($<1\sigma$) between their environments. Even if the sample is further subdivided as proposed, the three most luminous LBVs are spatially dispersed similar to late O-type dwarfs, which have much longer median lifetimes than expected for classical LBVs. The lower luminosity LBVs have a distribution associated with red supergiants (RSGs), but these RSGs are dominated by stars of 10–15 $M_\odot$ initial mass, with much longer lifetimes than expected for those lower luminosity LBVs. If one's view is restricted to the *highest luminosity* LBVs, then the appropriate comparison is with *early* O-type stars that are their presumed progenitors; when this is done, it is clear that even the high-luminosity LBVs are more dispersed than expected. Humphreys et al. also suggest that velocities of LBVs support the single-star view, being inconsistent with runaways. A quantitative analysis of the radial velocity distribution of LBVS in M31 and M33 contradicts this; modest runway speeds expected from mass gainers in binary evolution are consistent with the observed velocities, although the data lack the precision to discriminate.

Key words: binaries: general – stars: evolution – stars: winds, outflows.

1 INTRODUCTION

The eruptive mass-loss exhibited by luminous blue variables (LBVs) is thought to be an important ingredient in stellar evolution (see, e.g. Smith & Owocki 2006; Smith 2014), but the way LBVs actually figure in this evolution and the physical mechanisms of their outbursts remains challenging to understand. Moreover, LBVs are thought to be related to some extragalactic non-supernova (SN) transients (Smith et al. 2011; Van Dyk & Matheson 2012) and their mass-loss is reminiscent of extreme pre-SN eruptions (Smith 2014).

In a recent study, Smith & Tombleson (2015; hereafter ST15) analysed the projected spatial distribution of LBVs on the sky and found them to be surprisingly isolated from O-type stars. ST15 concluded that the results were inconsistent with expectations for the traditional picture of LBVs in single-star evolution (e.g. Humphreys & Davidson 1994), wherein LBVs are descended from very massive main sequence O-type stars, and where LBVs are the key agent that provides the required mass-loss to drive them into the Wolf–Rayet (WR) phase. In particular, ST15 found that LBVs were more dispersed from O stars on the sky than WR stars, making it impossible for the observed population of LBVs to turn into the observed population of WR stars. ST15 concluded that many LBVs are likely to be the product of binary evolution, where stars are spun-up, chemically enriched, and rejuvenated by mass transfer, and possibly kicked by their companion's SN explosion. In this view, LBVs are evolved massive blue stragglers.

Humphreys et al. (2016; hereafter H16) present a contrasting viewpoint, arguing that environments of LBVs are instead consistent with the traditional view if one divides and culls the sample of LBVs in the way they prefer. They also claim that observed kinematics indicate that none of the confirmed LBVs are runaway stars. The discussion below critically examines these claims, since the role played by LBVs and their mass-loss is fundamental to our understanding of massive star evolution and the origin of WR stars. Essentially, it is found that the claims made by H16 are not quantitatively justifiable based on the data, even if one permits the selective subdivision of the LBV sample as they envision. In some cases the quantitative implication of the data yields the opposite of their qualitative interpretation.

This paper undertakes a critique of the claims made by H16. Before examining their analysis, Section 2 first corrects some errors

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and points out misconceptions that influence the data and expectations in the H16 paper. Section 3 concentrates on the claimed difference between confirmed and candidate LBVs (each corresponding to about half the sample in ST15), showing that their environments are indistinguishable with available data. Section 4 reassesses the analysis of H16; here we permit the subjective subdivision of the sample as preferred by H16, and we ignore small number statistics. Even with these accommodations, we find that the central conclusions found by H16 were not the correct conclusions indicated by their suggested division of the data. This is because if one wishes to split a cumulative distribution, one must also split the distribution of comparison objects in order to draw a meaningful conclusion. Finally, Section 5 provides a quantitative analysis of the claims by H16 regarding radial velocities, finding them to be invalid. Runaway LBVs are certainly allowed by the radial velocity data, although not clearly required.

2 SOME CORRECTIONS AND MISCONCEPTIONS

Although Conti (1984) originally defined LBVs rather broadly to include a number of types of luminous blue supergiants (BSGs) with high mass-loss, H16 provide explanations for why they choose to include or exclude certain stars from ST15's statistical sample of LBVs in the Magellanic Clouds. This is discussed below. Even if those qualifications are accepted, there are some factual errors and misconceptions in the H16 paper that should be corrected before one considers their interpretation.

An apparent error concerns HD 5980, the most luminous star in the SMC. H16 note that numerous authors describe HD 5980 as a confirmed LBV that suffered a giant eruption, and they therefore choose to include it in their table 2 as an LBV. However, they do not include HD 5980 in the cumulative distribution plot of separations from O stars (their fig. 5), even though they do include the lower luminosity star R40 in the SMC. This might significantly influence the main claim of their paper, since with such a high luminosity, HD 5980 should be included with the high-luminosity LBVs (i.e. the 'LBV1' group), of which there are only three objects. Adding a fourth, which happens to have the highest separation from O stars (∼21 pc) among this sample, skews the distribution a noticeable amount. H16 do not state a reason for omission of this star from the cumulative distribution, so one may assume this was an oversight.

H16 claim that ST15 have a duplicate entry in their sample of LBVs, but this is false. Referring to ST15's sample, H16 state that 'MWC 112 was included twice; it is the same as Sk -69°142a'. However, consulting the SIMBAD data base reveals that MWC 112 is in fact not -69°142a as they claim; the correct Sanduleak designation of MWC 112 is Sk -69°147. The J2000 coordinates of the two stars, which are 2.82 arcmin apart on the sky, are reproduced in Table 1. MWC 112 is listed as an F5 Ia supergiant in the LMC (not WN10h as listed in table 3 of H16; this should be for Sk -69°142a). Whether or not this is the same star that was concluded to be an LBV by van Genderen & Sterken (1996) is unclear, since some authors have confused MWC 112 and Sk -69°142a multiple times before in the literature (see, for example, Humphreys & Davidson 1994 and van Genderen & Sterken 1996, where in both cases MWC 112 is erroneously listed as the same star as HDE 269582 = Sk -69°142a). Interestingly, in the original Mount Wilson Catalog (Merrill & Burwell 1933), MWC 112 is listed as a type 'Beq' with no luminosity class (P Cygni is listed as B1eq in the same catalog) with a photographic magnitude of 13.0 mag, whereas Rousseau et al. (1978) list it as F5 Ia with $B = 11.8$ mag. This seems to suggest a change in spectral type and magnitude reminiscent of LBVs that are true S Doradus variables (i.e. 1.2 mag brighter in its cooler eruptive phase), although a renewed examination and perhaps monitoring to resolve this would be worthwhile. This correction is important for future studies, but has little influence on the results here because MWC 112 is roughly in the middle of the distribution of O-star separations.

Table 1. Coordinates for two stars claimed to be the same star by H16.

Sanduleak name	R.A.(J2000)	DEC.(J2000)	other name
Sk -69°142a	05:27:52.657	-68:59:08.56	HDE 269582
Sk -69°147	05:28:21.987	-68:59:48.20	MWC 112

LBVs reside in a part of the HR Diagram that overlaps with other stars of similar luminosity (L) and apparent temperature (T) that have not been observed to exhibit the same instability. H16 state that LBVs are known to be distinguished from these other stars with similar L and T because they have higher L/M ratios. However, this is an assertion that has no empirical verification. There is no LBV with a stellar mass that has been measured directly in a binary system; the idea that they have higher L/M ratios than other stars of similar L is a conjecture from single-star evolutionary models, not observations.

There is another misconception expressed by H16, which is key to one of their central qualitative arguments. They claim that the observed radial velocities of LBVs in M31/M33 and the LMC are consistent with their positions in those galaxies, and that except in one case, there is no evidence for nebular bowshock morphology that is expected if the stars are runaways. They cite these points as a counterargument that LBVs are not likely to be runaway mass gainers. H16 do not quantify the velocities or velocity distribution that they expect, but based on the arguments and information in the paper, one might conjecture that they expect runaway velocities in excess of 100 km s^{-1}. This is based on their claim that observed LBV velocities seem to be within ±40 km s^{-1} of the expected velocities from rotation curves (and are therefore consistent with no runaways), and also the claim that such motion would significantly influence the morphology of nebulae that are expanding at 10–50 km s^{-1}. H16 assert that these motions are consistent with not being runaways, although they give no analysis to support this. This point is addressed below. Here the misconception about the expected velocities is clarified.

In a close binary that has experienced mass transfer, with one star being the mass gainer, the mass donor will likely explode first (although not always first) as a stripped-envelope SN and may provide a kick to the mass gainer. This is one of the ideas to help explain the distribution of LBVs (ST15), which H16 argue against. Here, the 'kick' might be recoil from a neutron star kick and an asymmetric SN, which could induce a fairly high speed runaway in the companion. However, even without this explosive kick, a more likely case is that the mass gainer will have resulting motion that is simply its orbital velocity and trajectory at the time when its companion explodes (note that the compact companion may also remain bound and the binary system may have net motion). The key point here is that the mass gainer has become much more massive than its companion (which is now a much lower mass He core that has donated its H envelope to the mass gainer). As a consequence, the mass gainer's orbital speed will not be so fast at the time of explosion. For a 30 M$_{\odot}$ mass gainer and a ∼4 M$_{\odot}$ stripped He core mass donor, for example, expected kick velocities are only of order 5–20 km s^{-1} depending on the orbital period appropriate for systems that do not merge.[1] Models of binary stellar populations predict relatively slow runaways – or 'walkaways' – of only a few to 10 km s^{-1} in many cases involving mass stripping (Eldridge, Langer & Tout 2011; de Mink et al. 2014). Faster runaways are actually hard to get from binary evolution without a favorable neutron star kick, and may require a two-step ejection (Pflamm-Altenburg & Kroupa 2010). Therefore, H16 were not correct to conclude that the observed velocities argue against the presence of runaways among LBVs; the radial velocity values they listed are unable to quantitatively justify such a claim (see below). It is not at all clear that modest speeds of this order would lead to easily identified bow shock morphologies, as asserted by H16, because the runaway speed may actually be substantially less than the speed of the nebular shell. However, even such modest speeds of ∼10 km s^{-1} are enough to move LBVs a few 10s of pc in a few Myr. A key point is that the relatively slow kick velocity acts together with a longer lifetime (longer than expected in single-star evolution for the observed luminosity) to make the stars appear more isolated. The longer lifetime allows O-type stars from the same birth population to die in the mean time.

In a similar vein, H16 argue that simple OB association random drift velocities of 10 km s^{-1} can yield the inferred motions of LBVs required to explain their degree of isolation. However, the critical point here is that random velocity dispersion in a cluster or OB association applies to *all* stars, whereas the projected distribution of LBVs on the sky indicates that they are *preferentially* more isolated than even the late-type O stars. In other words, statistically LBVs appear to receive an *extra* velocity spread (or longer lifetimes than expected), beyond that given to the rest of massive stars. This is why one must consider an appropriate comparison between a full *distribution* of separations, rather then picking a few stars out of a sample to conclude that a late O-type star or RSG is seen nearby. H16 noted some projected massive star neighbours to LBVs in M31/M33 and deemed this sufficient to claim that they are consistent with single-star evolution, but they did not present an appropriate statistical analysis.

Regarding binarity, H16 stated that some LBVs are observed to be in binary systems, and that this therefore contradicts the scenario proposed by ST15 where LBVs are mass gainers. This statement is false for two reasons. First, in the scenario where LBVs form through mass transfer in binaries, there will indeed be some cases where the mass donor companion has exploded, leaving a runaway single star, but there will also be some cases where this has not yet occurred so that the LBV is still in a binary system awaiting its first SN. The time for the mass gainer to evolve to the LBV phase and the time for the mass donor to explode depend on various factors, including the initial masses and how much mass was transferred (see, e.g. Langer 2012). It would, however, be interesting to investigate the nature of these companions of LBVs to see if they are consistent with being a mass donor. Secondly, even if LBVs are the products of mergers or if their mass donor has already exploded, LBVs can potentially still be seen in binary systems (especially wide binaries) with unevolved companions because hierarchical triple and multiple systems are the norm among massive stars, not the exception (Abt, Gomez & Levy 1990; Sana et al. 2012; Duchene & Kraus 2013; Rizzuto et al. 2013; Sana et al. 2014, Moe & Di Stefano, in preparation). These studies generally find companion frequencies per primary around 2 (i.e. triple systems are very common). Combining unresolved close spectroscopic/eclipsing binaries with spatially resolved wide companions, Sana et al. (2014) estimate that the frequency of multiple systems may well be 100 per cent among O stars in particular. Furthermore, with the relatively weak SN kicks expected in the mass-gainer scenario, the resulting binaries (which were originally triples) may survive disruption and may yield highly eccentric and wide orbits. Interestingly, the companions that have been noted for LBVs so far are all in wide orbits: η Car has a 5.5 yr orbital period with very high eccentricity (Damineli, Conti & Lopes 1997); HR Car is a wide resolved binary with a period close to 5 yr (Rivinius et al. 2015); both HD 168625 and MWC314 have wide companions that are directly imaged (Martayan et al. 2016). The interesting question to ask is not whether there are some LBVs in binaries, as noted by H16, but rather, whether there is a statistically significant difference in the binary fraction of LBVs as compared to that of O stars and other types of evolved massive stars. Martayan et al. (2016) estimate a binary fraction among LBVs of only 27 per cent, whereas it is much higher for O-type stars (essentially 100 per cent if one includes wide binaries, as noted above). This fraction is admittedly preliminary, since fainter companions are hard to detect around very bright LBVs.

3 CONFIRMED VERSUS CANDIDATE LBVS

LBVs are rare because massive stars are intrinsically rare, because they are in a brief evolutionary phase, because their variability seems to turn on and off, and perhaps also because they are the product of special circumstances. When faced with these small numbers, selecting out only the top end of the subset that meets some specific criteria leaves one with a sample size that is too small to make any statistical claims. An interesting question is whether or not there is reason to separate LBVs confirmed to have exhibited the characteristic variability from those that resemble them in terms of their quiescent properties (candidates), which is about half-and-half.

H16 proposed that lumping together confirmed and candidate LBVs led ST15 to an incorrect conclusion about the statistics of their environments. A KS test allows one to determine if such a claim is quantitatively valid. Fig. 1 shows the distributions of projected separation to the nearest O-type stars (D1 from table 1 of ST15, for Magellanic Cloud LBVs only), plotted with all LBVs lumped together (black) and with the confirmed LBVs (blue) separated from the candidate LBVs (dashed orange). A KS test of these two separate distributions gives a p-value of 38 per cent (less than 1σ). To claim that confirmed and candidate LBV populations are drawn from separate parent distributions, a p-value less than 5 per cent is required. Thus, confirmed LBVs and LBV candidates are quantitatively consistent with being drawn from the same sample as far as their environments are concerned. The claim by H16 that not separating them will corrupt the statistical interpretation of their environments is therefore found to be invalid.

Confirmed LBVs do seem to have a tail reaching to smaller distributions than the candidates in Fig. 1, which was a central point made by H16. There is no statistical significance to this difference, but there may be some physical significance if this were to persist in a larger sample size. In that case, one might simply infer that the most luminous LBVs have shorter duty cycles in their eruptive behaviour (perhaps because of a closer proximity to the Eddington limit), making it more likely for them to be confirmed by their observed variability on time-scales of modern observations. There is also a selection effect that the more luminous LBVs have a larger change in temperature in an S Dor cycle, and hence a larger amplitude in their visible brightening, which makes them easier to

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[1] Somewhat higher runaway speeds can be achieved with lower mass gainers or non-conservative mass transfer, but these would not be the cases expected to yield an LBV-like object.

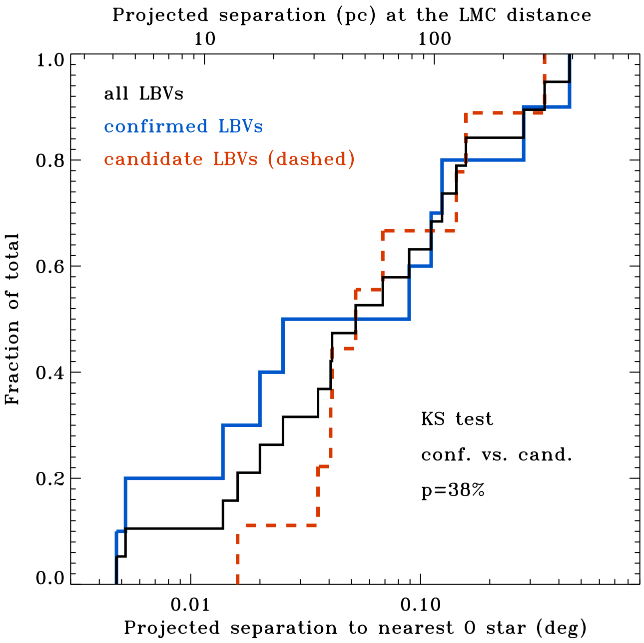

Figure 1. Cumulative distributions of separations from O stars for LBVs from ST15, plotting all LBVs together (black) as well as separate distributions for confirmed (blue) and candidate (dashed orange) LBVs. The results of a KS test between the confirmed and candidate distributions is noted.

detect. Lower luminosity LBVs may have longer periods between the emergence of their eruptive variability and smaller amplitudes in their brightening, making it more likely for them to be disregarded as mere candidates, even if they originate from a similar evolutionary pathway and the same distribution of environments.

4 CHERRY-PICKING THE SAMPLE

The central argument made in the original paper by ST15 was a statistical one. Namely, when one considers the *full distribution* of LBVs and related stars, they have a projected separation on the sky that appears to be inconsistent with being descended from the observed distribution of O-type stars, and moreover, inconsistent with being the precursors of the observed distribution of WR stars. Considering only stars in the Magellanic Clouds, ST15 made cumulative distribution plots of the projected separations on the sky between various different types of stars and their nearest O-type neighbours, finding that LBVs do not reside where one expects. ST15 therefore concluded that binary evolution is likely to be important for explaining origin of LBVs.

H16 have recently offered a contrasting viewpoint, arguing that this already small sample of stars should be further subdivided. They suggested that ST15 confused high-luminosity classical LBVs with lower luminosity LBVs, which, as some have argued, do appear to fall into two possibly separate groups (Smith, Vink & de Koter 2004). When culling of the sample is performed in the way they describe, H16 conclude that LBVs are consistent with single-star evolution after all. This contradiction warrants a detailed examination.

Adopting criteria from Humphreys & Davidson (1994), H16 take the sample of 19 Magellanic Cloud LBVs from ST15 and subdivide it into three smaller groups: (1) confirmed classical LBVs with only three members (called group 'LBV1'), (2) low-luminosity confirmed LBVs with four members ('LBV2'), and (3) unconfirmed or 'candidate' LBVs that are the remainder.[2] With this subdivided sample, H16 remake the cumulative distribution plot in fig. 4 from ST15 and infer very different conclusions. Namely, selecting only the three objects that are confirmed classical LBVs at high luminosity – which also happen to have the three smallest projected separations out of the other 19 objects – they find that the cumulative distribution of the LBV1 separation is smaller than the full sample of LBVs from ST15. They take this as an indication that LBVs in general are not as widely dispersed as claimed by ST15. Moreover, they find that when only the LBV1 subsample is considered, that its spatial distribution on the sky overlaps with late O-type dwarfs. From this, H16 conclude that the LBV1 group is consistent with traditional single-star views of LBVs. Similarly, they find that the lower luminosity LBV2 subsample overlaps with the distribution of red supergiants (RSGs), and H16 conclude again that this supports the traditional view, wherein lower luminosity LBVs are thought to be post-RSGs.

One may question the validity of selecting the tail end of a distribution of objects and then remaking the cumulative distribution comparison in the same way, not to mention the statistical significance of only three objects in the LBV1 group with unquantified selection bias. Nevertheless, even if this sort of cherry-picking of an already small sample is permitted, one can see that H16 interpreted their results incorrectly. To demonstrate this, let us separate the two cases of LBV1 and LBV2 below.

For the case of the LBV1 group, H16 find that their distribution of separations overlaps with late O-type stars, and they conclude that this association supports the traditional single-star view. However, if one extracts the tail end of a distribution, one must take care in the resulting comparison. These three stars are the high-luminosity classical LBVs in the LMC (R127, R143, and S Dor), which are representative of very luminous LBVs with implied initial masses (in the single-star evolutionary picture) of something like 60–100 $M_\odot$ and lifetimes of ∼2.5–3 Myr. H16 found that these have a similar distribution on the sky to late O-type dwarfs (O8 V and O9 V in the sample of ST15), which have initial masses of 18–22 $M_\odot$ and lifetimes of roughly 9–11 Myr. H16 should therefore have concluded from this comparison that classical LBVs are very overluminous for their distribution on the sky.

For the lower luminosity LBV2 sample, H16 find a dispersal on the sky similar to RSGs and conclude that this is consistent with these stars being post-RSGs as in the traditional view (Humphreys & Davidson 1994). However, here again one must be somewhat quantitative about what ages and initial masses are actually implied by each subgroup. The low-luminosity LBVs have luminosities that would require initial masses of 25–40 $M_\odot$ if they are evolved single stars (see, e.g. Smith et al. 2004, and ST15). If these are post RSGs, then they should be associated with the very most extreme RSGs with similar initial masses. However, the RSG comparison sample from ST15 included *all* the RSGs in the LMC. As noted by ST15, by number this is dominated by the low end of the mass distribution because of the slope of the initial mass function. Thus, the RSG comparison sample represents mostly stars of ∼10–15 $M_\odot$ initial mass, with ages of 20–100 Myr. These RSGs were not O-type stars on the main sequence; they were early B-type stars. The fact that low-luminosity LBVs are so well associated with them does *not* support the view that these LBVs are the product of mass-loss from the most extreme RSGs – in fact, it negates this possibility.

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[2] Note that other authors have suggested somewhat different subdivisions of LBVs (van Genderen 2001).

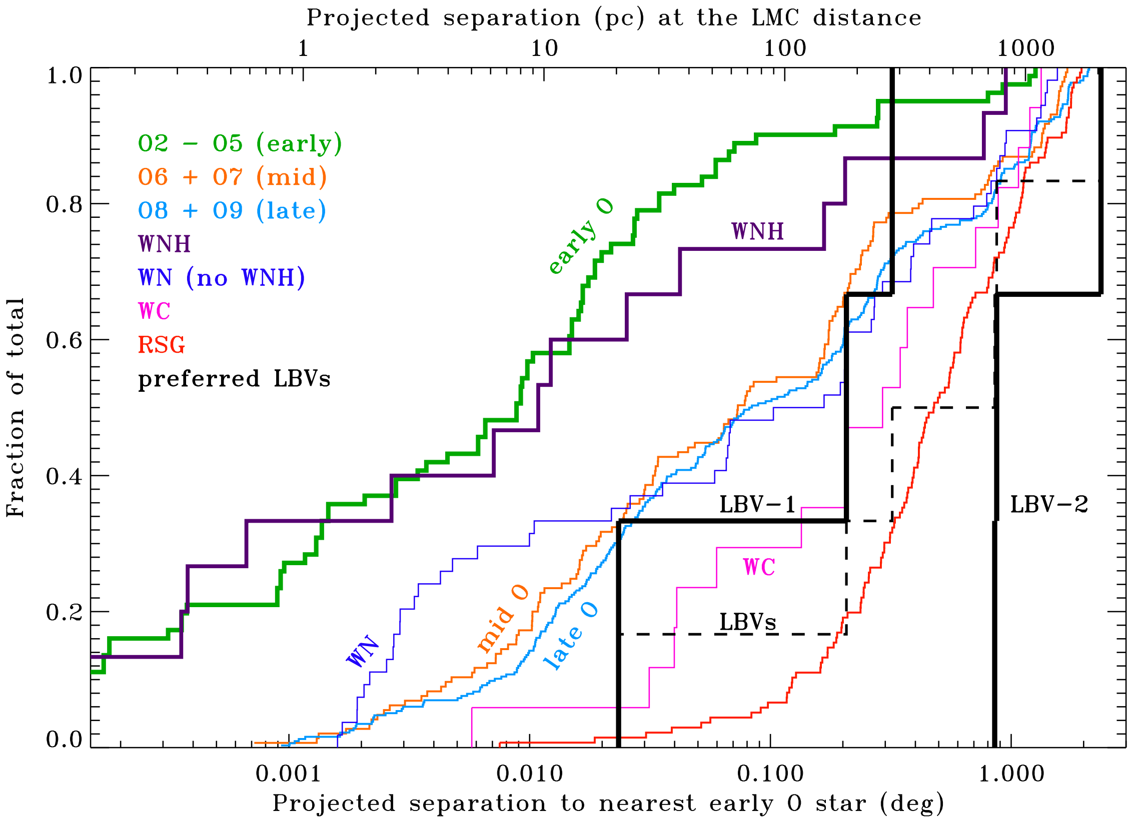

Figure 2. This is similar to the cumulative distribution plot in fig. 4 from ST15 (i.e. using the same star positions), except that (1) it shows the projected separation on the sky to the nearest early O-type dwarfs (O2-O5 V) rather than the separation to any O-type dwarf, and (2) it subdivides the confirmed LBVs into two groups as preferred by H16 (LBV1 and LBV2 are solid black lines, and the combination LBV1+LBV2 is the dashed black line.) Also, WNH stars are plotted separately from other WN stars.

Again, from this selective comparison, H16 should have concluded that the LBV2 group is highly overluminous for its distribution on the sky, and therefore very inconsistent with the traditional view of LBVs in single-star evolution (Humphreys & Davidson 1994). Unfortunately, serious confusion has arisen about the distinction between garden variety RSGs of 10–15 $M_\odot$ and the more extreme RSGs like VY CMa (see Smith, Hinkle & Ryde 2009 for a more detailed explanation).

If one wishes to extract only the tail end of a cumulative distribution plot, one must then make an appropriate comparison in order to draw the correct conclusion. ST15 quantified separations between various classes of massive stars and their O-type star neighbours. They did this by considering the nearest neighbouring O-type dwarf of *any* spectral subtype. This was because ST15 were analysing the full distribution of LBVs, which included both higher and lower luminosity LBVs and candidates in order to produce a statistically significant result. If one wishes to extract only the most luminous LBVs (as for the three objects in the LBV1 subsample defined by H16), then it would be appropriate to compare these to a subset of more massive and younger O-type stars within a similarly restricted luminosity range. In other words, only the early O stars are the putative progenitors of the LBV1 group, not late O-type stars, so early O stars should be the basis for comparison with LBV1.

Fig. 2 shows such a comparison. This is essentially the same as fig. 4 in ST15, but it plots the projected separation on the sky to the nearest star in the LMC with an *early* O spectral type (types O2–O5; the early O stars from ST15) rather than *any* O-type dwarf. This is a more appropriate comparison, since the early O stars (main sequence masses above roughly 35–40 $M_\odot$) must be the progenitors of classical LBVs in the traditional single-star view, and since late O-type dwarfs are scattered throughout this region of the LMC (as noted by ST15, many of the nearest neighbours to LBVs appear to be accidental line-of-sight coincidence). Following the suggestion of H16, LBVs are separated into the same LBV1 (classical) and LBV2 (low-luminosity) subgroups that they prefer.[3] This more appropriate comparison with early O-type stars shows that even the exclusive subsample of the most luminous LBVs (LBV1) is dispersed far from the locations of their supposed progenitors. LBV1 members are located 20–300 pc from the nearest early O stars, which reside mostly in young clusters. They are also more dispersed from O stars than most of the WN stars, only the most luminous of which should be their descendants. The main point in a plot like Fig. 2 is not to claim that any individual massive star can never be so far from other O stars, but rather, that the distributions of LBV1 and early O stars are inconsistent.

It is true that the LBV1 sample should be somewhat older than their main sequence progenitors and that they should be slightly more dispersed on the sky. But how much more? Fig. 2 shows that

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[3] These groups are the same as H16 with one exception. H16 chose to include the SMC star R40 in the LBV2 group, but did not include the SMC star HD 5980 in the LBV1 group. Both are confirmed LBVs. HD 5980 would have the largest separation from O stars on the sky and would have skewed the LBV1 sample to even larger separations. Fig. 2 therefore includes only LMC stars.

LBV1 has a distribution as old as or older than late O dwarfs, with lifetimes of 9–11 Myr. Since O stars typically spend the first 0.5–1 Myr embedded in their natal clouds, and since O stars get brighter as they age along the main sequence, the observed population of late O stars has a likely median lifetime of at least 5–6 Myr, if not older. The early O stars have H-burning lifetimes of only 2.5–3 Myr and median lifetimes (spending their early childhood embedded in ultracompact H II regions inside molecular clouds) of roughly 2 Myr. The high luminosity classical LBVs are thought to mark the transition from the end of core-H burning to He burning in these very massive stars (in the traditional picture), so they should have actual ages of 2.5–3 Myr. In fact, however, the LBV1 distribution has an apparent age that is more than double this value (similar to or larger than the median age of late O-type). This suggests that their longer lifetimes are more appropriate for a star of roughly *half their implied initial mass*.

An interesting comparison includes the WNH stars, which are usually thought to be approaching the end of core-H burning main sequence evolution in the most luminous stars (see, e.g. Moffatt & Seggewiss 1979; Crowther et al. 1995; Drissen et al. 1995; de Koter, Heap & Hubeny 1997; Smith & Conti 2008). At this point in their evolution near the end of the main sequence, their luminosities have increased and their stellar mass has decreased somewhat due to mass-loss, so that their proximity to the Eddington limit causes strong winds (Smith & Conti 2008; Gräfener et al. 2011). One would infer that these stars should have environments the same as LBV1 and fairly well associated with early O stars. We see that indeed, WNH stars are closely associated with early O stars. However, WNH stars have a distribution very unlike the classical LBVs, which should be their immediate descendants (the expected age difference between WNH and LBV1 is less than 1 Myr). Instead, the very luminous LBVs are more closely associated with late O stars and WC stars. Overall, this comparison to the locations of early O stars reinforces the anomalous locations of LBVs found by ST15, and directly contradicts claims made by H16.

Whether or not runaways are required to explain the dispersal of LBVs – or if instead their apparent dispersal on the sky can be explained by rejuvenation by gaining mass or merging in binaries – remains an open question in need of additional quantitative investigations with population synthesis models or other techniques. ST15 suggested that kicks may help explain the isolation, but they did not claim that such runaway motion is required. Whether or not there is any observational indication of runaway LBVs from kinematics is worth investigating as well. Nevertheless, it is clear that the apparent dispersal on the sky of LBVs is certainly not consistent with expectations of the traditional view in single-star evolution (Humphreys & Davidson 1994) because they clearly do not associate with stars of similar expected initial mass, even if they tolerate some moderately massive stars in their vicinity.

5 RADIAL VELOCITIES

In addition to the suggestion to subdivide the LBV sample as noted above, H16 also claimed that none of the LBVs in M31/M33 have high velocities consistent with being runaway stars, and that this supports the view of LBVs as single stars. H16 listed values for the observed radial velocity $V_r(Obs.)$ of LBVs and the expected velocity $V_r(Exp.)$ for M31 and M33 rotation curves in their Table 1. They did not present any analysis of these values, but claimed that they contradict runaway motion.

An important point, though, is that the expected runaway speeds are rather small (of order 10 km s^{-1} or even less) in the evolutionary scenario discussed for LBVs (see Section 2). Because the expected speeds are so slow, it is not at all clear that available radial velocity information for LBVs has the precision required to rule out this motion. In fact, a quantitative analysis shows that it does not.

Fig. 3 shows cumulative distributions of the residual velocities for LBVs in M31 and M33. These are the absolute value of the residual $V_r(Obs.) - V_r(Exp.)$ for the LBVs listed in table 1 of H16 (in dark blue) compared to the same quantity for RSGs of 'rank 1' (i.e. highly likely membership) from Drout et al. (2009) for M31 and Drout et al. (2012) for M33 (RSGs shown in red). In both cases, the LBVs appear skewed to higher velocities by a small amount, although the small number of LBVs do not allow a statistically significant difference to be determined. Note that most of the velocities seen here probably result from uncertainty in X and R for individual sources as compared to the model rotation curve for each galaxy (see Drout et al. 2009, 2012). Since M31 has a higher inclination and higher intrinsic rotation speed, the residuals are naturally higher. This makes it difficult to say anything about relatively slow runaways from the observational data for M31, while M33 is more favorable.

Also shown in Fig. 3 are empirical models for an expected distribution of velocities for stars that receive an extra kick. These are made from the observed RSG distribution for each galaxy, plus a randomized velocity from 0 km s^{-1} to the nominal kick velocity V_k. This is an idealized case where all LBVs have had their companion explode already, and all kicks have the same velocity V_k but are isotropic, resulting in an equal probability at any radial velocity between 0 km s^{-1} and V_k (in other words, the line profile from a thin expanding spherical shell of finite thickness is flat-topped). This is certainly an oversimplification, but it is conservative, and is suitable for the purpose of showing that it is difficult to rule out some runaways. When such extra motions are added to the RSG distribution after randomization, it results in the light blue distributions shown in Fig. 3. Two model distributions are shown for each galaxy; one is the case with the highest p-value in a Kolmogorov–Smirnov (KS) test, and the other has a p-value equal to that of the RSG population (in other words, an equal probability of having either no additional kick or this kick speed, respectively).

For M31, the data allow rather high runaway speeds for the full distribution. The highest p-value (84 per cent) is for $V_k = 20$ km s^{-1}, and additional kicks as high as $V_k = 50$ km s^{-1} have equal probably to zero kick (25 per cent). For M31, the data appear to be fully consistent with the hypothesis that all LBVs could have received motion larger than typical speeds expected in the mass-gainer scenario for LBVs (ST15).

For M33, the data are somewhat more constraining and higher speeds may be less likely. The highest probability is for $V_k = 5$ km s^{-1} (99 per cent), and additional kicks as high as $V_k = 8$ km s^{-1} have equal probably to no kicks (93 per cent). As noted earlier, relatively small kicks of only a few to 10 km s^{-1} are expected from mass gainers in binary evolution (Eldridge et al. 2011; de Mink et al. 2014), so the velocities for LBVs in M33 still permit this scenario for all LBVs. Strictly speaking, even larger speeds cannot be ruled out. The two additional magenta curves in Fig. 3 (right) show simulated distributions for kicks of 20 ($p = 32$ per cent or 1σ) and 35 km s^{-1} ($p = 5$ per cent or 2σ). These allowed speeds would increase if we admit that not necessarily every LBV has already had its companion explode.

One must bear in mind, of course, that since most massive stars are born in interacting binary systems (Sana et al. 2012; Duchene & Kraus 2013), the observed populations of RSGs in M31 and M33 (which served as a reference sample) *already contain a substantial*

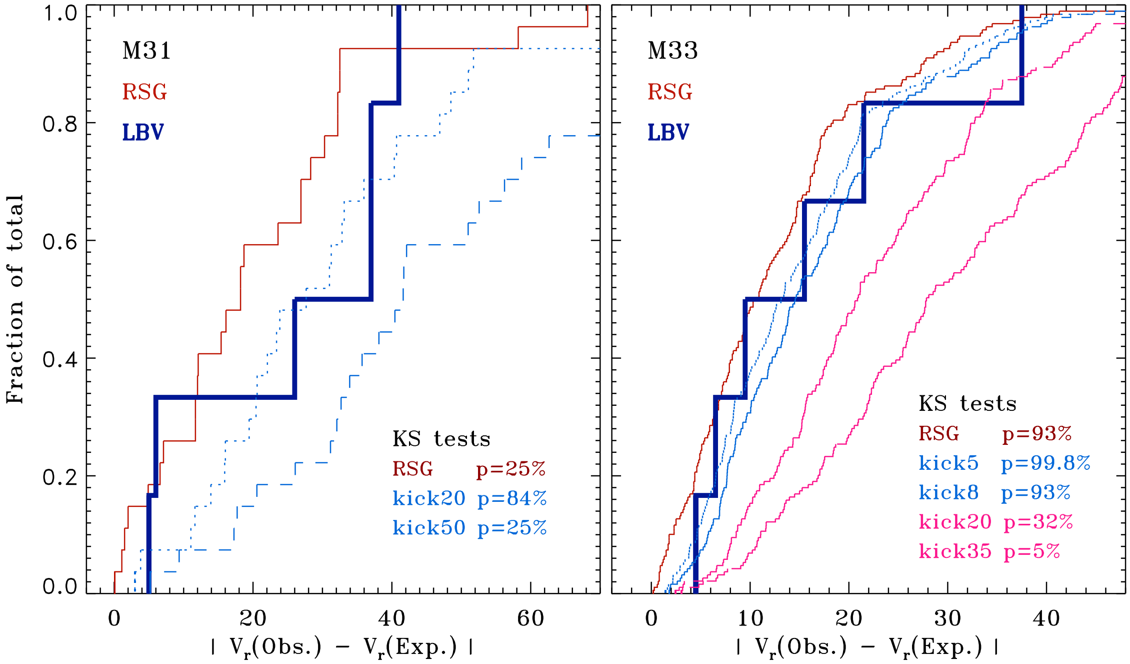

Figure 3. Cumulative distributions of velocities for RSGs (red) and LBVs (dark blue) in M31 and M33. Plotted here is the absolute value of the difference between the observed radial velocity $V_r(Obs.)$ and the radial velocity expected from the rotation curve $V_r(Exp.)$. Values for RSGs are 'rank 1' (i.e. highly likely membership) sources from Drout et al. (2009) for M31 and Drout, Massey & Meynet (2012) for M33. LBVs are calculated from values presented in table 1 of H16. Possible distributions with kicks are shown by adding a randomized kicks to the RSG distribution in each galaxy. Values shown are 20 and 50 km s^{-1} for M31 and 5 and 8 km s^{-1} for M33. Listed in each panel are the results of KS tests comparing LBVs to the three other distributions. The additional two magenta curves for M33 show simulated distributions with kicks of 20 and 35 km s^{-1}, which correspond to 1σ and 2σ.

fraction of stars that have received recoil motion from their companion's SN. Thus, some runaways were already included by nature in the observed RSG distribution, so the true kicks allowed by the data are even larger than the numbers quoted above.

Admittedly, it would be strange if the LBVs in M31 received systematically higher kicks than the LBVs in M33, as might be implied by their distributions. As noted above, however, most of the observed residual velocities can be attributed to uncertainty in deriving $V_r(Exp.)$ for a given star, which is larger for M31. Residual velocities are also strongly affected by errors in determinig $V_r(Obs.)$, which is difficult for LBVs that have strong and variable winds. The main conclusion of this exercise is that the available data do not have the precision required to discriminate between the hypotheses that LBVs are or are not runaways, aside from ruling out very high speeds of order 100 km s^{-1} for most of the sample, much larger than expected from binary evolutionary scenarios.

H16 also mentioned the velocities of LBVs in the Magellanic Clouds and claimed that their kinematics suggest that they are single stars and not runaways. However, H16 only listed the velocities and compared them to the average systemic velocity of the LMC without a quantitative analysis. The discussion of Magellanic Cloud LBV kinematics is postponed to a later paper because this investigation requires a different type of analysis than for M31/M33, and requires new data. However, it is noteworthy that the range of differential velocities listed by H16 spans 10s of km s^{-1}, and appears at first glance to be consistent with the relatively low-speed runaways expected in the mass gainer scenario (ST15).

One LBV is particularly interesting. R71 – the most isolated of the LBVs in the LMC, located more than 300 pc from any O-type star – has a radial velocity that is offset by −71 km s^{-1} relative to the systemic velocity of the LMC (according to table 3 in H16). At that speed R71 could easily reach its observed isolation in a few Myr.

6 SUMMARY

In conclusion, a quantitative look at the data of LBVs and their environments shows that even if one adopts the selective criteria advocated by H16, the results do not support their claims. When only a few objects from the tail of a distribution are extracted, there remains no statistical power to discriminate between that sample and the remainder. Moreover, the analysis above shows that even if those selections are permitted, the interpretation arrived at by H16 was incorrect, because they did not consider the quantitative implications of the comparison stars. Namely, one finds that the most luminous confirmed LBVs have environments similar to late O-type stars, which have median ages about twice as long as the presumed ages of those LBVs in a single-star scenario. Similarly, the lower luminosity confirmed LBVs have a distribution similar to RSGs, the bulk of which have initial masses (10–15 M$_\odot$), less than half that of the low-luminosity LBVs (25–40 M$_\odot$). This discrepancy rules out the traditional single-star view of LBVs, and requires instead that they are massive blue stragglers.

A statistical test of the confirmed and candidate LBVs shows no statistical difference between their environments, contrary to the central claim that motivated H16's reanalysis. Thus, it is not clear that it is appropriate to separate them.

Even if one does separate the confirmed and candidate LBVs, and if one further separates the low and high luminosity group of LBVs, the central results of ST15 remain the same – that LBVs are more isolated from O-type stars than they should be in the traditional single star view of stellar evolution. Rejuvenation by mass transfer and mergers, and possibly runaway motion from a companion's SN, are required to explain their isolation. Available kinematics of LBVs do not argue against SN-induced runaways, mostly because the expected motion is slow and the precision of available data cannot clearly discriminate. It will be interesting to see if there are other indications that LBVs do not have anomalous motion; if they do not, then this will point to rejuvenation in binary evolution (i.e. massive blue stragglers) as the main explanation for their isolated environments.

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NOTE ADDED IN PROOF

When this manuscript was in press, a revised version of H16 was published. Comments above refer mostly to the originally posted preprint (arXiv:1603.01278v1) since some statements changed in the final version.

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