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The isolation of luminous blue variables resembles aging B-type supergiants, not the most massive unevolved stars

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ABSTRACT

Luminous blue variables (LBVs) are suprisingly isolated from the massive O-type stars that are their putative progenitors in single-star evolution, implicating LBVs as binary evolution products. Aadland et al. found that LBVs are, however, only marginally more dispersed than a photometrically selected sample of bright blue stars (BBS) in the Large Magellanic Cloud (LMC), leading them to suggest that LBV environments may not exclude a single-star origin. In both comparisons, LBVs have the same median separation, confirming that any incompleteness in the O-star sample does not fabricate LBV isolation. Instead, the relative difference arises because the photometric BBS sample is far more dispersed than known O-type stars. Evidence suggests that the large BBS separation arises because it traces less massive ($\sim$20 $M_{\odot}$), aging blue supergiants. Although photometric criteria used by A19 aimed to select only the most massive unevolved stars, visual-wavelength colour selection cannot avoid contamination because O and early B stars have almost the same intrinsic colour. Spectral types confirm that the BBS sample contains many B supergiants. Moreover, the observed BBS separation distribution matches that of spectroscopically confirmed early B supergiants, not O-type stars, and matches predictions for a roughly 10 Myr population, not a 3–4 Myr population. A broader implication for ages of stellar populations is that bright blue stars are not a good tracer of the youngest massive O-type stars. Bright blue stars in nearby galaxies (and unresolved blue light in distant galaxies) generally trace evolved blue supergiants akin to SN 1987A's progenitor.

Key words: binaries: general – blue stragglers – stars: evolution – stars: massive – stars: Wolf–Rayet.

1 INTRODUCTION

The massive eruptive stars known as luminous blue variables (LBVs) are critical for understanding the evolution and fates of massive stars. This is because LBVs have the highest observed mass-loss rates of any class of stars, and because this mass-loss (which may or may not remove the H envelope) profoundly influences the fate of the star and the type of eventual supernova (SN) explosion (see Smith 2014). Understanding the physical mechanism of this mass-loss and its metallicity dependence is therefore critical for models of stellar evolution, whether it is driven by normal winds, eruptive events when a massive star exceeds the Eddington limit, or binary interaction episodes (Owocki, Gayley & Shaviv 2004; Smith & Owocki 2006; Podsiadlowski 2010; Smith et al. 2011; Groh et al. 2013a; Groh, Meynet & Ekström 2013b; Justham, Podsiadlowski & Vink 2014; Smith & Arnett 2014; Blagovest, Vink & Gräfener 2016; Götberg, de Mink & Groh 2017).

The standard view of LBVs has been that they correspond to a very brief *transitional* phase of the most massive single stars, when the star moves from core H burning to core He burning. In this view, LBV winds or eruptions are the prime agent that removes the H envelope to produce Wolf–Rayet (WR) stars (Langer et al. 1994; Heger et al. 2003; Meynet & Maeder 2003; Meynet et al. 2011). This transition from single O-type stars to WR through their own mass-loss is often referred to as the 'Conti scenario' (Conti 1976). The reliance upon the LBV phase for making WR stars from single stars is even more acute because of lowered O-star wind mass-loss rates (Bouret, Lanz & Hillier 2005; Fullerton, Massa & Prinja 2006; Smith & Owocki 2006; Smith 2014). It is therefore critical to have model-independent tests of this single-star evolutionary paradigm.

Single versus binary scenarios can be addressed by studying the ages and environments of LBVs. For stars at the same place on the HR diagram, the age of the surrounding environment can differentiate binary evolution products from single stars, since mass gainers and mergers may have had significantly lower initial masses and longer lifetimes than effectively sin-

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gle supergiant stars of the same current luminosity (Gallagher 1989). A clear prediction is that in the single-star scenario, where LBVs occur immediately after core H exhaustion in transition to their He burning phase as WR stars, the spatial locations of LBVs should follow those of massive, young, early O-type stars that are their immediate progenitors. At these high initial masses, the lifetimes are very short (3–4 Myr), and there is not enough time to move far from their birth sites. In a binary scenario, on the other hand, LBVs should be more dispersed than young O-type stars because they have been rejuvenated after a delay due to their longer main-sequence lifetime (or they may have received a kick from a companion's SN), whereas the most massive O-type stars have already died.

Most stellar age indicators are too imprecise for this task, because one is interested in being able to distinguish between ages of around 3–4 Myr (main-sequence lifetimes of $M_{\rm ZAMS} > 40\,{\rm M}_{\odot}$ stars, for e.g. appropriate to classical LBVs) or a factor of only about 2–3 older corresponding to $\sim$20 M$_{\odot}$ stars with longer lifetimes that have been rejuvented though mass accretion or mergers. For example, in the star formation history study of the LMC by Harris & Zaritsky (2009), there is one single age bin for all ages $<$9 Myr; so whether they are single or binary, almost all the LBVs should be lumped into one bin. Since LBVs are generally not in clusters, age estimates based on turnoffs, RSG luminosity, or luminosity functions (Schneider et al. 2014; Eldridge et al. 2017; Beasor et al. 2019) generally can't be applied to LBVs. The most reliable clock for the highest mass stars turns out to be using a spatial association with other stars that must have very short lifetimes: i.e. early O-type stars. A spectrum of a single O star doesn't provide an age, of course, but the relative degree of clustering of those O-type stars does give a relative statistical age, because O stars are born in clusters that disperse with time. These are the same stars that should be the single-star progenitors of classical LBVs. Smith & Tombleson (2015) performed this spatial comparison, examining the cumulative distributions of separations to the nearest O-type stars on the sky for O star subtypes, LBVs, WR stars, and other classes of evolved stars in the Large Magellanic Cloud (LMC). Smith & Tombleson (2015) found LBVs and LBV candidates to be remarkably isolated from massive O-type stars, much more so than allowed by single-star models, thus apparently ruling out the single-star evolutionary scenario for LBVs. LBVs in the Milky Way showed a similar avoidance of O stars, although extinction in the Galactic plane and uncertain distances made this harder to quantify than in the LMC. In brief, LBVs showed a clear preference to avoid massive, young clusters of O-type stars. This led Smith & Tombleson (2015) to suggest an alternative hypothesis that the observed isolation of LBVs could only be understood if they are primarily the products of close binary evolution. In this alternative view, LBVs are not the most massive single stars in transition, but instead, LBVs are evolved massive blue straggler stars.

Using a model for the passive dispersal of aging massive stars in clusters that drift apart with age due to their birth velocity dispersion, Aghakhanloo et al. (2017) demonstrated that such a model could quantitatively explain the observed distribution of O-star subtypes (early, mid, and late O-type stars). However, they confirmed that the same dispersal of clusters could not account for the locations of LBVs as single stars with ages and initial masses appropriate to their current luminosity. LBVs require either much faster drift speeds than O stars (i.e. kicks from a companion's SN) or older ages commensurate with those of stars at lower initial masses around 20 M$_{\odot}$. Interestingly, this blue-straggler view of LBVs as mass gainers or mergers in binaries also agreed with independent theoretical studies seeking to understand how LBVs might be SN progenitor stars (Justham et al. 2014).

This new blue straggler view of LBVs is in direct contradiction to the traditional view for their role in stellar evolution. In addition to giving a different origin for LBVs themselves, it also has the consequence of removing LBVs from the single-star evolutionary scenario, wherein they play a crucial role in removing the H envelope to make WR stars. This modification has sparked some debate. In particular, Humphreys et al. (2016) had a different take on subdividing the data, and preferred the traditional single-star view. Humphreys et al. (2016) noticed that if one excludes most of the LBV sample, then the three most luminous LBVs in the LMC do have a median separation similar to that of O-type stars, which in their interpretation supported the single-star scenario after all. Humphreys et al. (2016) also pointed out that the lower luminosity LBVs have a separation distribution similar to red supergiants (RSGs), taken as support for a single-star view wherein these LBVs are post-RSGs from initially 30–40 M$_{\odot}$ stars. For both points, however, Smith (2016) showed that this was a mischaracterization of the data. The most luminous LBVs should have initial masses of around 50–100 M$_{\odot}$, but the common O-type stars with a similar spatial distribution noted by Humphreys et al. (2016) were dominated by late O-type stars with initial masses around 18–25 M$_{\odot}$. Similarly, the population of RSGs was dominated by relatively low initial masses of $\sim$15 M$_{\odot}$, so their similarity to the low-luminosity LBV distribution (expected to have single-star initial masses of 30–40 M$_{\odot}$) contradicts a single-star scenario. Moreover, Smith (2016) demonstrated that there is no significant difference between LBVs and LBV candidates, so that including 'candidate' LBVs would not skew the results as Humphreys et al. (2016) argued. (Note that 'candidate' LBVs are stars with similar spectra and luminosities to LBVs, often with circumstellar shells that indicate a prior outburst, but which have not yet been observed photometrically to undergo LBV eruptions.)

Motivated to weigh in on this debate, Aadland et al. (2019; A19 hereafter) aimed to provide an independent check on the isolation of LBVs. A19 were concerned primarily about how the unknown level of incompleteness of the spectroscopically confirmed O star reference sample might skew the results (i.e. O stars missing from the sample because they don't have spectra might make LBVs appear artificially isolated from their nearest known O star neighbours). A19 therefore chose a complimentary approach with different selection criteria. Instead of spectroscopically confirmed O-type stars as a reference for a clustered young massive population, they chose to compare LBVs to a photometrically selected sample of bright blue stars (BBS). Their intent was that photometric selection could yield a complete sample of the most massive unevolved stars in the LMC. Using the BBS sample as a reference, A19 found the median BBS separation to be only about 30 per cent smaller than the LBV median, whereas the median separation for spectroscopically confirmed O-type stars was 10 times smaller than for LBVs. A19 attributed this difference to incompleteness in the spectrocopically confirmed O stars, and interpreted the smaller difference from LBVs as not contradicting the standard picture of massive single-star evolution.

In this paper, we take a closer look at the BBS sample and the conclusions of A19. First, in Section 2, we point out that the median separation of LBVs from either BBS or O-type stars was identical in the two studies of A19 and Smith & Tombleson (2015), confirming earlier suggestions (Smith & Tombleson 2015) that any incompleteness of the O star sample has no impact on the apparent isolation of LBVs. Then we investigate potential concerns with the BBS sample of A19 and its interpretation, quantifying the effects of choosing to exclude all the massive O stars in 30 Doradus (Section 3), and quantifying how reliably the colour cuts can select the most massive unevolved stars (Section 4), as required for this comparison. After demonstrating that colour selection cannot reliably select only the most massive unevolved stars because of contamination from older B supergiants, we demonstrate (Section 5) that in fact, the distribution of separations for the photometric BBS sample is practically identical to the spatial distribution of known, spectroscopically confirmed early B supergiants. We also comment (Section 6) on the related implications for observed separation distributions of WR and specifically WN3/O3 stars, which have been tested with the same methods. We conclude that the less severe isolation of LBVs when compared to the photometric BBS sample arises because the BBS sample is old, not because LBVs are young.

2 INCOMPLETENESS OF COMPARISON SAMPLES HAS LITTLE IMPACT

Finding that LBVs are isolated from massive O-type stars overturns a long-held paradigm of massive star evolution, but it is a statistical result that could have potential selection bias, and so independent checks with alternative selection criteria could be valuable. The main motivation for undertaking an independent study using a photometric sample was that A19 were concerned about the possible incompleteness of spectroscopically confirmed O-type stars, because not all massive stars in the LMC have known spectral types. If, for example, past efforts to gather spectra for massive stars have concentrated on clustered regions in the LMC, and have therefore neglected field stars, then there may be additional unknown O-type stars in the field that are not being counted in the analysis of spatial separations between LBVs and the nearest O-type star. A19 were concerned that this incompleteness might skew the results and cause LBVs to appear artificially isolated.

This potential concern was noted originally by Smith & Tombleson (2015), who argued that it wouldn't matter much. O-type stars are known to reside mostly in clusters and they essentially provide a map of the space density of young massive stars. Adding some O stars in the field may serve to raise the quantitative value of the local minimum slightly, in terms of the number of O stars per unit sky area, and it can therefore alter the numerical value of the age one infers based on that space density (Aghakhanloo et al. 2017). It does not, however, alter the fact that O stars have a high concentration in clusters. Having a complete count of all the field O-type stars is not needed for this study. What is very important is that most of the O-star *clusters* are known, and that LBVs are not in those clusters. What would be needed to make LBVs consistent with a single-star scenario would be to have unrecognized clusters of O stars surrounding each LBV, which is unlikely given that most LBVs in the LMC have been imaged with the *Hubble Space Telescope* to look for shell nebulae.

In the end, the results of the analysis conducted by A19 confirmed that possible incompleteness of the O star sample has no impact on the outcome. This is evident from the resulting median of the distribution of separations between LBVs and the nearest BBS star or O star.[1] Using BBS stars as a reference, A19 measured a median separation between LBVs and their nearest BBS neighbor of 181 arcsec. Using a sample of spectroscopically confirmed O-type stars as a reference, Smith & Tombleson (2015) measured a median separation between LBVs and their nearest O-star neighbour of 0.05° or 180 arcsec. The results are essentially identical. *If incompleteness of the spectroscopically confirmed O-star sample were to blame for the apparent isolation of LBVs, then LBVs would show a smaller median separation when using a 'more complete' sample of young massive stars.*

What happened instead is that the reference sample of BBS stars shifted to much larger median separation than known O-type stars, making them more isolated than O stars and therefore more similar to LBVs. For their BBS sample, A19 quote a median separation to the nearest other BBS star of 129 arcsec (or a projected separation of 31 pc). By contrast, known early O-type stars have a median separation 10 times less, or only 3 pc (Smith & Tombleson 2015). Mid and late-type O stars have somewhat larger median separations than early O-types, but still less than 10 pc (Smith & Tombleson 2015).

At this point, one must question the BBS sample as a tracer of the most massive unevolved stars, simply because they are not tracing a clustered population. The median separation between BBS stars and their nearest BBS neighbour is 31 pc, and critically, less than about 4 per cent of the BBS sample has a separation to the nearest neighbour that is closer than ∼5 pc. By contrast, 70 per cent of the spectroscopically selected early O stars have a separation less than 5 pc. If it were true that the BBS stars are *a complete sample of the most massive unevolved single stars*, then this observed distribution would upend most of what we understand about the birth environments of massive stars and massive star formation.

It is well established that most O stars are found in clusters and associations (Blaauw 1964; Lynds 1980; Garmany, Conti & Chiosi 1982; Gies 1987). From a fairly complete magnitude-limited sample of bright Galactic O-type stars, Gies (1987) estimates that at least 70 per cent reside in known young clusters and associations, while the remainder was thought to be a mix of runaway stars ejected from clusters and some stars that are the most massive star in a less massive cluster (see also Eldridge, Langer & Tout 2011; Renzo et al. 2019). This seems to be in very good agreement with the observed separation distribution of spectroscopically confirmed early O-type stars in the LMC (Smith & Tombleson 2015), but the separation of BBS stars (A19) seems incompatible with known clustered environments of O-type stars. The inescapable conclusion seems to be that the BBS sample must be contaminated by an older population of evolved bright blue stars in the field.

Understanding why the BBS sample is more dispersed than young O stars is critical for correctly interpreting the different results found by A19 and Smith & Tombleson (2015). This discussion follows in the next few sections.

Before that, however, an important point should be made concerning the mechanics of this sort of comparison. The analysis method in these two studies used the observed distributions of separation to a nearest massive star neighbour as a way to infer *relative* ages of populations of stars, in order to discriminate between single and binary star evolutionary scenarios. There are two essential requirements that must be met for this method to be valid:

First, the reference sample to which populations of stars are being compared must, in fact, be confidently known to be young. The way that the comparison works is that a separation distribution indicates whether a sample of target stars (in this case LBVs) is as old or older than a reference sample (in this case, the photometric BBS sample or O-type stars). More to the point, the age of that reference population must be known at least as precisely as the difference in age one is trying to test for. Spectroscopy allows one to select a

[1]Note that the 'nearest' neigbour excludes possible unresolved companions in a binary; both studies refer to the nearest spatially resolved stars.

reference sample of early O-type stars that are certain to be both massive and young. While wide-field photometric samples can be useful to flag issues related to severe incompleteness, it is much more difficult to guard against contamination from older stars in a photometric sample, as discussed below. This means that the typical age of a star in a photometric sample of blue stars is much harder to judge. Contamination by older stars will skew a distribution to larger separations on the sky.

Secondly, the reference sample to which populations of stars are being compared must, in fact, be clustered, otherwise the relative spatial distribution on the sky is not meaningful. In other words, this test equates a high degree of clustering with youth. It relies upon the assumption that massive stars are mostly born in clusters, and that as a population of stars ages, they drift apart and the O-type stars die off, such that the average separation to the nearest O-type star grows with time. If the comparison sample is not highly clustered, then this logic dissolves. The gradual dispersal of clusters accompanied by removal of the most massive stars as they die was modelled quantitatively by Aghakhanloo et al. (2017), who calculated values for the expected median separation and separation distributions of such samples. In these models, the most massive unevolved stars should have a typical separation from the nearest other O star of only a few pc, which again, is found to be in quite good agreement with the observations of spectroscopically confirmed early O-type stars. Thus, whatever the incompleteness may be, the spectroscopic O star sample behaves as expected and is not strongly affected by incompleteness in terms of its overall spatial distribution. On the other hand, Aghakhanloo et al. (2017) calculate that a median separation of ∼30 pc corresponds to post-main-sequence ages of around 10 Myr and initial masses of ∼20 $M_{\odot}$. According to the observed median separation of the BBS sample of 31 pc, one would conjecture that the BBS sample is dominated by evolved ∼20 $M_{\odot}$ stars on average, not the most massive unevolved stars of 40–100 $M_{\odot}$. This contamination, rather than single-star evolution, explains A19's result. Possible causes of contamination or bias are explored below.

3 EXCLUDING 30 DOR

One potential source of bias in the photometric BBS arises because A19 made a choice to exclude all stars within a 10 arcmin radius of the 30 Dor region. The reason for this choice was that they expected crowding to be severe in 30 Dor, possibly compromising the ground-based photometry. A19 did not evaluate the effect that this exclusion might have on the resulting statistics. There is cause for potential concern, since this region around 30 Dor contains about half of the known O-type stars in the LMC (de Koter et al. 2011) and most of the known early O-type stars that are the putative progenitors of LBVs in single-star models. Stars in the central regions of 30 Dor are among the most densely clustered O-type stars, so excluding them might selectively remove stars from the small end of the separation distribution, shifting the median to larger separations. On the other hand, if crowding is severe and some of the most densely clustered stars are missed, excluding 30 Dor might not have much impact, because these stars are already undercounted. This is straightforward to test.

Fig. 1 shows a cumulative distribution plot for separations of O stars to the nearest other O-type star. The thin green, orange, and blue lines are early, mid, and late O-types stars, respectively, which are essentially the same as in the original sample of Smith & Tombleson (2015). The thicker lines of the same colours show what happens to these distributions when we remove all the stars within a 10 arcmin radius from the centre of 30 Dor. The result is that the O-type distributions are indeed skewed to larger separations as qualitatively expected, but not by much. The effect is more significant for early O subtypes (a factor of ∼2 in separation and implied age). The exclusion of 30 Dor has less of an effect on the separation distributions for mid and late O types, perhaps because these samples of later O types are highly incomplete in the most crowded regions. Fig. 1 also shows how this exclusion influences the LBV separation distribution (thin dashed purple versus thick solid purple line), making the point that it has no significant effect. This is because most LBVs are not in clusters anyway.

Thus, while excluding 30 Dor does skew the statistical distributions to larger separations, it is not a large enough effect to fully explain the discrepancy between spectroscopic O stars and the BBS sample. This is somewhat reassuring, as it indicates that despite the large number of O-type stars in 30 Dor, there is nothing particularly anomalous about the clustering *distribution* of O stars there, and so it seems to be representative of O stars in general. In other words, outside 30 Dor in the rest of the LMC, O stars follow the same pattern of being highly concentrated in clusters. For early O-type stars outside 30 Dor, the median separation is 5–6 pc and mid and late O stars somewhat larger, still in good agreement with expectations from models of cluster dispersal with age (Aghakhanloo et al. 2017), and in good agreement with general expectations for O stars residing in clusters.

This exercise of excluding 30 Dor does highlight an interesting point about LBVs, however, concerning total numbers. Excluding 30 Dor rejects about *half* the known O-type stars, and *most* of the early O-type stars as noted above. In stark contrast, excluding 30 Dor only removes 1 out of 26 LBVs in the sample (4 per cent). (That one LBV is R143.) The vast majority of LBVs (25/26) are not located in the most active region of star formation in the LMC. This underscores the crucial point (Smith & Tombleson 2015) that LBVs preferentially avoid O star clusters.

If spectroscopically confirmed O stars are highly clustered as expected both inside and outside 30 Dor, why, then, does the BBS sample have such a large median separation of 31 pc? Something else is needed to reconcile the large difference between the median separations of known O stars and the BBS sample. As discussed below, this is most likely because the photometrically selected BBS sample is contaminated by an older population and does not trace the spatial distribution of the most massive unevolved stars.

4 CONTAMINATION IN THE PHOTOMETRIC BBS SAMPLE

4.1 Likely sources of contamination

Concerned that the spectroscopic coverage of O-type stars in the LMC might be spotty (past efforts to obtain spectra may have focused on clusters while neglecting field stars, for example), A19 aimed to create a more complete sample of the most massive unevolved stars using broad-brush photometric criteria. However, 'more complete' can also mean 'more contaminated', because the youngest luminous O-type stars and older luminous B-type supergiants have essentially the same colour at visual wavelengths. While the broad brush technique might be more inclusive of all the bright O-type stars, it may sweep up many other blue stars that are not necessarily the most massive unevolved stars. As demonstrated below, the dangers of unavoidable contamination in a photometric sample of blue stars outweighs the benefit of higher completeness,

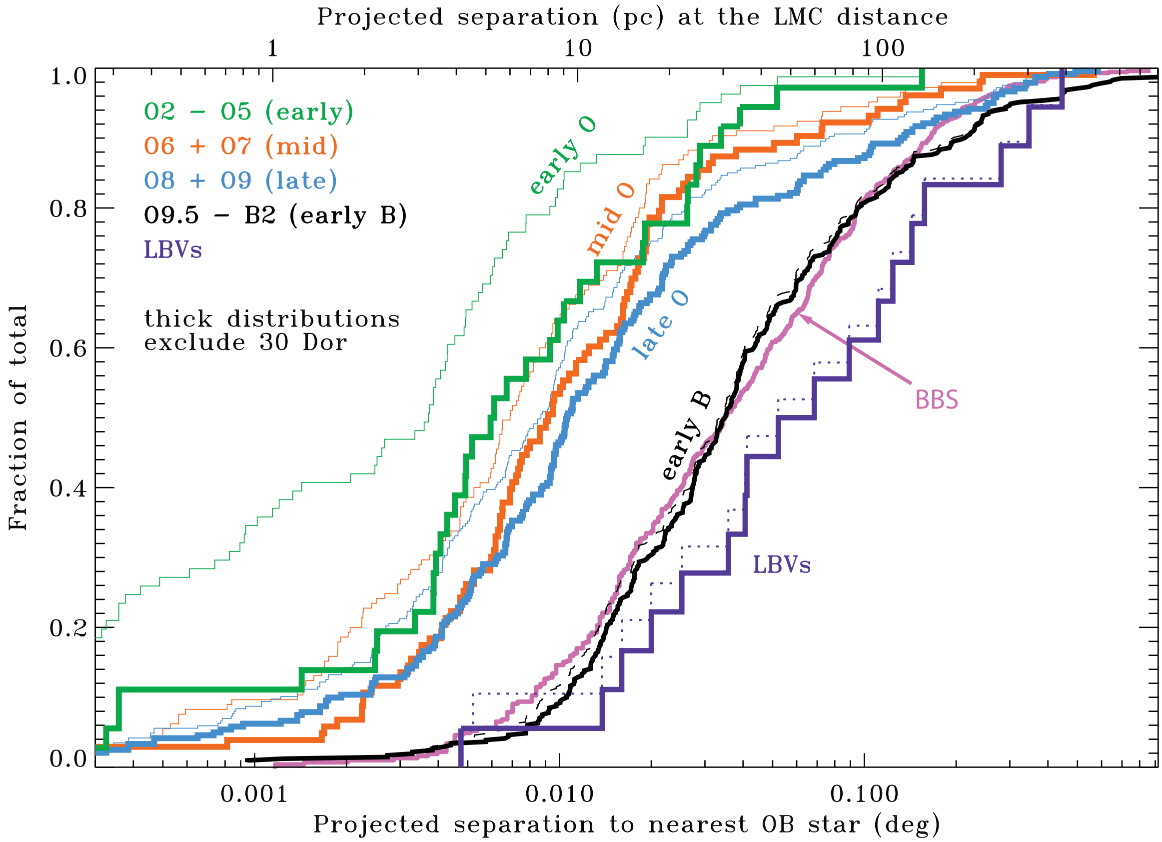

Figure 1. Cumulative distribution of separations from the nearest O star (or B star). The thin distributions of early, mid, and late-type O stars (green, orange, and blue, respectively), as well as the dashed purple distribution of LBVs, are the same as in Smith & Tombleson (2015). These are distributions of separations on the sky to the nearest spectroscopically confirmed O star of any subtype or luminosity class. The thicker solid distributions, however, exclude from these samples all stars within 10 arcmin of the centre of 30 Dor (following A19). The dashed black distribution is for spectroscopically confirmed early B-type stars (ranging from later than O9.5 up to and including B2), measuring the separation to the nearest other B-type star in that same sample. This 'early B' sample also excludes any stars with an apparent *V* magnitude fainter than 13.9 mag (again following A19). The solid black distribution is the same spectroscopic early B-star sample, but excluding all stars within 10 arcmin of the centre of 30 Dor. The magenta distribution is the BBS sample from A19, which is indistinguishable from the sample of spectroscopically confirmed early B stars.

and artificially skews the result. A19 adopted *UBV* photometric criteria intended to provide a sample of the most massive unevolved stars that would be complete for initial masses above 40 $M_{\odot}$. However, as emphasized by Massey et al. (1995), it is not possible to do this reliably (i.e. without contamination) using photometry alone. There are several compounding concerns, all of which can push a photometric sample in the same direction of more contamination from older, less massive stars:

Degenerate colours: The chief difficulty in selecting out the hottest stars with photometry is degeneracy: O stars and early B-type stars over a wide range of effective temperatures have essentially the same intrinsic broad-band colours and magnitudes at visual wavelengths, because *UBV* photometry samples only the Rayleigh–Jeans tail of a hot star's spectral energy distribution. Their $B-V$ colours differ by only about 0.02–0.03 mag from early O to early B types. This is comparable to or smaller than the photometric uncertainty in a single filter for many stars in the data used by A19 (see below). Spectra are needed to reliably distinguish young and initially massive O-type stars apart from older and less massive B supergiants.

Binaries: Compounding this problem of contamination is the fact that massive stars are mostly in binary systems (Blaauw 1961; Sana et al. 2012; Moe & Di Stefano 2017). Even without interaction, an unresolved binary in ground-based photometry can be brighter than it deserves for its age and spectral type simply because there are multiple stars, but it may have essentially the same colour as a hotter and more massive star. Hence, a less massive, older star with a companion will masquerede as a more massive, younger star in a photometric sample.

Relative numbers and lifetimes: While A19 acknowledged that their colour cuts may allow some B stars to enter the sample, they presumed that the contamination would be minimal, and that because of the *V* magnitude cut ($V = 13.9$ mag, corresponding to $M_V = -5$ mag with an average extinction correction) most of the B stars in their sample would be very luminous B supergiants that are the most massive stars at the end of the main sequence. However, a concern is that the B supergiants that correspond to a >40 $M_{\odot}$ star will be extremely rare, but lower mass B supergiants may be far more numerous. Because the initial mass function favours lower masses, and because of longer lifetimes at lower initial masses, B supergiants of 20–30 $M_{\odot}$ that just barely make the *V* mag cut and colour cut (perhaps legitimately, or by photometric error, see below) can outnumber the very rare 40–100 $M_{\odot}$ stars that fleetingly pass through this cooler phase in single-star models. (In other words, one might expect that most of the stars in the box are near the lower boundary of the box; this is tested and confirmed below.) Using the photometric criteria adopted by A19, there is no way to exclude these ∼20 $M_{\odot}$ B supergiants.

Expectations from single-star models versus a real population with binaries: A related complication has to do with expectations for contamination by cooler stars guided by single-star models. A19 expected that any B-type star contamination should be small, since they spend a very small fraction of their lifetime passing through the cooler end of the main sequence. A19 therefore assume that their colour–magnitude selection space should be dominated by the most massive unevolved stars at hotter temperatures. This expectation, however, depends on the assumption that single-star models adequately describe a real population of massive stars. A long-standing problem in massive star evolution has been the large observed number of blue supergiants (Fitzpatrick & Garmany 1990; Evans et al. 2007), which is not satisfactorily explained by the single-star models (Ekström et al. 2012) that A19 used for comparison. Binary models can produce larger numbers of long-lived blue supergiants at older ages as a result of mass transfer and mergers (Podsiadlowski, Joss & Hsu 1992; Eldridge, Izzard & Tout 2008; Vanbeveren et al. 2013; Justham, Podsiadlowski & Vink 2014; Eldridge et al. 2017; Menon & Heger 2017; Farrell et a. 2019). Contamination should therefore be higher than expected from considering only single-star models.

Bleeding from photometric errors: If the colour cut worked perfectly as intended, there would be only O-type stars in the BBS sample. However, one must also consider possible bleeding due to photometric errors, differences in reddening, or other effects. In this way it might be possible that even older and redder BSGs than the quoted colour cut could contaminate the BBS sample. To select their BBS sample from the *UBV* photometry of Zaritsky et al. (2004), A19 relied upon the so-called reddening-free index Q, defined as $Q = (U-B) - 0.72 \times (B-V)$. A19 chose to restrict the sample to $Q < -0.88$ mag, intending to select only stars hotter than about 35 000 K. If effective, this colour cut would correspond to O dwarf spectral types of O8.5 or earlier (Martins, Schaerer & Hillier 2002). As noted above, the actual differences in the intrinsic colour between an early or mid O-type star and an early B-star are very small (of order 0.02–0.03 mag in $B-V$, or about 0.05 mag in Q). A significant problem, however, is that this intrinsic colour difference is smaller than the photometric uncertainty and the corresponding colour uncertainty, making such a cut unreliable for the goal of selecting only the most massive unevolved stars. Zaritsky et al. (2002, 2004) quote zero-point uncertainties of 0.02 mag in B and V, and 0.03–0.04 mag in U, and they note typical rms scatters of $\sigma_U = 0.13$, $\sigma_B = 0.07$, and $\sigma_V = 0.06$ mag. These typical uncertainties, even in a single filter (and significantly worse in the resulting Q value or $B-V$ colour) are larger than the small colour differences one is trying to select against. Moreover, Zaritsky et al. (2004) note that stars in their catalogue that are brighter than 13.5 mag in B or V are prone to 'substantial photometric uncertainty' (or flaring of 0.1 mag or larger errors in various filters). This substantial uncertainty affects most of the stars in the BBS sample of A19, where the V mag cut-off was brighter than 13.9 mag. This would seem to compromise the ability to select the most massive unevolved stars by colour.

Concerning this last point, A19 attempted to guard against bad photometry by excluding stars with $Q < -1.2$ mag, being unphysically blue, as well as excluding $U-B > -0.5$ mag, and $B-V > 0.2$ mag. These criteria only prevent one from counting stars whose large errors yield unrealistic colours (and they may also exclude very massive stars that are highly reddened). They do not, however, guard against cases where a star's large photometric errors may shift it *inside* the colour–magnitude cut, even though its true temperature and luminosity may belong outside. The problem is that this type of contamination can be severe because the very massive stars that are the intended target of the photometric cuts are extremely rare, whereas they are vastly outnumbered by lower mass stars that should reside just outside the cuts (see below). As such, if even a small fraction of the stars outside the cut can bleed in, they can strongly influence the median age of the resulting sample.

4.2 Expected contamination by B stars

A19 conducted their analysis using the resulting photometric BBS sample, noting that they 'expect them all to be high-mass stars, primarily of O-type.' Below we argue, however, that quantitative tests of contamination were needed, because it is impossible to photometrically select only the hottest stars when colour differences are small compared to photometric errors or reddening variation. Moreover, some simple tests confirm that the BBS photometric sample should be heavily contaminated by an older population, and therefore unable to address the question of clustering and youth of LBVs.

Here we provide a brief illustration of the problem using O and B stars with known spectral types. We create a pseudo-BBS sample, drawing from O and early B stars with known spectral types from SIMBAD.[2] We use these known spectral types as a rough indicator of the true stellar temperature, to check against temperature inferred from photometric colours. As in Smith & Tombleson (2015), we take all O-type stars in the LMC with spectral types earlier than O9.5. For the early B-types, we take stars with spectral types between O9.5 and B2. Both classes are restricted to stars with apparent V magnitudes brighter than 13.9, as in A19, and we exclude stars within 10 arcmin of 30 Dor. In this resulting spectroscopically selected pseudo-BBS sample, the early B-type stars outnumber the O-type stars roughly 3–1, although the implications of this are unclear since we don't know the level of incompleteness for either.

Fig. 2 shows an HR diagram with the spectroscopic OB stars plotted without (left) and with (right) an average reddening correction of $E(B-V) = 0.13$ mag applied (the average value for OB stars in the LMC adopted by A19). Also shown for comparison are LBV stars in the LMC and SMC, plotted using $T_{\rm eff}$ and $L_{\rm Bol}$ values from the literature (see Smith et al. 2019), and single-star evolutionary tracks (Brott et al. 2011). OB stars are placed on this HR diagram by taking their apparent or reddening corrected $B-V$ colour as a proxy for temperature, and the luminosity comes from the V mag and a bolometric correction for the corresponding $T_{\rm eff}$ value, with relations adopted from Torres (2010) and Flower (1996). These are by no means intended to be taken as accurate $T_{\rm eff}$ and $L_{\rm Bol}$ values; they are meant to illustrate the range of these values one might infer from apparent magnitudes and colours when only photometry is available. The red diagonal lines in Fig. 2 indicate where the V mag cut-off resides. Even though these are not the same stars as in the photometric BBS sample, there are several salient points that one can glean from Fig. 2.

First, the true temperature (indicated by the spectral type) has little or nothing to do with the temperature inferred from photometric colours. O and early B stars are thoroughly mixed with one another in Fig. 2, and it is impossible to differentiate hotter O-type stars from cooler early B-type stars based on colour. The resulting range of temperatures is entirely a result of different reddening along

[2] http://simbad.u-strasbg.fr/simbad/

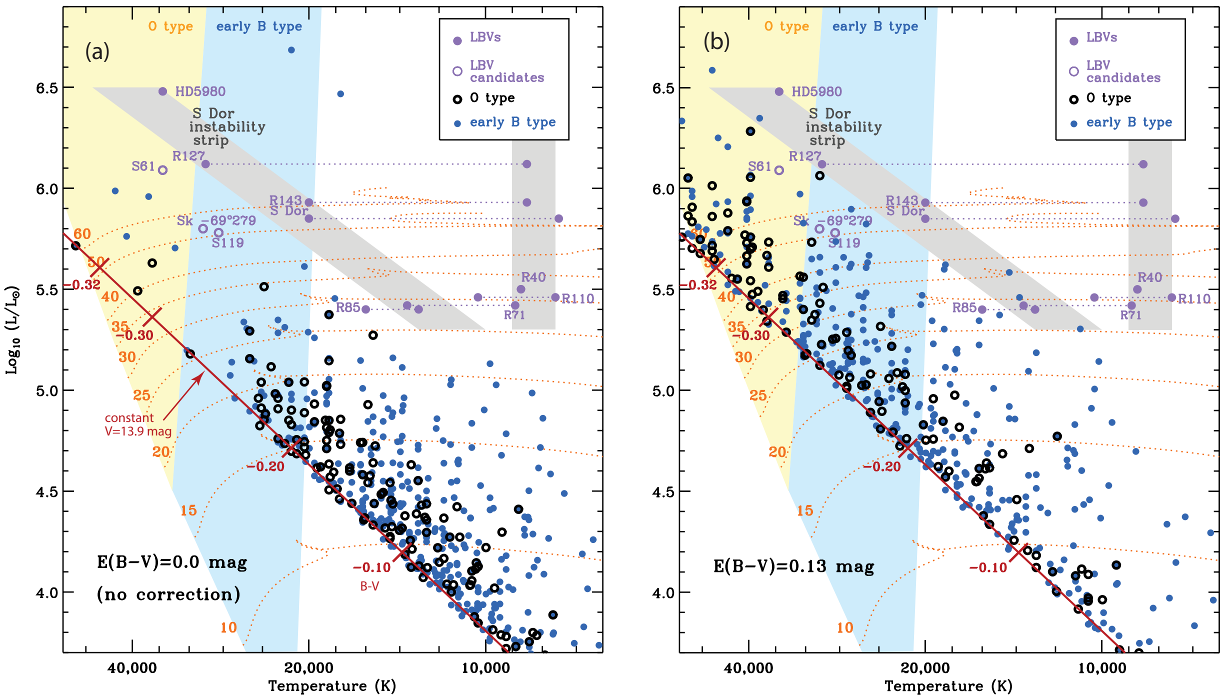

Figure 2. HR diagrams comparing LBVs to inferred properties of OB stars derived from photometric colours. The $T_{\rm eff}$ value used to plot each OB star is the temperature one would infer by converting the apparent $B - V$ colour to a temperature, and the luminosity comes from the bolometric correction for that $T_{\rm eff}$ value (relations adopted from Torres 2010 and Flower 1996) and its apparent V magnitude. The left-hand panel (a) shows the result when no reddening correction is adopted, whereas the right-hand panel (b) shows the values after applying a single average correction for $E(B - V) = 0.13$ mag to all OB stars. The black unfilled circles are spectroscopically confirmed O-type stars (similar to the sample in ST15), and the blue filled circles are spectroscopically confirmed early B-type stars, with spectral types between O9.5 and B2 (see text). Both samples are limited to spectroscopically confirmed O or early B stars brighter than $V = 13.9$ mag (to be consistent with the value adopted by A19), corresponding roughly to an absolute V magnitude of $M_V = -5$. The diagonal red line in each panel shows the cut-off of $V = 13.9$ mag, and the four red hash marks show temperatures corresponding to different values of $(B - V) = -0.32, -0.30, -0.20$, and -0.10 mag. In both panels, the orange dashed lines are single-star evolutionary tracks from Brott et al. (2011), with initial masses in $M_\odot$ labelled in orange. Light yellow and blue shaded areas indicate expected effective temperature and luminosity ranges for O-type and early B-type stars (Crowther, Lennon & Walborn 2006), respectively. LBVs with estimated $T_{\rm eff}$ and $L_{\rm Bol}$ values in the LMC and the S Doradus instability strip are included for reference, taken from Smith et al. (2019). The main point of this figure is to demonstrate that the resulting $T_{\rm eff}$ value that one infers from the apparent $B - V$ colour has little to do with the star's true temperature; it is mainly determined by reddening (or lack thereof), since all these stars have small differences in their intrinsic $B - V$ colour, but a relatively large spread in $E(B - V)$ from one object to the next. Different values of reddening, whether corrected by a single average $E(B - V)$ value or with no correction (panels *b* and *a*, respectively), lead to a huge spread in the inferred temperature that is much larger than the true temperature range of these spectroscopicaly selected O and early B-type stars (shaded yellow and blue areas). Importantly, when applying a single reddening correction to all, it is inevitable that many cooler stars (B stars) will be artificially shifted into the O star regime, and will therefore contaminate any colour-selected sample of the bluest stars. Note that the majority of stars that make the V mag cut are close to that cut-off, and not in the region of >40 $M_\odot$ stars.

individual lines of sight, plus photometric error. Adopting a single average value for the reddening is clearly invalid, and applying such a reddening correction simply shifts both swarms of O and B stars to higher inferred temperatures and luminosities. One would infer from Fig. 2 that a colour selection of the bluest stars would result in a sample that is split between O and early B stars (this is indeed the case for the BBS sample, see below), if not dominated by early B-type stars.

Secondly, Fig. 2 confirms that the V mag cut-off does not reliably select the most massive stars. Among OB stars that make the V mag cut, many are concentrated near the faint cut-off. If we were to deredden the early B-type stars to their appropriate temperatures of 20–30 kK, they would mostly land along evolutionary tracks for 20–30 $M_\odot$ stars, not >40 $M_\odot$ stars. Without spectra, there is no way to reliably estimate the star's temperature and luminosity at the precision needed to distinguish a cooler 20–30 $M_\odot$ B supergiant star from a hotter and more massive O-type star. Using visual-wavelength colour–magnitude cuts to produce a sample of the most massive unevolved stars is therefore invalid for the purpose of testing LBV evolution.

Fig. 2 also presents a cautionary tale against using apparent $B - V$ colours alone as a proxy for temperature.[3] While all O and early B stars have nearly identical intrinsic $B - V$ colours, much larger differences in reddening from one star to the next of only 0.1 mag or more in $E(B - V)$ can lead to a gigantic spread in the inferred temperature that crosses much of HR diagram in Fig. 2. OB associations in the LMC have a wide range of different reddening values, even varying significantly among individual OB stars in the same association (Lucke 1974). Selecting by blue colour and bright V mag will favour those with the least reddening, not necessarily the hottest, youngest, or most luminous stars. This could potentially yield a systematic bias against the highest mass stars, and to instead preferentially select older, lower mass, evolved blue supergiants in a population. This is because evolved BSGs with longer lifetimes

[3] A19 used a Q parameter selection as noted above, so the rest of this paragraph does not apply specifically to that study. However, some studies of stellar populations use only $B - V$ or $V - I$, for example, to infer properties about the stellar population.

are more likely to have cleared away or drifted away from their surrounding natal clouds, and may therefore have bluer apparent colours because of lower reddening. The youngest and most massive stars, which have essentially the same intrinsic $B - V$ colour, are more likely to still be partly embedded, and therefore more reddened by dust from their surrounding natal environment that has not yet cleared away (Blanco & Williams 1959; Reddish 1967; Yadav & Sagar 2001).

4.3 Confirmed contamination by B stars

So far this evaluation has been hypothetical; i.e. considerations for why there *could be* or *should be* contamination of a photometrically selected sample of bright blue stars. In fact, it has already been demonstrated observationally that the photometric BBS sample is strongly contaminated by cooler B supergiant stars. A19 noted that among their BBS sample, about half the stars have known spectral types available, while the other half have no spectral types. Of those BBS stars with available spectra, slightly less than half are O stars (135 stars, or 49 per cent) and slightly more than half are early B stars (140 stars, or 51 per cent). So although the intent of the colour selection was to include only massive stars hotter than $T_{\rm eff} = 35$ kK (corresponding to dwarfs of type O8.5 and earlier, as noted above), the BBS sample nevertheless includes many cooler stars (early B supergiants have $T_{\rm eff}$ values of roughly 20–30 kK; Crowther et al. 2006, 2008).

For B-type stars included in the BBS sample, A19 assumed that these would be limited to the most massive stars near the end of the main sequence due to the bright *V* mag cut-off. However, examining Fig. 2, it is clear that most of the early B stars that satisfy the *V* mag cut and would make it into the sample, by number, are not the most massive stars that are at the end of the main sequence. Instead, most are stars clustered near the *V* mag cut-off that just barely pass the cut. These are overwhelmingly lower mass evolved BSGs. This contamination dramatically alters the resulting distribution of separations. Overlooking this contamination undermines the analysis, as demonstrated below.

Moreover, even for those spectroscopically confirmed O stars in the BBS sample, a majority might be later O-types (O8, O9), which make up the majority of O stars by number. This distinction is important, since later O type stars can have much longer lifetimes and may come from lower initial masses than early O types, as seen from the breakdown of separations for late versus early O subtypes (Smith & Tombleson 2015). Similarly, most of the spectroscopically confirmed O-type stars that satisfy the *V* mag cut in Fig. 2 are at the low-luminosity boundary near the *V* mag cut-off, not in the region corresponding to >40 M$_\odot$ stars.

Interestingly, examining table 1 from Smith & Tombleson (2015), the nearest or second nearest spectroscopically selected O-type star to each LBV is, in the vast majority of cases, a late-type O star (O8/O9) and not an early O-type star. Since the median separation of LBVs is the same for the spectroscopic O sample (Smith & Tombleson 2015) and the photometric BBS sample (A19), we can surmize that these nearest neighbours are in many cases the same stars.

5 CONTAMINATION EXPLAINS THE BBS SEPARATION DISTRIBUTION

From the discussion above, it is clear that the BBS sample is contaminated by older, evolved B supergiant stars, rather than being restricted to only the most massive unevolved main-sequence stars that the sample was intended to trace. The next question to ask is whether such contamination could plausibly explain the observed large separation distribution of BBS stars that A19 found. One can address this by asking the pertinent question: What does the distribution of projected separations on the sky look like for stars that we know are cooler, evolved B-type supergiants? How does it compare to the BBS sample and to O-type stars?

One can test this by considering a sample of stars that are known to be early B supergiants because they are confirmed by spectroscopy. A sample of spectroscopically confirmed early B supergiant stars in the LMC was extracted from SIMBAD, as noted above, the same way that Smith & Tombleson (2015) produced spectroscopically confirmed samples of O-type stars. We chose this 'early B' sample to include LMC stars with spectral types later than O9.5 and up to B2, of any luminosity class. This range was chosen because their small differences in intrinsic colour compared to O-type stars would pass the selection criteria of A19, especially considering photometric errors. The spectroscopic sample was also restricted to an apparent *V* magnitude cut-off brighter than 13.9 mag, to be consistent with the BBS sample of A19, and therefore selects primarily B supergiants. With $T_{\rm eff}$ values as low as 20 kK, this sample will include a large number of evolved B supergiants with initial masses around 20 M$_\odot$, and possibly even down to 15 M$_\odot$. This sample of early B supergiants is plotted alongside spectroscopically confirmed O-type stars in Fig. 2. Importantly, one can see from Fig. 2 that only a handful of these B supergiants are luminous enough to be late-main-sequence stars of >40 M$_\odot$; the vast majority of the early B supergiants that make the *V* mag cut are consistent with less massive stars (15–30 M$_\odot$ single-star tracks) and are therefore older than presumed single-star progenitors of LBVs.

The resulting cumulative distribution of separations for these early B stars is shown in Fig. 1. The black cumulative distribution in Fig. 1 is for this sample of spectroscopically confirmed early B-type stars, where the separation is measured to the nearest other early B star in the same sample (not the nearest O star). Note that, pertinent to the discussion in Section 3 above, the *dashed* black distribution is for all the known early B stars in this sample, whereas the *thick solid* black distribution excludes stars within 10 arcmin of 30 Dor (to be consistent with A19). There is little difference, because B supergiants are not clustered on small scales.

The most interesting result here is that the separation distribution of this sample of spectroscopically confirmed early B supergiants matches that of the photometric BBS sample (shown in magenta in Fig. 1) from A19. One may debate if the potential sources of bias and contamination discussed above are actually to blame, or if some other effects are important. But whatever the exact reason, the outcome confirms that the photometric BBS separation distribution is characteristic of an older population than expected for LBVs, because its median separation is identical to stars that are spectroscopically confirmed to be cooler, evolved, lower mass stars. The BBS separation distribution is clearly incompatible with confirmed early O-type stars that are known to be the most massive unevolved stars.[4] Thus, one may conclude that contamination by older stars is the dominant explanation for the large median separation of the BBS sample and its consequent similarity to LBVs.

[4]Note that the resulting large separation distribution of spectroscopically confirmed early B-type stars in Fig. 1 would seem to contradict the presumption that past efforts to obtain spectral types have been heavily biased toward clustered regions. It was already demonstrated in Section 2 that any such incompleteness in the spectroscopic sample does not impact the result.

In other words, the similarity between the BBS and LBV separation distributions arises because the photometric BBS sample is old, not because the LBVs are young.

Although harder to demonstrate in the same way as above for the LMC, it is quite likely that the same conclusion about the age of bright blue stars applies to the BBS samples for M31 and M33 that A19 discussed. For BBS stars in M31/M33, A19 found a median separation of 65 pc, indicating that this BBS sample clearly does not trace a clustered reference population either. The M31/M33 sample from ground-based photometry may also have the added drawback of inadequate angular resolution to trace clustered young stars. Since it is not tracing clustered stars, it fails the requirement to use spatial dispersal on the sky as a relative age indicator. Those M31/M33 distributions are therefore similarly not indicative of LBV youth.

6 WR AND WN3/O3 STARS

As noted above in Section 2, one of the key requirements for the separation distribution method to work as an age indicator is that the reference population *must* be tracing a clustered population. If the reference sample is not clustered, then the resulting separation distribution is simply not measuring a relative age. Consider the alternative in the following *gedanken*-experiment: Imagine an evenly spaced grid of blue stars that is distributed over a portion of the sky with adjacent stars each separated by $\sim$30 pc. Now randomly drop in a less numerous population of stars (either WR stars or LBVs, for example) and measure the resulting separation distribution. One will find that the separation between WR stars and the nearest blue stars, or the separation between LBVs and the nearest blue star, will both also tend to be around 30 pc. This is not providing information about the relative clustering or youth of the WR stars or the LBVs; it is merely indicating the typical separation between one blue reference star and the next (i.e. one cannot find a median separation from a WR star or LBV to a blue star much different from 30 pc, because that is the grid spacing). With a dispersed sample serving as the comparison, distributions get squeezed together on a separation plot because the test is not precise enough to distinguish differences in age.

This explains why A19 found BBS stars, LBVs, and WR stars to all have roughly the same separation distribution (see their Fig. 2). A19 noted that a KS test showed no statistical difference between them. Rather than indicating that all three groups are young and consistent with the evolution of the most massive single stars, this similarity is merely tracing the typical separation between BBS stars themselves. If a clear difference in separation distribution is not revealed by this comparison, then it is incorrect to conclude that the samples are all equally young – one may only conclude that the test is not precise enough. A19 did find a significant difference in the resulting separation distribution of RSGs, but this is probably because RSGs with typical initial masses of only 9 $M_{\odot}$ in their sample are much older than the BBS stars, and tend to occupy regions of the LMC where most blue supergiants are long-since dead.

This issue of how weak clustering in the reference sample will undermine the outcome also resolves a recent debate in the literature about WN3/O3 stars based on their separation distribution on the sky. WN3/O3 stars are a subclass of WR stars found in the LMC, which, like typical WR stars in the SMC, have transitional spectra with both emission and absorption lines (Massey et al. 2014).

Using the same methodology that Smith & Tombleson (2015) used for LBVs, Smith, Götberg & de Mink (2018) examined the distribution of separations between WN3/O3 stars and spectroscopically confirmed O-type stars in the LMC. They found that WN3/O3 stars are extremely isolated from clustered O stars (even more so than LBVs), having a distribution on the sky similar to 15–20 $M_{\odot}$ RSGs. This makes it unlikely that WN3/O3 stars are very massive stars that have evolved as rapidly rotating single stars through quasi-chemically homogeneous evolution or wind mass-loss. Instead, Smith et al. (2018) proposed that they arise from moderately massive (15–20 $M_{\odot}$) progenitors that have had their H envelopes stripped through interaction with a lower mass companion star. Götberg et al. (2018) demonstrated that such stars arise naturally in a grid of binary evolution models with model atmospheres. They occur in a transitional zone at the low-mass and low-luminosity end of the range of normal WR stars that form in binaries, where winds are still dense enough to have emission lines, but are thin enough to also see absorption lines in the underlying hot photosphere. At LMC metallicity, these stars are expected to arise from initial masses around 15–20 $M_{\odot}$ (Götberg et al. 2018), in good agreement with the observed spatial distribution of WN3/O3 stars (Smith et al. 2018). As such, the WN3/O3 stars would be of interest as candidates for common progenitors of stripped-envelope SNe.

A debate that echoes the one over LBV separation and ages also arose for these WN3/O3 stars. Neugent, Massey & Morrell (2018) re-examined the separation distribution of WN3/O3 stars by comparing them to a photometrically selected sample of bright blue stars, and much like A19 with LBVs, found them to be less isolated from these stars than when they are compared to spectroscopically confirmed O-type stars (Smith et al. 2018). Neugent et al. (2018) also chose a photometrically selected comparison sample of bright blue stars from the same Zaritsky et al. (2004) photometric catalogue; their selection criteria were similar to the criteria adopted by A19, although somewhat more relaxed (with $V < 15$ mag instead of $V < 13.9$ mag, and less restrictive colours with $Q < -0.80$ mag instead of $Q < -0.88$ mag, for example).

One might anticipate that the photometric comparison sample of blue stars used by Neugent et al. (2018) falls victim to the same pitfalls as the BBS sample used by A19, for the same reasons discussed above. First, it will be contaminated by less massive B supergiants with initial masses around 15–20 $M_{\odot}$, similar to the proposed binary initial masses of WN3/O3 stars (Smith et al. 2018). The contamination by lower mass B supergiants is likely to be even more severe than the BBS sample of A19, because the BBS sample from Neugent et al. (2018) goes a magnitude fainter in V and accepts redder stars. Secondly, this photometric sample of blue stars is also not clustered, and therefore cannot be used to test relative ages. Neugent et al. (2018) found that their comparison to photometric blue star locations yielded separations for WN3/O3 stars (156 arcsec or 37 pc) that were statistically indistinguishable in a KS test from those of classical early WN stars (110 arcsec or 26 pc). These are both similar to the median separation between BBS stars and other BBS stars of 31 pc (A19). Following the same explanation as discussed above for the BBS sample of A19, the likely reason that these distributions are all so similar is because the measured separation distributions of WR stars are limited by the typical separation amongst the unclustered blue stars themselves.

7 SUMMARY AND DISCUSSION

Using the dispersal on the sky can be a powerful way to rank relative ages of different classes of stars and to discriminate between single and binary evolution channels, but this particular method only works as an age indicator if one is comparing to a reference population that (1) is known to be young and (2) is highly clustered. If both of these criteria are not clearly met, then the results of the comparison are invalid. The method relies upon the assumption that massive stars begin their lives mostly in clusters, and that their relative separation increases with time because clusters disperse and the most massive stars die quickly.

This method was initially used to demonstrate that LBVs are more isolated than they should be in the traditional scenario where they have massive single-star progenitors. The proposed reason was either because they have received kicks from a companion's SN, or because they have been rejuvenated by mass transfer or mergers in binaries (Smith & Tombleson 2015; Smith 2016; Aghakhanloo et al. 2017). Either case requires that LBVs are mainly a product of close binary evolution. This was inferred using spectroscopically confirmed O stars as a tracer of clustered young stars, revealing that LBVs clearly do not reside in the same places in the sky as known O-type stars.

A19 recently conducted a similar type of study, but drew the opposite conclusion for LBVs – i.e. that their distribution on the sky does not contradict a single-star evolutionary scenario. This was because A19 found the separation distribution of LBVs to be not too different from that of a photometrically selected BBS sample. Arriving at this interpretation, A19 assumed that the photometric BBS sample was reliably tracing the most massive unevolved stars, so that the similar separation distribution of LBVs would imply that LBVs are not so old. On the other hand, if the BBS sample was tracing older stars, then one draws the opposite conclusion.

The preceding sections of this paper have discussed ways in which the single-star interpretation is problematic, largely because the two key critieria for this type of study to work (outlined above in Section 2) are not met by the photometric BBS sample:

(1) First, the stars in the BBS sample are not confidently known to be young, because *UBV* photometric colour selection does not provide a robust way to separate the youngest, hottest, and most massive O stars from older, somewhat evolved, less massive B and late-O supergiants. This is because they all have similar intrinsic colour. Differences in intrinsic colour are less than effects of reddening and photometric errors. Being able to make this distinction reliably is, however, critical to the interpretation, because it links to the difference between single and binary progenitor scenarios for LBVs. If LBVs descend from massive single stars, they should have ages similar to the most massive unevolved early O-type stars. If LBVs descend from lower mass binaries that experience rejuvenation though mass transfer or mergers, then they should have a true age that is similar to the lower mass B and late-O supergiants. If LBVs have a separation distribution that is similar to a photometric BBS sample, then one's conclusion can flip depending on whether or not the BBS sample is really dominated by the youngest most massive stars. In fact, it is clear that the BBS sample is contaminated at a substantial level, because among the half of the BBS sample with available spectra, more than half of these are B supergiants (many of the remainder are probably late-O supergiants). This confirms that substantial contamination by older stars has occurred, despite the intent of restrictive photometric selection. This is at least partly due to the fact that the photometric errors were larger than intrinsic colour differences.

(2) Secondly, the stars in the BBS sample are not highly clustered, and so they cannot be used as a reliable reference for diagnosing youth. The median separation from a BBS star to its nearest neighbour in the LMC is 31 pc (or 65 pc for BBS stars in M31/M33), meaning that the BBS sample is not concentrated in young dense clusters, as O stars are known to be. Less than 4 per cent of the BBS sample has a separation commensurate with being in young massive clusters, whereas the spectroscopic O-star sample matches expectations for young O stars. Instead, the distribution of BBS stars is matched well by the observed separation distribution of spectroscopically confirmed early B supergiants. This gives a strong confirmation that whatever the intent, the photometric BBS sample ends up tracing the separation distribution of an older population of evolved, lower mass stars, and not the presumed massive single-star progenitors of LBVs. Invoking incompleteness of the spectroscopic O-star sample does not explain why the BBS sample is so unclustered.

Overall, LBV environments match quite well expectations for binary evolution, where LBVs are massive blue stragglers produced either by mass accretion from companion and possible kicks, or by rejuvenation in stellar mergers (Gallagher 1989; Kenyon & Gallagher 1989; Lortet 1989; King 2000; Smith & Tombleson 2015; Smith 2016; Aghakhanloo et al. 2017). If one is willing to accept the notion that close binaries are so common that they may dominate the evolutionary paths of massive stars (Paczynski 1961; Sana et al. 2012; de Mink et al. 2014; Eldridge et al. 2017; Moe & Di Stefano 2017), then this result is not so surprising. Quantitatively, the median separation of the BBS sample matches expectations from a simple dispersing cluster model for ages of 9–10 Myr (Aghakhanloo et al. 2017), and it matches the observed separation distribution of known B-type supergiants, as noted above. LBVs have a similar separation distribution indicating that they are this old as well, or older. This could not be the case if LBVs occur immediately after the main sequence in massive stars with lifetimes of only 3–4 Myr.

More broadly, the analysis above offers a cautionary tale when analysing photometric samples of bright blue stars in resolved stellar populations. The typical bright blue star is more likely to be an evolved, moderately massive blue supergiant (akin to the $\sim$18 $M_{\odot}$ progenitor of SN 1987A; Arnett et al. 1989) and is less likely to be a very young, very massive main-sequence O-type star. Both types of stars have almost the same intrinsic colours and magnitudes at visual wavelengths, but those with earlier spectral types, higher luminosity, and higher initial mass are disfavoured by number due to the initial mass function and shorter lifetimes. Similarly, in more distant galaxies with unresolved stellar populations, this implies that a blue colour in surrounding galaxy light will tend to favour an age of 10–15 Myr, rather than a very young population around 3–4 Myr. Bluer does not necessarily mean younger. This is important for interpreting the relative ages and initial masses we associate with different SN types based on their surrounding host colour, for example (Kelly & Kirshner 2012). As has been suggested for the progenitor of SN 1987A (Podsiadlowski 2010), many of these BSGs that produce the blue light in stellar populations may be products of binary interaction (mergers and mass gainers, producing blue stragglers), and they may therefore be more common than one might expect from a single-star population. Anecdotally, it is interesting to note that the most distant multiply lensed SN that has been detected was an SN 1987A-like event from a BSG (Kelly et al. 2016), and the most distant individual lensed star (in that same host galaxy) appears consistent with a BSG (Kelly et al. 2018).

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REFERENCES

Aadland E., Massey P., Neugent K. F., Drout M. R., 2019, AJ, 156, 294 (A19)
Aghakhanloo M., Murphy J., Smith N., Hlozek R., 2017, MNRAS, 472, 591
Arnett W. D., Bahcall J. N., Kirshner R. P., Woosley S. E., 1989, ARA&A, 27, 629
Beasor E. R., Davies B., Smith N., Bastian N., 2019, MNRAS, 486, 266
Blaauw A., 1961, Bull. Astron. Inst. Neth., 15, 265
Blaauw A., 1964, ARA&A, 2, 213
Blagovest P., Vink J. S., Gräfener G., 2016, MNRAS, 458, 1999
Blanco V. M., Williams A. D., 1959, ApJ, 130, 482
Bouret J. C., Lanz T., Hillier D. J., 2005, A&A, 438, 301
Brott I. et al., 2011, A&A, 530, A115
Conti P. S., 1976, Mem. Soc. R. Sci. Lie'ge, 9, 193
Crowther P. A., Lennon D. A., Walborn N. R., 2006, A&A, 446, 279
Crowther P. A., Lennon D. A., Walborn N. R., Smartt S. J., 2008, ASP Conf. Ser., 388, 109
de Koter A. et al., 2011, J. Phys. Conf. Ser., 318, 012022
de Mink S. E., Sana H., Langer N., Izzard R. G., Schneider F. R. N., 2014, ApJ, 782, 7
Ekström S. et al., 2012, A&A, 537, A146
Eldridge J. J., Izzard R. G., Tout C. A., 2008, MNRAS, 384, 1109
Eldridge J. J., Langer N., Tout C. A., 2011, MNRAS, 414, 3501
Eldridge J. J., Stanway E. R., Xiao L., McClelland L. A. S., Taylor G., Ng M., Greis S. M. L., Bray J. C., 2017, Publ. Astron. Soc. Aust., 34, e058
Evans C. J., Lennon D. J., Dufton P. L., Trundle C., 2007, A&A, 464, 289
Farrell E. J., Groh J. H., Meynet G., Kudritzki R. P., Eldridge J. J., Georgy C., Ekstrom S., Yoon S. C., 2019, A&A, 621, A22
Fitzpatrick E. L., Garmany C. D., 1990, ApJ, 363, 119
Flower P. J., 1996, ApJ, 469, 355
Fullerton A. W., Massa D. L., Prinja R. K., 2006, ApJ, 637, 1025
Gallagher J. S., 1989, in Davidson K., Moffat A. F. J., Lamers H. J. G. L. M., eds, Physics of Luminous Blue Variables. Kluwer, Dordrect, p. 185
Garmany C. D., Conti P. S., Chiosi C., 1982, ApJ, 263, 777
Gies D. R., 1987, ApJS, 64, 545
Götberg Y., de Mink S. E., Groh J. S., 2017, A&A, 608, 11
Götberg Y., de Mink S. E., Groh J. S., Kupfer T., Crowther P. A., Zapartas E., Renzo M., 2018, A&A, 615, A78
Groh J. S., Meynet G., Georgy C., Ekström S., 2013a, A&A, 558, A131
Groh J. S., Meynet G., Ekström S., 2013b, A&A, 550, L7
Harris J., Zaritsky D., 2009, AJ, 138, 1243
Heger A., Fryer C. L., Woosley S. E., Langer N., Hartmann D. H., 2003, ApJ, 591, 288
Humphreys R. M., Weis K., Davidson K., Gordon M.S., 2016, ApJ, 825, 64
Justham S., Podsiadlowski P., Vink J. S., 2014, ApJ, 796, 121
Kelly P. L., Kirshner R. P., 2012, ApJ, 759, 107
Kelly P. L. et al., 2016, ApJ, 831, 205
Kelly P. L. et al., 2018, Nat. Astron., 2, 334
Kenyon S. J., Gallagher J. S., 1989, ApJ, 290, 542
King N. L., 2000, PhD thesis, NMSU
Langer N., Hamann W. R., Lennon M. D., Najarro F., Pauldrach A. W. A., Puls J., 1994, A&A, 290, 819
Lortet M. C., 1989, in Davidson K., Moffat A. F. J., Lamers H. J. G. L. M., eds, Physics of Luminous Blue Variables. Kluwer, Dordrect, p. 45
Lucke P. B., 1974, ApJS, 255, 28
Lynds B. T., 1980, AJ, 85, 1046
Martins F., Schaerer D., Hillier D. J., 2002, A&A, 382, 999
Massey P., Lang C. C., Degioia-Eastwood K., Garmnany C. D., 1995, ApJ, 438, 188
Massey P., Neugent K. F., Morrell N., Hillier D. J., 2014, ApJ, 788, 83
Menon A., Heger A., 2017, MNRAS, 469, 4649
Meynet G., Maeder A., 2003, A&A, 404, 975
Meynet G., Georgy C., Hirschi R., Maeder A., Massey P., Przybilla N., Nieva M. F., 2011, Bull. Soc. R. Sci. Lie'ge, 80, 266
Moe M., Di Stefano R., 2017, ApJS, 230, 15
Neugent K. F., Massey P., Morrell N., 2018, ApJ, 863, 181
Owocki S. P., Gayley K. G., Shaviv N. J., 2004, ApJ, 616, 525
Paczynski B., 1961, Acta Astron., 17, 355
Podsiadlowski P., 2010, New Astron. Rev., 54, 39
Podsiadlowski P., Joss P. C., Hsu J. J. L., 1992, ApJ, 391, 246
Reddish V. C., 1967, MNRAS, 135, 251
Renzo M. et al., 2019, A&A, 624, A66
Sana H. et al., 2012, Science, 337, 444
Schneider F. R. N. et al., 2014, ApJ, 780, 117
Smith N., 2014, ARA&A, 52, 487
Smith N., 2016, MNRAS, 461, 3353
Smith N., Arnett D., 2014, ApJ, 785, 82
Smith N., Owocki S. P., 2006, ApJ, 645, L45
Smith N., Tombleson R., 2015, MNRAS, 447, 598
Smith N., Li W., Silverman J. M., Ganeshalingam M., Filippenko A. V., 2011, MNRAS, 415, 773
Smith N., Götberg Y., de Mink S. E., 2018, MNRAS, 475, 772
Smith N., Aghakhanloo M., Murphy J. W., Drout M. R., Stassun K. G., Groh J. H., 2019, MNRAS, 88, 1760
Torres G., 2010, AJ, q40, 1158
Vanbeveren D., Mennekens N., Van Rensbergen W., De Loore C., 2013, A&A, 552, A105
Yadav R. K. S., Sagar R., 2001, MNRAS, 328, 370
Zaritsky D., Harris J., Thompson I. B., Grebel E. K., Massey P., 2002, AJ, 123, 855
Zaritsky D., Harris J., Thompson I. B., Grebel E. K., 2004, AJ, 128, 1606

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