The Binary Origins of OBe Stars in the Small Magellanic Cloud

Matthew M. Dallas and M. S. Oey
Department of Astronomy, University of Michigan, 1085 South University Ave., Ann Arbor, MI 48109-1107, USA

Originally formatted as an iposter for AAS 239

Abstract

Classical OBe stars are rapidly rotating OB stars with emission lines produced in a decretion disk. The origins of the fast rotation and subsequent disk are not yet well understood. In this work we add to the growing evidence that OBe stars form from massive binary systems. The model proposes that OBe stars gain angular momentum if their massive binary companion evolves to fill its Roche lobe. These close binary interactions should result in OBe stars residing farther into the field on average than OB stars, because mass transfer can prolong the life of the OBe star, allowing it to drift longer in the field; or, the companion’s supernova can impart a runaway velocity on the OBe star. To test for this effect, we analyse the distances between OBe stars and their nearest O stars in the Small Magellanic Cloud. These distances serve as an effective measure of how far into the field each star resides. We find that OBe stars reside at a median distance of 36 ± 3.3 pc into the field vs 22 ±1.8 pc for OB stars, consistent with the expectation that post-mass-transfer objects are more isolated. Furthermore, the Oe and Be populations themselves are equally isolated in the field, with Oe stars residing at 34 ± 9.4 pc into the field and 39 ± 5.0 for Be stars. This is to be expected if their birth masses are obscured by mass transfer. We note that OBe stars and high-mass X-ray binaries (HMXBs) are closely related, with 39/49 HMXBs in the sample being OBe stars. These HMXBs have a median distance of 48 ± 6.5 pc, which further supports the scenario that most OBe stars are post-binary supernova objects released into the field. Finally, we show that supergiant OBe stars, which are known to not have formed via binary interactions, have a spatial distribution consistent with OB supergiants rather than non-supergiant OBe stars. Our analysis therefore finds multiple lines of evidence supporting the binary formation model of OBe stars, which has implications ranging from binary population models to gravitational wave astronomy.

Background

Classical OBe stars are non-supergiant OB stars that exhibit Balmer emission lines in their spectra, first observed in 1830. The emission lines result from circumstellar disks that are expelled by near-critical stellar rotation (e.g., Rivinius et al. 2013), and how the stars obtained their fast rotation is not well understood.

The focus of this research is to test the model that these circumstellar disks form from the transfer of mass and angular momentum in massive binaries (Kříž & Harmanec 1975). In the binary model for OBe stars, the more massive primary fills its Roche lobe and becomes a mass donor to the companion, thereby increasing the mass gainer's angular momentum enough to generate the decretion disk. Massive donors later explode as supernovae, accelerating the mass gainers and often unbinding them from star clusters in a binary supernova ejection (e.g., Blaauw 1961).

If OBe stars form in binary systems as described above, their enhanced transverse velocities would cause them to be more isolated than they would be in single-star models for the OBe phenomenon. The work presented here confirms that OBe stars in the Small Magellanic Cloud (SMC) are more isolated than non-OB stars, strongly supporting this model.

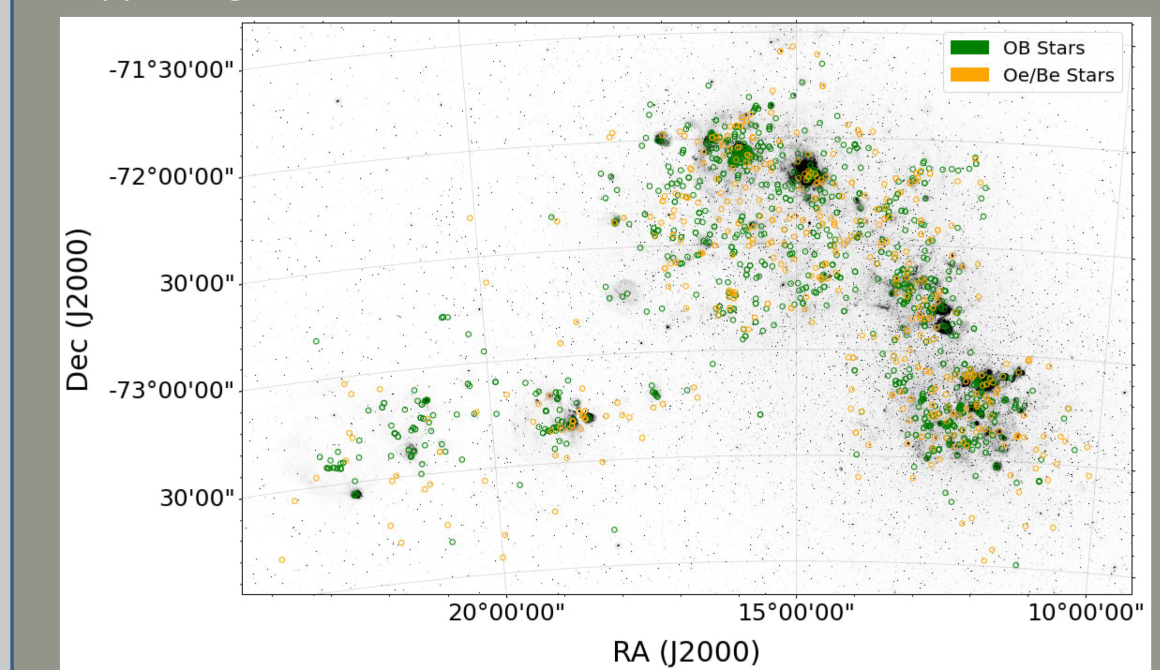

Figure 1 – Hα image of the SMC (Smith et al. 2005) with positions of OB and OBe stars indicated in green and orange respectively.

We show in Figure 1 a plot of the positions of the stars in our sample on the sky, with OB stars in green and the OBe stars in orange. Without any quantitative analysis Figure 1 shows that OBe stars have a greater spatial extent than OB stars, which is particularly evident in the southern regions of the map.

Results

Figure 2 below plots the the cumulative distribution function (CDF) of the projected separations between different types of massive stars in the SMC and their nearest O-stars that are not Oe, HMXB or supergiant.

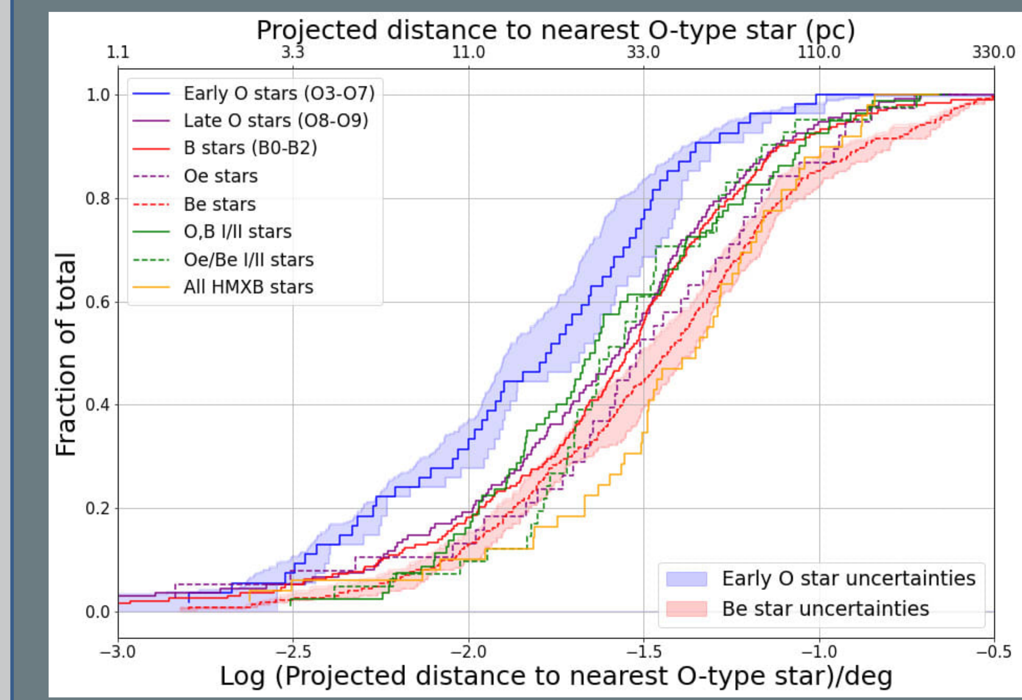

Figure 2 – Cumulative distribution functions of distances to the nearest O-type star for the shown populations. The top and bottom axes show separation in pc and degrees, respectively. These are obtained by first constructing the maximum CDF using all stars in a given population, including those with uncertain spectral types; and second, only stars with spectral types that are not reported to be uncertain. This range is shown by the shaded regions for the O and Be star populations as representative examples. The adopted CDFs are then the medians between these extremes.

The main results from this plot are:

- OBe stars reside consistently further into the field than both OB stars and evolved OB supergiants.
- The Oe population and the Be population CDFs reside in the same locus.
- OBe stars approach the high-mass X-ray binaries (HMXBs), a known post-SN binary population, in degree of separation.
- OBe supergiants are found at the same distances as OB supergiants and not with the other OBe stars. This is consistent with an evolved population that has a different origin for the emission lines, which are believed to form in the stellar winds rather than a decretion disk (Puls et al. 2008).

These trends are supported by Mann-Whitney statistics, which test for difference in location of distributions.

- The p-values for comparing the Late O vs Oe and B vs Be CDFs are 0.089 and 0.005, respectively. In contrast, $p > 0.5$ for both Late O vs B, and Oe vs Be.
- The p-value comparing both the Oe and Be CDFs with HMXBs is 0.28.
- The p-value comparing OBe supergiants to OB supergiants is 0.33, compared to 0.05 when comparing OBe supergiants to regular OBe stars

Methodology

Smith & Tombleson (2015) measured the relative isolation of luminous blue variables to demonstrate that they are likely mass gainers that are "kicked" into the field by supernova ejections. We apply the same spatial analysis to test whether OBe stars systematically avoid clusters compared to non-emission line stars. We compile the cumulative distribution function (CDF) of the projected separations between OBe stars and their nearest O stars, and we compare with the non-OBe stars. Since we expect O stars to not travel far from their birth clusters, the distance to the nearest O star effectively measures the relative isolation of the target star.

We use the Oey et al. (2004, hereafter OKP) sample of massive stars in the SMC with spectral types earlier than ~B2. This sample is photometrically selected, based on the *UBVI* survey of Massey (2002), and it is spatially complete over most of the star-forming body of the SMC.

Existing OB spectral types are obtained from spectroscopic data compiled in the SIMBAD database, primarily from the SMC surveys of Lamb et al. (2016), Massey (2002), and Evans et al. (2004). In the rare cases where there were two conflicting spectral types reported for a given star, the type with the highest spectral resolution was chosen; if more than two spectral types were found, the most frequently identified type was adopted. Stars with no published spectral type are retained as OB candidates. OKP OBe stars not identified from the main spectroscopic surveys above were mostly identified from Meyssonnier & Azzopardi (1993), who carried out a spatially complete, objective prism survey of the entire SMC, targeting Hα emission-line objects down to a photographic magnitude of 18 in the continuum. If a star was listed in Meyssonnier & Azzopardi (1993) as an emission-line object, and was given a spectral type of O or B in a different catalog, it was included in the Oe and Be star lists, respectively. Table 1 presented in the Discussion section provides the number of stars identified for each spectral type.

Since Lamb et al. (2016) obtained spectra of nearly all the field stars, the parent OKP sample has a strong bias for available spectral types in the field relative to groups, using the definition of "group" stars as stars within 28 pc of another as adopted in OKP. However, what matters here is whether there is a *relative* bias against OKP OBe detections in clusters compared to field. Comparison with the Evans (2004) survey shows no evidence of such a bias, especially considering that the survey specifically considers the rich clusters NGC 330 and 346. In fact, based on data for these clusters we find that there is a slight bias towards overdetecting OBe stars in groups, rather than vice versa.

Further Analysis

Table 1 below presents the breakdown of our sample as well as the numerical results. Almost all the OB stars with uncertain classifications (rows 4, 7, and 8) are in groups, rather than field; and moreover they constitute almost half of our entire OB sample. However, since the OKP sample is based on uniform photometric selection of OB stars, the main uncertainty is in the spectral classifications, which is accounted for with our method of determining the CDFs, as described in the caption to Figure 2. As shown by Aadland et al. (2018), the numbers presented in Table 1 are highly dependent on the population of O stars serving as "home base" stars. We note that the nearest O star does not necessarily represent a field star's cluster of origin, since this metric also depends on the mean separation between clusters. However, here, the main result here that OBe stars are more isolated relative to OB stars, still holds.

Table 1 – Populations of SMC OB stars

		Numbers in Populations[a]				Nearest O-Star Separations (pc)[b]		
Row	Spectral Type	Field	Groups	Total	Proportion in Field	Median	Mean	Std Err
(1)	Early O (O3–O7)	15	39	54	0.28 ± 0.08	19	28	5.1
(2)	Late O (O8–O9)	60	75	135	0.44 ± 0.07	28	40	4.2
(3)	B (B0–B2)	91	102	193	0.47 ± 0.06	30	45	4.4
(4)	OB[c]	11	383	394	0.03 ± 0.01	13	21	1.6
(5)	Oe	22	16	38	0.58 ± 0.16	34	56	9.4
(6)	Be	115	108	223	0.52 ± 0.06	39	63	5.0
(7)	OBe[c]	11	107	118	0.09 ± 0.03	21	30	28
(8)	OB or OBe[c]	5	24	29	0.17 ± 0.08	···	···	···
(9)	O,B HMXB[d]	4	3	7	0.57 ± 0.36	54	54	5.5
(10)	OBe HMXB	19	20	39	0.49 ± 0.14	47	61	8.1
(11)	Total confirmed O[e,f]	81	121	202	0.40 ± 0.05	26	37	3.1
(12)	Total OB[f,g]	174	599	773	0.23 ± 0.02	22	36	1.8
(13)	Total OBe[g]	167	251	418	0.40 ± 0.04	36	57	3.3
(14)	Total OB and OBe[f,h]	346	874	1220	0.28 ± 0.02	···	···	···
(15)	Total HMXB[i]	24	25	49	0.49 ± 0.12	48	58	6.5
(16)	Cross-class binaries[f]	7	3	10	0.47 ± 0.21	···	···	···
(17)	O,B I/II	21	59	80	0.26 ± 0.06	24	42	4.9
(18)	OBe I/II[d]	6	35	41	0.15 ± 0.06	29	46	7.7

[a] OKP stars with spectral type ≤ B2. Supergiants (luminosity class I/II) are excluded from all categories except in rows 15, 17, and 18. HMXBs are excluded from rows 1–8, but included in rows 11–15. "Group" stars are non-field stars.

[b] Listed means are the median of the means for the maximum and minimum CDF samples (see text). Standard errors are calculated using the number of objects in the latter sample.

[c] "OB", and "OBe" stars have uncertain classification between Early vs Late O, O vs B, and Oe vs Be, respectively. "OB or OBe" have uncertain emission-line status. There are no published spectral types for 373 "OB" stars and 107 "OBe" stars.

[d] Includes one star of uncertain emission-line status.

[e] Includes 5 Field and 7 Group stars of uncertain Early vs Late O status from row 4, and 1 Field O HMXB from row 9.

[f] For our analysis, binaries with two stars of the same classification are treated as a single star of the relevant class, as are binaries with a member not meeting our selection criteria. Ten binaries in row 15 have components individually included in rows 1–4, but treated as single stars in rows 11, 12 and 14.

[g] Total number excluding row 8.

[h] Total number including row 8.

[i] All OKP HMXBs, including 1 B[e] HMXB and 2 supergiant HMXBs, which are excluded from rows 9–14. These all represent post-SN objects.

We numerically observe the trends present in Figure 2, showing that the OBe stars are more isolated compared to the OB stars. Furthermore, if OBe stars are binary supernova-ejected objects, then their CDF should reside at a locus similar to that of other known binary supernova-ejected populations. Figure 2 and Table 1 indeed show that the Oe and Be populations approach a similar degree of isolation as the HMXBs in our sample, which are known post-SN objects. We do see that 39 of the 49 are confirmed OBe stars, thus the comparison is not independent, but this demonstrates a close link between OBe stars and HMXBs.

Implications

Binary mass transfer is increasingly seen as the mechanism for spinning up classical OBe stars, enabling formation of their decretion disks. Using the spatially complete sample of 1344 OB stars in the SMC from Oey et al. (2004), we show that the spatial distribution of OBe stars further confirms that these objects experienced binary supernova ejections.

Our results show that:
The isolation of OBe stars is consistent with a high frequency of SN ejections, as expected from the binary formation model of OBe stars.
On average, Be stars do not drift further into the field than Oe stars, contrary to expectations based on the relative lifespans of O and B stars. This can be readily explained if the masses of the gainers are obscured by mass transfer.
There is a link between HMXBs and OBe stars, with 39/49 HMXBs in the sample being OBe stars and the distribution of OBe star separations approaching that of HMXBs.

Thus, we show several lines of evidence indicating that OBe stars largely originate as mass gainers in close, post-SN, massive binary systems. This model allows OBe star observations to be used for a variety of new purposes, such as frequencies and properties of gamma-ray bursters and gravitational wave events.