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Do O-stars form in isolation?

Richard J. Parker[1]⋆ and Simon P. Goodwin[1]†
[1] *Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK*

arXiv:0707.0605v1 [astro-ph] 4 Jul 2007

ABSTRACT

Around 4% of O-stars are observed in apparent isolation, with no associated cluster, and no indication of having been ejected from a nearby cluster. We define an isolated O-star as a star $> 17.5 M_\odot$ in a cluster with total mass $< 100 M_\odot$ which contains no other massive ($> 10 M_\odot$) stars. We show that the fraction of apparently isolated O-stars is reproduced when stars are sampled (randomly) from a standard initial mass function and a standard cluster mass function of the form $N(M) \propto M^{-2}$.

This result is difficult to reconcile with the idea that there is a fundamental relationship between the mass of a cluster and the mass of the most massive star in that cluster. We suggest that such a relationship is a typical result of star formation in clusters, and that 'isolated O-stars' are low-mass clusters in which massive stars have been able to form.

Key words: stars: formation – stars:mass function – open clusters and associations

1 INTRODUCTION

It is believed that the vast majority of stars in the Galaxy form in clusters with masses of a few 10s to $\sim 10^5 M_\odot$ (Lada & Lada 2003). The stars in these clusters appear to form with an almost universal initial mass function (see Kroupa 2002, 2007; Chabrier 2003).

For a typical initial mass function it is thought that one massive O-star forms per $200 - 300 M_\odot$ of stars. It has been suggested that mass of the most massive star in a cluster correlates with the mass of the cluster, with clusters less massive than $\sim 250 M_\odot$ being incapable of forming an O-star (e.g. Larson 1982; Weidner & Kroupa 2006). However, de Wit et al. (2004, 2005) have found that roughly 4 % (± 2 %) of *all* O-stars appear to have formed in isolation, in that no (significant) host cluster is present, and they cannot be accounted for as a runaway ejected star.

The observations of de Wit et al. (2004, 2005) can be explained in one of two ways. Firstly, it may be that some very low-mass clusters are able to form O-stars, and therefore there is no limit on the maximum mass of a star in a low-mass cluster (other than the total mass of that cluster). Therefore these isolated O-stars are just the extreme tail of a distribution of stellar masses in low-mass clusters (see e.g. de Wit et al. 2005). Secondly, if there *is* a limit on the maximum stellar mass a cluster of a given mass may produce, then these isolated O-stars must be formed by a different mechanism to the vast majority of stars that form in clusters, or that the host clusters must rapidly disperse.

⋆ r.parker@sheffield.ac.uk
† s.goodwin@sheffield.ac.uk

In this paper we address the possible origin of these isolated O-stars. In Section 2 we describe our Monte Carlo methods, and we present our results in Section 3. We conclude in Section 4.

2 METHOD

We form a population of clusters and stars by randomly sampling first from a power-law cluster mass function, and then populating that cluster from an initial mass function (IMF).

Cluster masses are selected from a power-law cluster mass function (CMF) of the form $N(M) \propto M^{-\beta}$ between a lower and an upper mass limit. The lower mass limit is usually taken to be $M_{c0} = 50 \, M_\odot$, the upper mass limit is allowed to vary, but is usually in the range $M_{c1} = 10^4 - 10^5 \, M_\odot$. The *total* mass of clusters in each Monte Carlo run is $10^9 \, M_\odot$ in order to fully sample the mass range of clusters.

2.1 The stellar IMF

Each cluster is populated with stars drawn from a two-part Kroupa (2002) IMF of the form

$$N(M) \propto \begin{cases} M^{-1.3} & m_0 < M/M_\odot < m_1 \, , \\ M^{-2.3} & m_1 < M/M_\odot < m_2 \, , \end{cases}$$

where m_0 and m_2 are the lower and upper limits of the IMF respectively, and m_1 is the mass at which the IMF slope changes.

We choose $m_0 = 0.1 \, M_\odot$, and $m_1 = 0.5 \, M_\odot$ (see Kroupa 2002). We note that whilst brown dwarfs are numerous, their

contribution to the total mass of the cluster is very small and so we do not include them in our calculations.

There are two ways of determining the population of stars within a cluster. Firstly, the IMF can be sampled to allow the possibility of a small cluster to contain a star close to the total mass of the cluster. Secondly, we can limit the maximum mass of a star in a cluster to be related to the mass of the cluster (cf. Weidner & Kroupa 2004).

2.1.1   Random sampling of the IMF

When randomly[1] sampling the IMF we set $m_2 = 150\,M_\odot$, the fundamental upper limit on the mass of stars (Oey & Clarke 2005; Figer 2005; Weidner & Kroupa 2004). Recent studies (Oey & Clarke 2007) point out that this upper mass limit may be as high as $200\,M_\odot$, however we us the more standard upper stellar mass limit of $m_2 = 150\,M_\odot$ throughout this paper.

Stars are added to a cluster until the *total* mass of the stars in a particular cluster is between 98 % and 105 % of the mass of that cluster. If the final star to be added to the cluster exceeds the 105 % limit then the cluster is *entirely* re-populated (see e.g. Goodwin & Pagel 2005).

Our sampling technique differs from that used by Elmegreen (2006) who used a 'soft-sampling' method in which the final star to be added to the cluster can be of any mass, and thus the final mass of the cluster could be greater than the initially sampled mass. We note that our results differ only negligibly using 'hard' or 'soft' sampling. This is due to the very low probability of selecting an O-star as the last star in an almost fully populated cluster.

2.1.2   Limiting the upper mass limit

It has been suggested that there is an upper limit to the mass of a star in a cluster which depends on the mass of that cluster (e.g. Larson 1982; Weidner & Kroupa 2004). Weidner & Kroupa (2004) parameterise the maximum stellar mass within a cluster, m_{max}, as a function of the initial (embedded) cluster mass, M_{ecl}, (see Weidner & Kroupa 2004, their Section 2.2). We solve Weidner & Kroupa's eqn. 8 numerically to obtain the $m_{max} - M_{ecl}$ relationship (as illustrated in figs. 2 & 3).

For a randomly sampled cluster of a given mass, we determine m_{max} and set the maximum mass m_2 in the IMF (eqn. 1) to be $1.1m_{max}$. We then proceed as above to populate the cluster with stars. We note that this is not ideal as the actual maximum mass selected for a given cluster tends to be somewhat smaller than the m_{max} determined by the Weidner & Kroupa (2004) relationship. However, as we shall show, the details of this method are unimportant as limiting the upper mass of a star in a cluster can *never* reproduce the isolated O-star fraction.

3   RESULTS

de Wit et al. (2004, 2005) found that $\sim 4\%$ of the *total* number of Galactic O-stars are found in apparent isolation. de Wit et al. (2005) found that when random sampling from an IMF that they are able to reproduce the isolated O-star fraction of $\sim 4\%$ by selecting clusters from a power-law of slope $\beta = 1.7$, and that selecting from a standard cluster mass function (CMF) with $\beta = 2$ produces too many isolated O-stars. de Wit et al. (2005) calculated the fraction of isolated O-stars by summing the number of O-stars in clusters that only contain a single O-star, and dividing by the total number of O-stars in *all* clusters.

Note that throughout the rest of this paper we will use the term 'isolated O-star', however a better term would be 'apparently isolated O-star' as, whilst there is not a significant population of other stars present around these O-stars, there could be (and we suggest there is) a small population of low-mass stars.

Our results are summarised in Table 1. Following de Wit et al. (2005) we define an O-star to be a star with mass $> 17.5\,M_\odot$[2]. We agree with the results of de Wit et al. (2005) and find that $\sim 6\%$ of the total number of O-stars are single when drawn from a CMF with $\beta = 1.7$, while $\sim 17\%$ of O-stars are single for a CMF with $\beta = 2$.

However, many of those single O-stars are present in large clusters (up to $\sim 10^3 M_\odot$, see fig. 1) which should have been detected by de Wit et al. (2004). In addition, many of the clusters containing just a single O-star also contain one or more B-stars that would also have been detected by de Wit et al. (2004, 2005) (unless they were close companions to the O-star).

To account for the lack of other massive (B-) stars and significant numbers of low-mass companions around isolated O-stars, we restrict the definition of an isolated O-star to be one in which the total cluster mass is $< 100M_\odot$, and one which has no B-stars (defined as stars with masses $10 > M/M_\odot < 17.5$). Hence the fraction of isolated O-stars becomes the number of O-stars in small clusters with no B-star companions, divided by the total number of O-stars in all clusters.

The effect of including these extra restrictions is dramatic. Fig. 1 shows the $\beta = 2$ CMF of all clusters (solid line), as well as the CMF of clusters containing a single O-star (dotted line), and the CMF of clusters $< 100M_\odot$ containing a single O-star and no B-stars (dashed line). The fraction of O-stars that are 'isolated' falls from 16.7 % to 4.6 %. Note that this agrees with the observation by Oey et al. (2004) showing that (in the SMC) a power-law of $\beta = 2$ describes the cluster richness distribution down to clusters containing single O-stars. For $\beta = 1.7$, however, the fraction of isolated O-stars falls to 1.3 % (with the same restrictions).

The results are not very sensitive to the maximum mass of a cluster within which an O-star is considered isolated (taken to be $100M_\odot$). Cluster masses much in excess of $100M_\odot$ often also include B-stars and so are discounted on those grounds, and clusters less massive than $\sim 50M_\odot$

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[1] Formally the cluster is populated in a constrained sampling, as the mass of the most massive star cannot exceed the mass of the cluster.

[2] We note that changing the minimum mass of an O-star within a reasonable range of values does not change the results significantly.

Stellar Sampling	β	Cluster upper mass limit	Maximum number of B-stars	Isolated O-star fraction
random	1.7	M_{c1}	Any	6.0 %
random	1.7	M_{c1}	0	3.1 %
random	1.7	$< 100\,M_\odot$	Any	1.5 %
random	1.7	$< 100\,M_\odot$	0	1.3 %
random	2	M_{c1}	Any	16.7 %
random	2	M_{c1}	0	9.7 %
random	2	$< 100\,M_\odot$	Any	5.2 %
random	2	$< 100\,M_\odot$	0	4.6 %
CMMSM	2	M_{c1}	Any	4.0 %
CMMSM	2	M_{c1}	0	0.4 %
CMMSM	2	$< 100\,M_\odot$	Any	0 %
CMMSM	2	$< 100\,M_\odot$	0	0 %

Table 1. A summary of the main results. The columns show the parameters for (a) the type of stellar IMF sampling, (b) the slope of the cluster mass function (β), (c) the upper limit for the mass of a cluster to contain an isolated O-star, (d) the number of B-stars allowed in a cluster, and (e) the resulting isolated O-star fraction. The first four calculations are for a cluster mass function with $\beta = 1.7$ (as adopted by de Wit et al. (2005)). The next four calculations are for a 'standard' cluster mass function with $\beta = 2$ (Lada & Lada 2003). In both cases the maximum allowable mass of a star in a cluster is the cluster mass (random sampling). The final four calculations are for a $\beta = 2$ cluster mass function, but with the maximum mass of a star in a cluster constrained by the cluster mass-maximum stellar mass (CMMSM) relationship.

almost never produce an O-star (indeed, only $\sim 10\,\%$ of $100 M_\odot$ clusters ever produce an O-star).

The fraction of isolated O-stars is slightly sensitive to the upper mass limit of the CMF. When the upper mass limit is changed from 10^4 to $10^5\,M_\odot$ the fraction of isolated O-stars changes from 6.8 % and 4.6 % for $\beta = 2$ and between 3.0 % and 1.3 % for $\beta = 1.7$ (due to the increasing number of very massive clusters that are able to fully sample the IMF up to the $150 M_\odot$ stellar mass limit).

Thus a standard CMF with $\beta = 2$ as observed for clusters in the Solar Neighbourhood (Lada & Lada 2003) is able to reproduce the isolated O-star fraction when reasonable limits are placed on the presence of other massive (i.e. B-) stars, and on the total stellar mass that can be associated with the O-star (usually less than $\sim 80 M_\odot$ of M-, K-, and G-dwarfs).

This suggests that the only limit on the most massive star in a cluster is whichever is smaller of the cluster mass and the fundamental upper-limit of stellar masses (which we take to be $150 M_\odot$).

The random sampling model predicts that there should be a population of single O-stars in fairly small clusters of a few hundred $M_\odot$. de Wit et al. (2004, 2005) find a similar fraction of their field O-star sample lie in small clusters as are found to be isolated (see tables 1 and 3 in de Wit et al. 2005, 12/43 associated with clusters compared to 11/43 isolated). The fraction of single O-stars with no B-stars in clusters of mass $100 < M_{\rm ecl} < 300 - 500\,M_\odot$ drawn from a CMF with $\beta = 2$, is $\sim 4\%$, consistent with the fraction of single O-stars in modest clusters found by de Wit et al. (2004, 2005).

3.1 The cluster mass-maximum stellar mass relation

It has been suggested that there is a cluster mass-maximum stellar mass (CMMSM) relationship (Larson 1982; Weidner & Kroupa 2006; however see Elmegreen
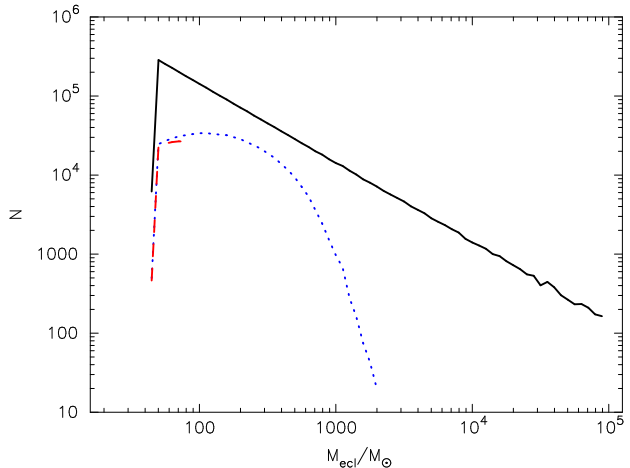

Figure 1. A plot of the cluster mass functions (CMFs) for a slope of $\beta = 2$. The CMF for all clusters is shown by the black (solid) line; the CMF for clusters containing only one O-star is shown by the blue (dotted) line; and the CMF for clusters containing one O-star, no B-stars and a cluster mass $M_{\rm ecl} < 100\,M_\odot$ is shown by the red (dashed) line.

2005). In order to contain a star of $> 17.5\,M_\odot$ a cluster must be more massive than $\sim 300\,M_\odot$ (Weidner & Kroupa 2006).

Clearly, in such a situation, *no* O-stars could fulfil our criteria of 'isolation'. Monte Carlo simulations of a CMF with $\beta = 2$ and limiting the maximum mass of a star within a cluster according to the Weidner & Kroupa (2006) relationship (see Section 2.1.1) gives a single O-star fraction of $\sim 4\%$. However, including our extra constraints that no B-stars are present reduces this fraction to 0.4 %, and further adding the constraint that the maximum mass of the cluster is $< 100 M_\odot$ (unsurprisingly) reduces this fraction to zero.

3.2 Is there a cluster mass-maximum stellar mass relationship?

Thus, if there exists a CMMSM relationship, the population of isolated O-stars apparently cannot be accounted for within the clustered mode of star formation. We are left with two possibilities. Firstly, that isolated O-stars form from a different mode of star formation to the dominant clustered mode. Secondly, that stars do form in clusters with the CMMSM relationship, but some of those clusters rapidly disperse leaving an isolated O-star (e.g. due to low star formation efficiencies and then gas expulsion, see Bastian & Goodwin 2006; Goodwin & Bastian 2006). We note however, that the distribution of star formation efficiencies would have to be such as to mimic the results of random sampling from the CMF which would presumably require fine-tuning.

In fig. 2 we show the numbers of clusters of a given mass (M_{ecl}) harbouring a star of a given maximum mass (m_{max}). In order to remove the potentially confusing effect of the CMF, in fig. 2 we plot the contours for a uniform ($\beta = 1$) CMF. The hashed region corresponds approximately to our definition of an isolated O-star[3]. The dashed-line shows the CMMSM relationship from Weidner & Kroupa (2006). Interestingly, the CMMSM relationship falls a little below the *median* of the distribution (shown by the open circles), suggesting that the CMMSM relationship may simply be the 'typical' result of star formation in clusters.

In order to test the possibility that the CMMSM relationship reflects 'average' clusters, we pre-select a set of 16 clusters with masses very similar to those in the observed sample of Weidner & Kroupa (2006, see e.g. their fig. 7/table 1). We then populate these clusters randomly from the IMF and examine how often the most massive stars in each of the clusters lie close to the CMMSM relationship. We find that only $\sim 10\%$ of the time all of the 16 clusters have a CMMSM relationship that is within 0.25 dex of the 'true' CMMSM relationship. In 90% of trials at least one (most often one or two) cluster lies more than 0.25 dex from the relationship.

This might suggest that the CMMSM relationship represents more than the 'average' cluster. However, in almost all cases the clusters that lie far from the CMMSM relationship are low-mass clusters that contain an overly massive star. That is, clusters that do not fit the CMMSM relationship lie in or around the 'isolated O-star' region of fig. 2.

In fig. 3 we show the numbers of clusters with a mass M_{ecl} and a maximum stellar mass m_{max} when clusters are drawn from a power-law with slope $\beta = 2$. Low-mass clusters are by far the most common clusters, and the most common deviations from the CMMSM relationship are towards the top left of the diagram - in the region populated by isolated O-stars. Therefore, the clusters most likely to fall significantly away from the CMMSM relationship appear to be isolated O-stars and are therefore not included in any CMMSM relationship.

[3] The region shows $m_{max} > 17.5 M_\odot$ and $M_{ecl} < 100 M_\odot$, but we are unable to also illustrate the constraint that there are no B-stars. However, the no B-star constraint has little effect in low-mass clusters.
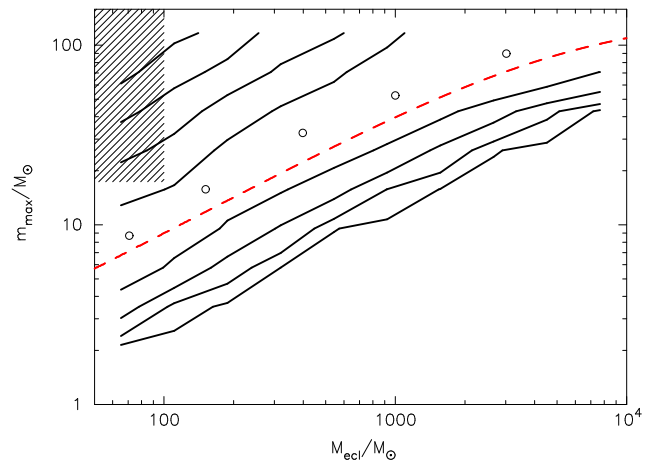

Figure 2. A contour plot of the numbers of clusters of mass M_{ecl} having a most massive star of mass m_{max} drawn from a uniform ($\beta = 1$) cluster mass function. Weidner & Kroupa's (2006) relationship between M_{ecl} and m_{max} is shown by the red dashed line. The region in which isolated O-stars would be found (i.e. $m_{max} > 17.5 M_\odot$ and $M_{ecl} < 100 M_\odot$) is indicated by the hashed region in the top left of the figure. The contour levels from the CMMSM line outwards are 200, 100, 40 and 10 clusters (from a total of 9248 clusters). The median stellar mass for clusters in a mass bin range of 0.2 dex is also shown by the open circles.
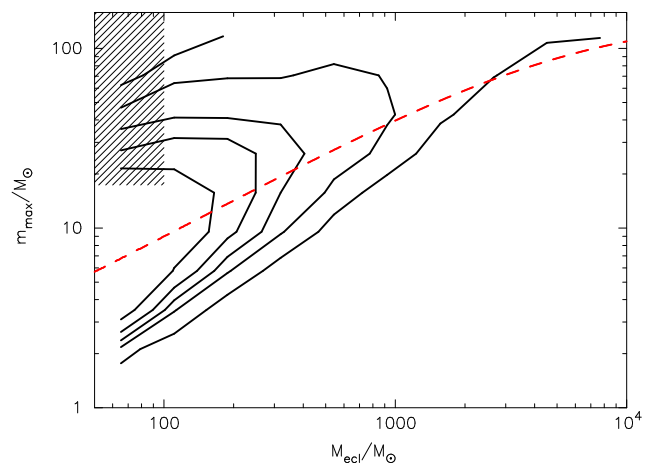

Figure 3. As fig. 2 but for cluster masses drawn from a $\beta = 2$ power-law cluster mass function. The contour levels from the CMMSM line outwards are 400, 250, 150, 70 and 30 clusters (from a total of 8513 clusters).

3.3 Other massive stars

In a series of papers, Testi et al. (1997) and Testi, Palla & Natta (1998, 1999) analysed infra-red observations of clusters surrounding Herbig Ae/Be stars. They define a 'richness indicator' - proportional to the number of stars in the surrounding cluster and plot this as a function of spectral type (see Testi et al. 1999, their fig. 3). From inspection of fig. 3 in Testi et al. (1999), the fraction of B-stars in very modest clusters appears to be around 5% (although with very large error bars).

We can define an 'isolated B-star' in a similar way to isolated O-stars: a single star of mass $10 M_\odot < M_{B\star} \leqslant$
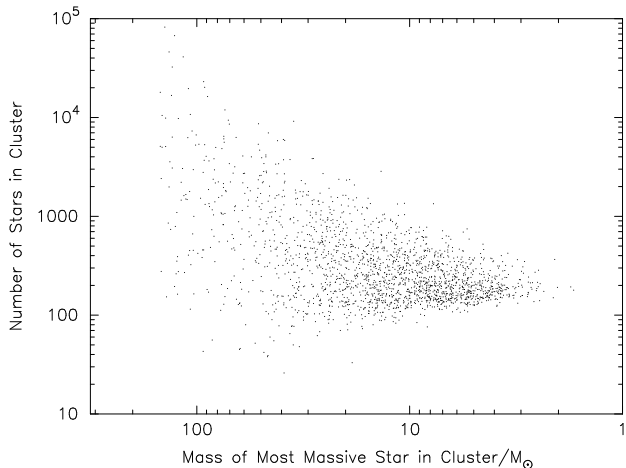
Figure 4. The number of stars in a cluster plotted as a function of the most massive star in that cluster for a random sampling of the IMF.

Figure 5. The number of stars in a cluster plotted as a function of the most massive star in that cluster for a fixed sampling of the IMF using the CMMSM relation advocated by Weidner & Kroupa (2004, 2006).

$17.5\,M_\odot$, within a cluster of mass $M_{\rm ecl} < 100M_\odot$ which also contains no O-stars. With such a definition we can predict that there should be an isolated B-star fraction of $\sim 6\,\%$, somewhat higher than (but within the error bars of) the isolated O-star fraction, and consistent with Testi et al. (1999).

We model the analysis of Testi et al. (1999) by plotting the number of stars in a particular cluster as a function of the most massive star in that cluster for two scenarios. Firstly, we populated clusters randomly from the IMF, and secondly using the CMMSM relation. Figs. 4 and 5 show the distribution of cluster richness (the total number of stars in each cluster) for the random and CMMSM sampling respectively. Comparison of figs. 4 and 5 with fig. 3 from Testi et al. (1999) shows that the random sampling reproduces the observations far better. We note again that the rapid dispersal of some clusters would add a scatter to the initially strong CMMSM relationship, however, once more the dispersal of clusters would have be fine-tuned to match the predictions of the random sampling model.

4 CONCLUSIONS

We use Monte Carlo simulations to form clusters from a power-law cluster mass function (CMF) and then populate these clusters with stars from a stellar initial mass function (IMF). We sample randomly from a Kroupa (2002) IMF with an upper limit of $150M_\odot$ or with an upper limit set from the cluster mass-maximum stellar mass (CMMSM) relationship from Weidner & Kroupa (2006).

de Wit et al. (2004, 2005) find that $4 \pm 2\,\%$ of O-stars ($M > 17.5M_\odot$) form in apparent isolation, i.e. with no associated cluster, no other massive stars, and with no apparent ejection from a nearby cluster.

We agree with de Wit et al. (2005) that from a CMF with slope $\beta = 1.7$ around $4\,\%$ of O-stars form in clusters that contain no other O-stars, and that for a 'standard' CMF of $\beta = 2$ (e.g. Lada & Lada 2003) this fraction is $\sim 17\,\%$.

When we include additional constraints that an isolated O-star must also have no B-stars in the same cluster, and must form in a cluster of $< 100M_\odot$ (in order to match the

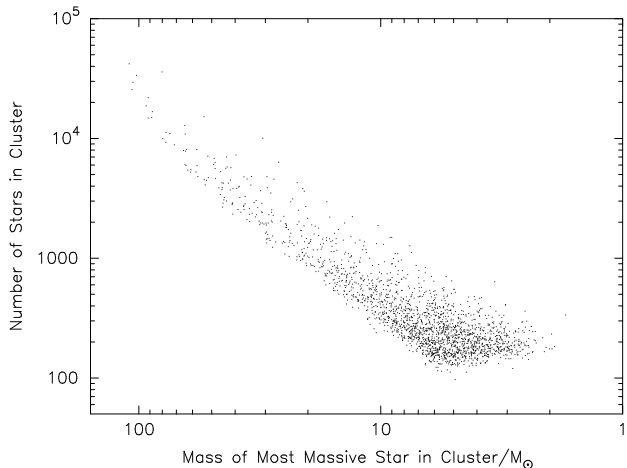observational constraints from de Wit et al. (2004, 2005)), we find that the fraction of isolated O-stars for a CMF with $\beta = 2$ falls to $\sim 5\,\%$ in-line with the observations, whilst for $\beta = 1.7$ the fraction falls to $\sim 1\,\%$. This suggests that the isolated O-stars can be explained from a standard CMF if stellar masses are drawn randomly from an IMF, and therefore very low-mass clusters do have a (small) probability of forming a very massive star.

If there is a cluster mass-maximum stellar mass (CMMSM) relationship (e.g. Larson 1982; Weidner & Kroupa 2006) then there is *no* chance of isolated O-stars forming in clusters as the lowest mass cluster that can form an O-star is $\sim 275M_\odot$. The CMMSM relation also appears not to hold for clusters in which the most massive star is of spectral type B or A. We find that we can reproduce the observations by Testi et al. (1999) if we randomly sample the IMF, whereas introducing the CMMSM relation into our simulations produces something altogether different.

If the CMMSM relationship is physical, then either (a) isolated O-stars must form from a different mechanism to the bulk of stars that form in clusters with a power-law slope of $\beta \sim 2$, or (b) clusters containing single O-stars must disperse rapidly leaving isolated O-stars. Option (a) is unsatisfying as it requires a different mode of star formation for a small fraction of the most massive stars. Option (b) is difficult to reconcile with the observations. The most probable cause for the rapid dispersal of some clusters is that they form with a low star formation efficiency and are destroyed after gas expulsion (see e.g. Bastian & Goodwin 2006; Goodwin & Bastian 2006). However, the star formation efficiencies of clusters must be fine-tuned so that they match the predictions of purely randomly sampling from a standard CMF. In addition, single O-stars form in clusters with large numbers of B-stars, and so the fields around apparently isolated O-stars should also contain many B-stars. Whilst this has not been actively searched for, there is no obvious sign of many isolated B-stars in the survey of de Wit et al. (2004).

Therefore we suggest that the CMMSM relationship is

an average relationship between the most common maximum stellar mass within a cluster of a given mass. In a sample of clusters chosen to mimic the sample of Weidner & Kroupa (2006), the CMMSM relationship is only recovered in $\sim 10\,\%$ of random populations of those clusters. However, most extreme deviations from the CMMSM relationship are very low-mass clusters which form a particularly massive stars: i.e. an 'isolated O-star', which are excluded from the CMMSM relationship as their identification with very low-mass clusters has previously been unclear.

We note that young stars, of all masses, tend to be X-ray bright (see e.g. Feigelson & Montmerle 1999; Ramírez et al. 2004; Getman et al. 2006). Therefore X-ray observations of the regions around isolated O-stars could provide an indication of the presence of associated young low-mass stars around apparently isolated O-stars.

In summary, the existence and number of isolated O-stars (de Wit et al. 2004, 2005) can be explained within a standard cluster mass function with $\beta = 2$ as long as very low-mass clusters are able to form massive stars (e.g. Elmegreen 2005, 2006).

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