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The origin of massive O-type field stars

II. Field O stars as runaways

W. J. de Wit[1,⋆], L. Testi[1], F. Palla[1], and H. Zinnecker[2]

[1] INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Florence, Italy
e-mail: dewit@obs.ujf-grenoble.fr
[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

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Abstract. In two papers we try to confirm that all Galactic high-mass stars are formed in a cluster environment, by excluding that O-type stars found in the Galactic field actually formed there. In de Wit et al. (2004) we presented deep *K*-band imaging of 5 arcmin fields centred on 43 massive O-type field stars that revealed that the large majority of these objects are single objects. In this contribution we explore the possibility that the field O stars are dynamically ejected from young clusters, by investigating their peculiar space velocity distribution, their distance from the Galactic plane, and their spatial vicinity to known young stellar clusters. We (re-)identify 22 field O-type stars as candidate runaway OB-stars. The statistics show that 4 ± 2% of all O-type stars with $V < 8^{m}$ can be considered as formed outside a cluster environment. Most are spectroscopically single objects, some are visual binaries. The derived percentage for O-type stars that form isolated in the field based on our statistical analyses is in agreement with what is expected from calculations adopting a universal cluster richness distribution with power index of $\beta = 1.7$, assuming that the cluster richness distribution is continuous down to the smallest clusters containing one single star.

Key words. stars: early-type – stars: formation – Galaxy: stellar content – stars: kinematics

1. Introduction

The relatively brief existence of massive stars renders it likely that the location where they form is where we observe them today. About 70% of the massive O-type stars in the Galaxy is observed to be associated with stellar clusters and/or OB-associations (Gies 1987; Mason et al. 1998; Maíz-Apellániz et al. 2004). At least a third of the remaining 30% of the O-type stars are runaway OB-stars (Gies 1987), and may therefore also have formed in a cluster, where it is known that OB stars acquire high spatial velocities after dynamical interactions or after supernova explosions in binary systems (Allen & Poveda 1971; van den Heuvel 1985; Gies & Bolton 1986; Clarke & Pringle 1992; Hoogerwerf et al. 2001). These statistical considerations leave an absolute number of ∼40 O stars in the Solar neighbourhood that are truly isolated, i.e. not known to be part of a cluster/OB association nor to be runaway stars. By retracing the formation history of these O-type field stars, we address in this paper the question whether a stellar cluster is a necessary condition for the formation of a high-mass star.

A dense stellar cluster may provide favorable conditions for the formation of a massive star through the process of coalescence of molecular cores in the very early stages of star formation or even by merging stars in more evolved stages, when the space density of these colliding objects exceeds some threshold value (Bonnell et al. 1998; Stahler et al. 2000; Bonnell & Bate 2002; Bally & Zinnecker 2005). This suggests a physical connection between the formation of a stellar cluster and a massive object, which is partly supported by observations of the less massive, pre-main sequence Herbig AeBe (HAeBe) stars. The gradual onset of clustering near these stars as a function of spectral type seems to indicate that as the mass of the most massive object increases, the richness of the associated cluster of lower mass stars also increases (Testi et al. 1999). However, as pointed out by Bonnell & Clarke (1999), this trend does not imply that a cluster is a necessity for the formation of a high-mass star. In general, the observed increase in richness of clusters with the mass of the most massive HAeBe member was shown by these authors to be compatible with random drawing of stellar clusters that are distributed in membership number according to a certain power law, and subsequently populated with stars following a universal stellar IMF.

Statistical IMF arguments allow for a finite probability of forming a massive star without the required cluster and indirectly provides support for the formation of a massive star set by conditions other than a stellar cluster, e.g. a sufficiently massive, non-fragmenting dense molecular core and an accretion disk (e.g. Yorke & Sonnhalter 2002; Li et al. 2003). Accretion disks near young massive stars have recently been suggested by mm observations (Beltran et al. 2004) and the near infrared

⋆ Now at CNRS, Laboratoire d'Astrophysique de Grenoble, France.

(Chini et al. 2004). Modeling of the near infrared CO bandhead emission may also indicate that a fraction of young massive stars is surrounded by rotating Keplerian disks (Bik & Thi 2004; Bik et al. 2005). Isolated formation of single massive stars could be occurring in external Galaxies (Large Magellanic Cloud and M 51, Massey et al. 1995; Lamers et al. 2002).

The field O-type star population provides the opportunity to test the "null hypothesis" that all massive stars form in stellar clusters. The validity of this hypothesis was addressed already in 1957 by Roberts (1957). Within this context, we try to elucidate here the formation history of the field O stars. Their properties in terms of location, radial velocity and binarity were already presented by Gies (1987, hereafter G87). He finds that field O stars have characteristics intermediate between O stars in clusters/associations and the runaway O stars, and suggested that a substantial fraction of them could belong in fact to the latter category. However, the possibility that some are actually formed at their present (isolated) location in the Galactic field is still open. In this second contribution of our series, we explore the possibility of a runaway nature that would explain their location in the Galactic field.

The paper is organized in the following way. In Sect. 2 we give a summary of the observational results obtained in de Wit et al. (2004, hereafter Paper I), in which we searched for the presence of subparsec scale stellar clusters near field O stars. In Sect. 3 we explore the dynamical ejection scenario for the origin of field O stars as a group by determining space velocities using Hipparcos proper motions, the distance to the Galactic plane, and the presence of nearby young clusters. We discuss our statistical results in Sect. 4 and compare these with theoretical expectations. The main conclusions are summarized in Sect. 5.

2. Main results from Paper I

The observational objective of Paper I (de Wit et al. 2004) was to determine by deep imaging the presence of small scale stellar clusters near the sample of field O-type stars (defined in Mason et al. 1998), as is found to be the case near the HAeBe stars (Testi et al. 1999). Given the low detection rate, we dismissed the possibility that the formation of a field O-type star proceeds in small stellar clusters, under our initial assumption that all the field O stars in the sample were actually formed in the Galactic field.

2.1. The absence of clusters near field O stars

We selected all 43 O-type stars characterized as field objects from the interferometric multiplicity study of ∼200 O stars by Mason et al. (1998, hereafter M98). We searched for hitherto unknown stellar clusters centred on the target stars using stellar density maps. High resolution density maps were constructed from deep K-band images taken with NTT/SOFI and TNG/NICS, probing linear scales of ∼0.25 pc. Lower resolution maps were constructed from 2MASS K-band covering tens of parsecs with a linear resolution of ∼1.0 pc. A 3σ deviation from the average stellar density was considered to be a cluster provided that it was centred on the target star. The maps are presented in Paper I along with the K-band images. In 5 cases we detect a clear stellar density enhancement near the field O star, four of which were previously thought to be visually single objects.

Paper I briefly describes each field O-type star, with the emphasis on their spectroscopic and visual multiplicity status, and the presence of star formation indicators in the field like IRAS sources, H II regions or dark clouds. Specific attention is given to runaway stars. Given the objective of the project to determine whether isolated massive stars form in an isolated way, a clear division is applied between field stars and runaway objects. In fact the M98 characterization of a field object depends on the strict definition of a runaway star (requirements regarding the radial velocity and the distance from the Galactic plane) and not on the star's (possible) birth-site as is appropriate for this study. For example, according to M98 the well known runaway objects ζ Pup and HD 75222 are considered field stars owing to their rather small radial velocity component. Within the framework of our study, we prefer to classify runaway stars as cluster members, and reserve the term "field star" for the objects that do not find an origin in a cluster.

If we would subdivide the 43 "field O stars" according to their visual multiplicity (based on G87 and M98), we get the following picture: 27 single objects, 5 optical binaries, 6 visual binaries, 2 visual multiple objects, and 3 runaway stars (ζ Pup, HD 75222, and the runaway X-ray binary HD 153919; Ankay et al. 2001). It is noteworthy that the vast majority are visually single objects. Since the three runaways are obviously not formed where they are currently located presently, we will not discuss their properties further, although we will keep them in the statistics.

The main result of Paper I is that the majority of the massive O stars are found not to be associated with clusters on scales of a few tenths to a few parsec. In fact, the stellar density maps of Paper I show that at least ∼85% of the high mass field stars are isolated objects. In only 5 cases we detected a cluster.

2.2. The 5 field O stars in newly detected clusters

Using deep infrared imaging, we detected small scale clusters associated with 5 field O stars (see Table 1). We quantify the stellar richness of these clusters using the I_C indicator introduced by Testi et al. (1997) in their study of clusters near HAeBe stars. The I_C parameter estimates the stellar *richness* of the cluster centered on the O star by counting the number of stars corrected for the back/foreground field contamination within the determined, assumed circular, cluster radius. The properties of the new clusters are given in Table 1.

The table reflects what is clear from the stellar density maps: the stars HD 52533 and HD 195592 are located in the richest cluster among the field O stars. HD 52533 was already known to be a visual multiple system, consisting of at least 4 components (M98), whereas HD 195592 has been catalogued as a visually single object (possibly a single line spectroscopic binary). The cluster detection for the other three stars is marginal as is reflected by their low I_C values.

Table 1. Field O stars in newly detected clusters. The asterisk indicates that the star is found in a region with star formation signposts (see Sect. 4.3). In Col. 2 we give the visual multiplicity (VM) of the stars, adopted from M98 and G87; VMS = Visual Multiple Star. In Col. 3 we use the following abbreviations for the spectroscopic multiplicity (SM): C = constant radial velocity, SB1 = single-lined spectroscopic binary, SB2 = double-lined spectroscopic binary. Addition of an "O" and/or "E" indicates that the orbit is known and/or an eclipsing system. A colon indicates uncertainty.

Name	VM	SM	I_C	Radius (pc)	$\log(\rho_{I_C})$ (stars pc^{-3})
HD 52266*	single	SB1?	4 ± 2	0.10	2.0 ± 1.0
HD 52533*	VMS	SB1O	15 ± 5	0.30	2.5 ± 0.9
HD 57682	single	C	4 ± 5	–	–
HD 153426	single	SB2:	5 ± 4	–	–
HD 195592*	single	SB1?	18 ± 3	0.25	2.6 ± 0.8

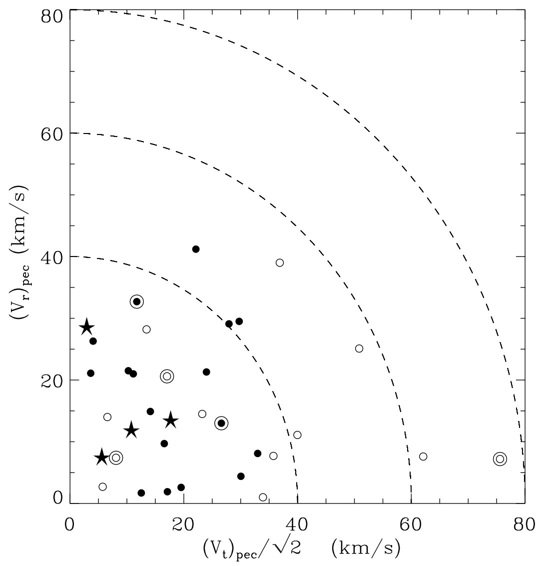

Fig. 1. The space velocity of field O stars. Note that not all field O stars under study have Hipparcos proper motions. The peculiar tangential velocities of the field O stars are derived from Hipparcos proper motions. The uncertainty has been calculated by propagating a 30% uncertainty in the distance. Symbols are as follows: filled asterisks indicate absolute uncertainty less than 10 km s^{-1}, filled circles an uncertainty between 10–20 km s^{-1}, and empty circles >20 km s^{-1}. Some field O stars have space velocities negligibly different from the bulk of the Galactic field. Five stars with clusters discussed in Paper I are encircled.

In Col. 5 of Table 1, we list the cluster radii for the cases with an approximately spherical density enhancement centered around the field O star. The average value of ~0.2 pc is remarkably similar to that of the clusters around HAeBe stars (Testi et al. 1999). We have used this average value for the radius to convert the I_C value to stellar spatial densities. We conclude that both the richness and extent of especially the clusters found near HD 52533 and HD 195592 show that what is observed among the highest mass HAeBe stars. In Appendix A we describe the details concerning the clusters found near these two stars.

3. The field O stars as candidate runaway stars

Our null hypothesis that massive stars are all formed in clusters requires that the absence of clusters near the Galactic massive field population is interpreted in terms of a dynamical ejection scenario, similar to (part of) the runaway OB stars (e.g. Hoogerwerf et al. 2001). In this section we test this possibility by examining the spatial velocities of our sample using Hipparcos (ESA 1997) proper motion measurements and published radial velocities, their distances above the Galactic plane, and the existence in the literature of very young stellar clusters with sufficient properties to be capable of producing high-mass runaway stars.

3.1. Space velocities

Knowledge of the spatial velocities of the field O stars can be used to exclude a runaway history on kinematic grounds. Traditionally, the minimum peculiar velocity for classifying a runaway star is 40 km s^{-1} (Blaauw 1961). The radial component of the peculiar space velocity of the O field stars is discussed in G87 who found that the average of $\langle(v_r)_p\rangle$ = 6.5 km s^{-1} is generally lower than for the runaways, but higher than that of O stars in clusters/OB associations. Below, we derive the motion in the plane of the sky from Hipparcos measurements of our targets.

Hipparcos proper motions are available for 34 stars of our sample. We derive the corresponding tangential peculiar velocities using the distance estimates taken from G87 and M98, as listed in Paper I. Following Moffat et al. (1998), we adopt a flat rotation curve with a Solar galactocentric distance of 8.5 kpc and a circular Galactic rotation velocity of 220 km s^{-1}. The adopted Galactic rotation model should be adequate for galactocentric distance between 3 and 18 kpc (Kerr & Lynden-Bell 1986). A 30% uncertainty in distance is propagated in the error estimate of $\langle(v_t)\rangle$.

The resulting $(v_t)_p$ normalized to one component against $(v_r)_p$ is presented in Fig. 1. The values of $(v_r)_p$ are taken from G87. The error is dominated by the distance uncertainty. Filled asterisks are stars with the most accurate measurements and an absolute uncertainty less than 10 km s^{-1}; dots have an absolute uncertainty between 10 and 20 km s^{-1}, and empty circles are for uncertainties in excess of 20 km s^{-1} (see the caption to Fig. 1). The five encircled symbols correspond to the stars in Table 1. Note that the relative uncertainty is smallest for the star with the largest absolute uncertainty, i.e. the suspected runaway HD 57682 (see de Zeeuw et al. 1999). Also note that stars with low velocities have uncertainties larger than their measurements. Therefore, the lower velocity part of the diagram is not very useful except that it makes clear that most field O stars do not have high velocities.

Figure 1 demonstrates that by applying a strict runaway limit of 40 km s^{-1} regardless of the error bars, the Hipparcos proper motions allow the identification of 7 additional candidate runaway OB stars, one of which with a *radial* velocity

Table 2. Runaway O-type candidate stars derived from Hipparcos proper motions and distance from Galactic plane (*Z*). The abbreviation in Cols. 2 and 3 are the same as in Table 1 and OPT = optical binary, VB = visual binary. The criterion for classification of the listed stars as candidate runaway stars is given in the last column.

Name	VM	SM	Remark
HD 1337	single	SB2OE	Z
HD 15137	single	SB2?	$v_{\rm pec}+Z$
HD 36879	single	C	$v_{\rm pec}$
HD 41161	VB	C	Z
HD 57682[1]	single	C	$v_{\rm pec}$
HD 60848	single	U	Z
HD 89137	single	SB1?	Z
HD 91452	single	C	$v_{\rm pec}+Z$
HD 105627	single	C	$v_{\rm pec}$
HD 122879	single	C	$v_{\rm pec}$
HD 163758	single	C	Z
HD 175754	single	C	Z
HD 175876	OPT	C	Z
HD 188209	single	C	Z
HD 201345	single	C	$v_{\rm pec}+Z$

[1] The star is also found to have a cluster in Sect. 2. See text.

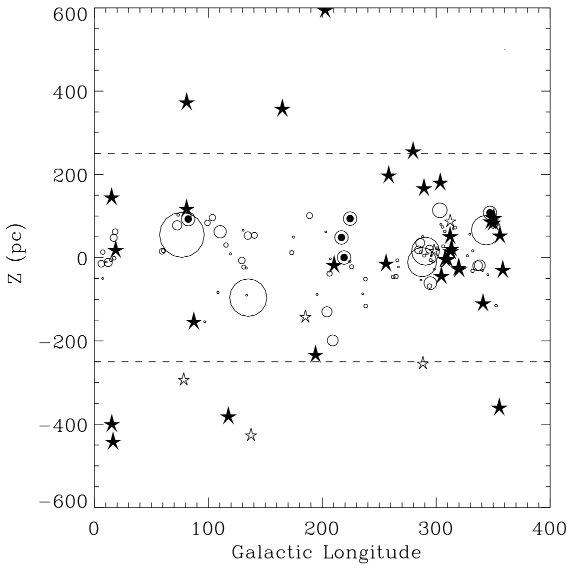

Fig. 2. Height above the Galactic plane (*Z*) as function of the galactic longitude for O field stars. The empty asterisks are suspected runaway stars from Table 2 and stars associated with clusters of Table 3. The five filled and encircled symbols have indication of a nearby cluster. All open circles indicate associations of OB stars within 3 kpc of the Sun from Mel'Nik & Efremov (1995). The size of each open circle is proportional to the estimated richness of the association.

component marginally larger than 40 km s^{-1}. They are listed in Table 2. While some of them have already been suggested as runaways, they were not classified as such by G87 due to the more stringent selection criteria applied; these stars were therefore instead classified in the more general terms of an O-type field star. Apart from the double line spectroscopic binary HD 15137, the other six stars are optical/spectroscopic singles (see Table 2). This would corroborate the hypothesis of a dynamical origin, because a high velocity ejection of a multiple system is not likely.

Finally, we note that the four stars with clusters (encircled symbols) do not have large spatial velocities. They occupy the region of the field population in Fig. 1. A exception is HD 57682, that has the largest proper motion of all. It therefore becomes probable that the cluster marginally detected is likely to be a statistical noise fluctuation (see also Paper I).

3.2. Distance from the Galactic plane

Distance from the Galactic plane (*Z*) is a useful and indirect tool to infer present (or past) high spatial velocities. The threshold distance for identifying runaway OB star is generally taken to be 500 pc (G87). This translates into a perpendicular *Z*-component velocity of ~30 km s^{-1}, given that high-mass star formation is confined to ~200 pc from the Galactic plane, as illustrated in Fig. 2. The figure shows the OB associations within 3 kpc radius of the Sun identified by Mel'Nik & Efremov (1995). The OB associations are represented by the circles whose size depends on the stellar richness. Star formation is assumed not to occur in the halo of Galaxy (e.g. Ramspeck et al. 2001).

To exclude possible OB-runaway stars from our sample, we adopt a threshold value of $Z = 250$ pc as the maximum allowed distance for the field O stars. This number is derived from the observed distribution of OB association and the "drift distance" of ~65 pc based on the O star main-sequence lifetime. Field O stars have an average peculiar radial velocity of 6.4 km s^{-1} (G87) and, moving ballistically, may therefore wander about 65 pc in an average lifetime of 10^7 yr.

Any O field star with *Z*-value larger than 250 pc is regarded as a candidate OB-runaway star. This strict constraint leads to the exclusion of 11 O-type stars, marked as asterisks in Fig. 2 that are above and below the dashed threshold distance. Among these, three stars (HD 15137, HD 91452, HD 201345) are also found to have large spatial velocities (the open asterisks).

As an example, we point out the remarkable star HD 41161 at a distance of $Z = 355$ pc and at $l = 165$ deg. At this distance from the Galactic plane this star is an OB-runaway candidate. This star shows evidence for a IR bow shock (Noriega-Crespo et al. 1995), which would strongly confirm its runaway status. However, HD 41161 is listed as a visual binary with 10 arcsec separation and a period of 243 000 yr (M98). Whether hard binaries may be able to dynamically eject a visual binary is very unlikely (Leonard & Duncan 1990). On the other hand, wide binaries are readily destroyed by stellar encounters in dense clusters. The nature of HD 41161 remains therefore unclear.

3.3. Low velocity ejection from young stellar clusters

The observations presented in Paper I show that less than 12% of the Galactic field O stars are found in small clusters. In the previous two subsections, we have seen that 15 additional stars

Table 3. Field O stars possibly associated with young clusters. See Tables 1 and 2 for the meaning of the abbreviations used in Cols. 2 and 3. The projected distance is with respect to the distance of the field O star.

Name	VM	SM	Proj. dist. (pc)	Cluster	Age (Myr)	Ref.
HD 117856	VB	SB2:	57	St 16	4	1
HD 125206	single	SB2:	45	NGC 5606	7	2
HD 154368	VB	SBE	42	Bo 13	6.3	3
HD 154643	single	SB1:	44	Bo 13	6.3	3
HD 158186	single	SBE	30	NGC 6383	1.7	4
HD 161853	single	SB1:	55	Col 347	6.3	3
HD 169515	single	SB2OE	65	NGC 6604	4	3

1: Turner 1985; 2: Vazquez et al. (1994); 3: Battinelli et al. (1994); 4: Fitzgerald et al. (1978).

can be considered as possibly dynamically ejected stars based on a high tangential peculiar velocity or a large distance from the Galactic plane. Here, we consider the possibility that the field O stars in the Galactic plane "ran away" from their birth clusters at a more moderate velocity than the classical runaway stars. However lacking precise proper motion data, we attempt to make basically a zero-order retracing of the field O stars back to their possible location of origin. We adopt the simple assumption that finding young clusters in the vicinity of an isolated O-type star supports the conjecture that the star originates there. The tangential peculiar velocities derived in the previous subsection are useful only for stars with high proper motions, while for the low tangential peculiar velocities the relative error is generally too large to allow an estimate of the direction of the stellar motion.

In Paper I we report for each O star the clusters with an age less than 10 Myr that are found within the projected "drift distance" of 65 pc (see previous section). We require that the distance to the Sun of the O star and cluster are similar within the uncertainty and adopt a distance uncertainty for the O stars of 30%. In 7 cases a young cluster is found to exist within the set boundaries. In Table 3 we list the basic information on each O-type field star and associated cluster. In these cases we assume that the probability to find such a cluster and an O field star in the same region of the sky is small. Below we describe briefly the characteristics of each cluster, as far as they are described in the literature:

Stock 16: a massive young cluster lying in the H II region RCW 75 containing a 09.5 V star HD 115071 (Penny et al. 2002) and for which the most luminous member is identified as an O7.5III((f)) star by Walborn (1973). This particular cluster stands out due to a large proportion of close binary systems among its present population (Dokuchaev & Ozernoi 1981) indicating possibly a dynamical past with frequent gravitational encounters between its members.

NGC 5606: the core of this cluster is reported by Vazquez et al. (1994) to be underpopulated in low-mass stars and showing "five bright stars forming a compact group". Such a hierarchical situation is expected to exist in a cluster able to expel massive stars (Clarke & Pringle 1992).

Bochum 13: no characteristics known.

NGC 6383: in the centre of the young cluster a spectroscopic binary HD 159176 (O7 V + O7 V, P = 3.37 days; Stickland et al. 1993) is found. The cluster may belong to the Sgr OB1 association.

Col 347: no characteristics known.

NGC 6604: the young cluster contains some massive components in the form of an eclipsing double-line spectroscopic O5-8V + O5-8V binary with a 3.3 day period. In addition a triple object containing an O8 If star is present (García & Mermilliod 2001).

In conclusion, the young clusters located within 65 pc of an O-type field star (Table 3) show the required characteristics (as far as we know) to be the possible hosts from which a massive star can be dynamically ejected (e.g. Clarke & Pringle 1992).

On the other hand, for the 15 runaway candidate stars discussed in Sects. 3.1 and 3.2 it is much less likely that there exists a young cluster within the drift distance of 65 pc. These candidate OB-runaway stars should have space velocities that would move them much further away from their birth sites. Indeed, this is borne out by our search that reveals no young cluster around any such object (see Paper I).

4. Discussion

Whether the generally observed relation between massive stars and clusters has a physical origin or is simply a statistical phenomenon is here reconsidered using our analysis of the sample of 43 O-type stars in the Galactic field. Assuming that all high-mass stars form in clusters, we have attempted to explain the current location of these stars by exploring two possibilities: (1) they are in fact members of small (or embedded) stellar clusters that have not been detected previously; (2) they have presumably been ejected from a cluster birth site. These two explanations for the current isolated location are found not to be satisfactory in a small number of cases. This indicates that a small percentage of high-mass stars may indeed form in an isolated way (Li et al. 2003).

4.1. The observed number of field O stars

In Paper I we have shown that 12% (5/43) of the massive field stars are found located in stellar density enhancements. In two cases, these newly detected clusters appear to be populous enough that the presence of a high-mass star is consistent with what is expected from a standard IMF. In the other three cases, the detection is more marginal. In particular the cluster marginally detected near HD 57682 could be a false detection, given the stars' high proper motion (see Sect. 3.1).

For the remaining stars we have sought an interpretation based on the dynamical ejection from young stellar clusters, adopting less stringent but still acceptable criteria in order to identify possible runaway stars. Using Hipparcos proper motions, we have identified 7 field O stars with peculiar tangential motion normalized to one component greater than 40 km s^{-1}.

Eight additional stars were found to exceed a distance of 250 pc from the Galactic plane. Such a distance corresponds to the limit of the observed vertical distribution of OB associations and to the maximum extent field O stars may wander given their average radial velocity. Additionally, we have tentatively associated 7 field O stars with clusters of age less than 10 Myr, located within a projected radius of 65 pc. The resulting 22 field O stars with a possible ejection history from a crowded environment are listed in Tables 2 and 3. In order to identify the genuine sample of isolated field O stars, we must discard HD 135240, and HD 135591 that have been suggested to be part of the stellar group Pis 20 (Mel'Nik & Efremov 1995) and the object HD 113658 that is reported to be member of the Cen OB1 association in the Luminous Star Catalogue (Humphreys & McElroy 1984; see Paper I).

The presented statistical analysis reduces the number of field O stars to 11 objects whose current isolated location may correspond to their actual birth location. They are given in Table 4. We note that all stars except two are in the Hipparcos dataset, and were therefore not found to have high proper motions in Sect. 3.1. The absolute number of 11 O-type field stars corresponds to 6% of the complete Galactic O-type star population with $V < 8^{\rm m}$, considering its total number of 193 O-type stars (M98). The percentage can be refined by considering the fact that if indeed the field stars in Table 4 have formed as single objects, traces of star formation (dark clouds, emission nebulae, etc.) in the surrounding field may still be present. Our search in Paper I for such tracers resulted in positive detections near four stars. They have been marked by an asterisk in Table 4 and would present the best examples for isolated Galactic high-mass star formation. However high-mass stars can eject enough momentum (mechanical and radiative) in the surrounding medium to efficiently remove hints of their formation in 10^6 years. Therefore the absence of star formation tracers near the remaining 7 stars does not exclude that the field O star has not formed in situ. We conclude that a refined percentage of 4 ± 2% of the high-mass stars in the Galaxy may have formed in isolation. The current incompleteness in the census of the embedded massive star population will not change this ratio; both the embedded massive stars in clusters and the embedded isolated massive stars will likely suffer from similar incompleteness percentages. We see thus that nearly 95% of the Galactic O star population is located in a cluster or OB association or can be kinematically linked with clusters/associations. We conclude that in the solar neighborhood, the probability of the formation of a high-mass star in special conditions seems unlikely, but cannot be completely excluded.

4.2. Comparison with the predicted number of field O-type stars

In this subsection we attempt to calculate the expected number of isolated field O-type stars, based on the assumption that stars form in clusters with a richness that is distributed according to a continuous power law down to the smallest clusters containing only one member.

Table 4. The final 11 O-type field stars that could not be associated with clusters. An asterisk indicates if the surrounding field shows signs of star formation as reported in Paper I. The abbreviations are the same as in Tables 1 and 2.

Name	VM	SM
HD 39680	OPT	C
HD 48279*	OPT	C
HD 96917	single	SB1:
HD 112244	VB	SB1:
HD 120678	single	U
HD 123056*	single	C
HD 124314*	VB	SB1:
HD 154811	single	C
HD 165319*	single	C
HD 193793	VB	SB2O
HD 202124	single	C

That the number of stellar clusters are distributed in mass according to a power law $dN/dM_{\rm cl} \sim M_{\rm cl}^{-\beta_{\rm CMF}}$ is becoming an established idea. The cluster mass function (CMF) in different astrophysical environments like super star clusters (Zhang & Fall 1999) or globular clusters (Harris & Pudritz 1994) are consistent with a value of $\beta_{\rm CMF} = 2$ (see also Elmegreen & Efremov 1997). Recently Oey et al. (2004) showed that in the Small Magellanic Cloud (SMC) the number of clusters/associations also appears to be distributed like a power law with the richness in OB members (N_*), i.e. $dN/dN_* \sim N_*^{-\beta}$. Empirically they found an index for $\beta = 2$ similar to the distribution of the number of clusters by mass.

An important finding by Oey et al. is that the cluster distribution by N_* can account for the cluster richness distribution for all observed OB clusters/associations in the SMC down to clusters containing only one OB star. One can extrapolate the Oey et al. result by assuming that (1) high mass and low mass stars are all formed in clusters, and (2) the cluster richness distribution follows a single power law, down to "clusters" containing a single star. This assumption allows one to calculate the expected number of isolated field O stars, by using a Monte Carlo simulation that draws cluster richness from a certain power law distribution and populate each cluster adopting a stellar IMF. We note that the cluster distribution function we adopt is by number of stars N_* contained in each cluster and not by the total mass of the cluster and these two distributions are in principle different. However in the following we continue to refer to this distribution as CMF.

In Fig. 3 the results of the Monte Carlo simulations are presented in the form of cumulative distributions. The distributions in each panel correspond to runs involving 0.5×10^6 clusters. Both panels show the cumulative distribution of two different parameters as indicated on the horizontal axis. The first parameter is the number of O-type stars per cluster (upper full curves in both panels). The second parameter is the stellar richness for each O-type star cluster, i.e. a cluster where the most massive

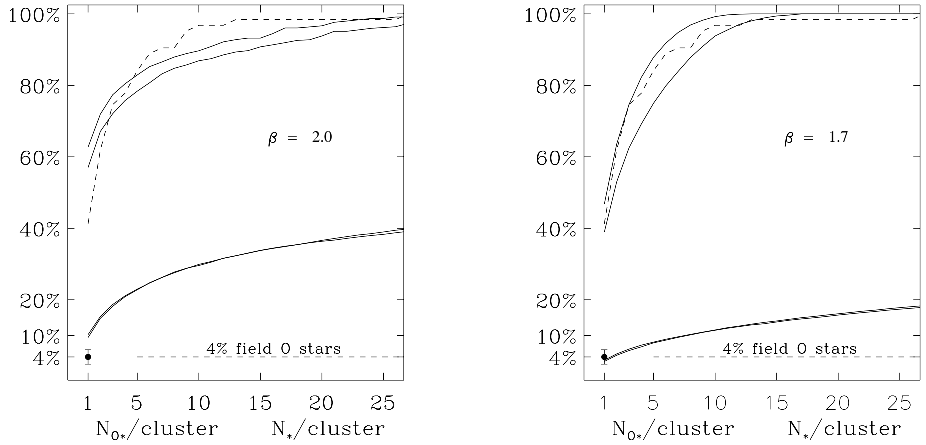

Fig. 3. Both panels show the calculated cumulative distribution for the total number of *stars per cluster* (lower full curves) and the number of *O-type stars per cluster* (upper full curves). The simulations have been done for 2 stellar IMFs (see text), therefore there are 2 upper and 2 lower full curves, although the latter are hardly distinguishable. An O-type star in the simulation is a star more massive than 17.5 $M_\odot$. The dashed curves correspond to observed number fraction for Galactic OB-associations. The point with the errorbar corresponds to the observed number of Galactic field O-type stars, following the analysis in this paper. The left panel is for a CMF with slope β = 2.0 and the right panel for β = 1.7. The right panel fits the observations.

member is of O-type[1] (lower full curves in both panels). There are two upper and two lower curves corresponding to two different stellar IMFs, viz. Salpeter (1955) and Kroupa (2002). The calculations are found to depend critically on the mass of the most massive cluster; more massive clusters have more O-type stars and therefore the cumulative distribution will rise more slowly. Observed quantities are represented in each panel by dashed lines. The cumulative distribution of the number of O-type stars per Galactic OB-association (corresponding to the upper curves) is derived from the catalogue of M98, where we took a pure statistical approach, in that a O-type binary logically counts for two objects.

The left panel in Fig. 3 shows the results for a CMF with a slope of $\beta = 2$. We applied the value of the most massive OB-association in the sample of M98 in the computation. The largest association in M98 is Sco OB 1 that contains 27 O-type stars, equivalent to $\sim 1.2 \times 10^4$ $M_\odot$. The upper full curves indicate that in this case ~60% of all massive clusters/OB-association contain only a single O-type star. The observed distribution (dashed line) indicates a somewhat lower percentage amounting to ~40%. We see therefore that a CMF of $\beta = 2$, produces too many single O-type star OB-associations. The same cluster size distribution also predicts that about 10% of the O-type stars are single stars (lower curves, left panel). Comparing this number with the rederived statistics in the previous subsection, i.e. 4 ± 2%, we see that this distribution predicts too many single isolated O-type stars.

In the right panel we try to fit the observations and find a best fit for a CMF with a slope of $\beta = 1.7$. The fit requires a maximum number of stars per cluster to be 3×10^3. As far as the distribution of the number of O-type stars per OB-association *and* the number of isolated O-type stars is concerned, we conclude therefore that the Galactic data for O-type stars is better fitted by a CMF with a slope of $\beta = 1.7$. This result differs from the value of $\beta = 2$ for the distribution of the number of OB-type stars per association in the SMC (Oey et al. 2004). On the other hand, a power law function of $\beta = 1.7$ is also preferred by Bonnell & Clarke 1999 in their calculations to fit the empirical richness distribution of the small-scale clusters near HAeBe stars (Testi et al. 1999), indicating possibly a difference in the the distribution of cluster richness between SMC and Galaxy.

4.3. The field IMF of massive stars

If all stars were formed in stellar clusters that have a continuous size distribution down to the smallest clusters, then the production of isolated high-mass stars is primarily dependent on the cluster mass function and to a much lesser extent sensitive to stellar mass functions, as shown in the previous subsection and clearly visible from the lower curve in Fig. 3. The above assumption also implies that an IMF derived from a field population will be found steeper than that of individual clusters. The latter observation is borne out in two recent papers by Kroupa (2004) and Kroupa & Weidner (2003) discussing the IMF of the Galactic field. They conclude that the IMF of the early type field population is steeper than the IMF of a stellar cluster, with $\alpha_{\rm field} \gtrsim 2.8$. As is correctly pointed out by the authors, this does not necessarily constitute a different star formation mode, but could be considered as the convolution of the cluster size and stellar mass distribution functions.

Similar reasoning may hold for the very steep mass functions found for the general stellar field in some external galaxies. These steep mass functions have led to the suggestion of star formation modes in these galaxies different from those observed in the Milky Way Galaxy. For example a very steep initial mass function for the field of the Large Magellanic Cloud is derived by Massey et al. (1995) and Massey (2002), based on their finding of high-mass field stars. Also the bulge of M 51 has been suggested to be capable of forming very high-mass

[1] An O-type star in this case would be a star more massive than 17.5 $M_\odot$.

isolated stars, possibly the result of a different star formation mode (Lamers et al. 2002). The interesting question now is whether the Galactic field O-type stars in Table 4 have a formation history similar to these extra-galactic objects, and whether the existence of these objects could again be the combined effect of a stellar mass function and a cluster size function. Proper motion observations for this particular set of stars are especially warranted.

5. Conclusion

Starting from the idea to test whether all massive stars form in clusters, we aimed at elucidating the formation mechanism of Galactic O-type field stars. Our two step approach consisted in a search for as yet undetected stellar clusters hosting the seemingly isolated high-mass stars (Paper I), and by testing whether the field O-type stars have undergone a dynamical ejection event from a young stellar cluster (this paper). The conclusion drawn in Paper I is that the field O-type stars are for the large majority isolated; the search for clusters resulted in the detection of only 5 possible clusters near a total number of 43 O-type field stars. In this paper we conclude that a high fraction of the O-type field stars (22/43) can be considered to be runaway star candidates, based on their present or former peculiar space velocity, and the vicinity of some of them to very young clusters (<10 Myr).

The main conclusion is that at present 4 ± 2% of the complete population of Galactic O-type stars cannot be traced to a formation in a cluster/OB-association. These stars could be the Galactic analogues of isolated high-mass stars found in the general stellar field of the Magellanic Clouds (e.g. Massey 2002). If true, this result implies that there is a small percentage of high-mass stars that may form in isolation. In fact statistical arguments using the IMF and a cluster mass function can actually reproduce such a percentage assuming that all stars are formed in clusters, that follow a universal cluster distribution (by N_*) with a slope of $\beta = 1.7$ down to clusters with a single member. Statistically the presence of high-mass stars in the field may represent the combined effect of a universal cluster size distribution *and* a stellar mass function. In physical terms, our study supports the conclusion about the rarity of the formation of a high-mass star outside a stellar cluster, but this mode (i.e. outside clusters) of high-mass star formation in the Galaxy cannot be excluded by our analysis presented here.

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Appendix A: Clusters near HD 52533 and HD 195592

HD 52533 is surrounded by a cluster with an estimated density of $\log(\rho_{I_C}) = 2.5 \pm 0.9$ stars per cubic parsec that is complete to a minimum mass of $\sim 0.8\ M_\odot$. This estimate is based on the I_C values converted to a volume density using the observed radius. The cluster stellar density is comparable to that of the richest clusters near early-type HBe stars like MWC 297 (Testi et al. 1999).

HD 195592 is a particularly interesting case as the associated IRAS source has a "bubble" or "bowshock" shape (van Buren 1995), typically found in runaway objects. The fact that HD 195592 is of luminosity class Ia does not affect the interpretation that in an evolutionary sense it is closer to its origin than to its dimise. For example, if we examine the MK spectral types of the Ori OB1 association, for a single spectral type (O9.5) we find all luminosity classes present as members (G87). Considering HD 195592, we also note that the density map (see Fig. 16 of Paper I) shows a second cluster centered on the bright early-type star to the NE of HD 195592. Unlike HD 52533, HD 195592 has a relatively high extinction ($A_V \sim 3^m$), easily seen in optical images that reveal the ionized emission originating from the swirls of interstellar gas in the region. Since a single O5 star can completely disperse a $10^4\ M_\odot$ molecular cloud in about 1 Myr (Yorke 1986), such a cloud could well be the remnant of the birth environment. All this indirect evidence suggests a relatively young age for HD 195592.

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