Massive Star Birth: A Crossroads of Astrophysics
Proceedings IAU Symposium No. 227, 2005
R. Cesaroni, M. Felli, E. Churchwell & C. M. Walmsley, eds.

doi:10.1017/S1743921305004758

Origins of field O-type stars

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Abstract. About 20% of the high mass O-type stars in the Galaxy are found outside stellar clusters and associations. In the solar neighbourhood this fraction amounts to 43 O-type stars. In the framework of high-mass star formation, we search for the origins of these stars. We aim at separating the O-type field stars from runaway O-type stars, where the former does not betray any indication of past dynamical interactions resulting in their present field location. We specifically search for the presence of stellar clusters, but also evaluate spatial velocities, distance from Galactic plane, locations in the Galaxy with respect to young stellar clusters. Among our sample of 43, we find that 5 stars are in fact observed in the K-band to be members of previously unnoticed small clusters. On the other hand it is plausible that nearly half the sample (22 objects) could have undergone a dynamical ejection from a young cluster. Based on the current available data, ~4% of the Galactic O-type stars cannot be associated with a stellar cluster. Finally by assuming that stars form in clusters with a power law in membership number with index −1.7 down to "clusters" consisting of single stars, we calculate the expected statistics regarding isolated O stars and O stars in OB-associations. We conclude that the results of the calculations are consistent with the observed statistics of O-type stars.

Keywords. stars: formation, stars: early-type, (Galaxy:) open clusters and associations: general

1. Introduction

The large majority of high-mass stars are part of stellar groups: young star clusters or OB-associations. This observation lead to the idea that the formation of a high-mass star is possibly intrinsically connected to the formation of a star cluster. Interactions between forming stars and gas in a clustered environment may play an important role by helping to redistribute angular momentum and enabling continuing accretion to occur (Larson 1990). Importantly, difficulties associated with the physics of standard mass accretion and high-mass star formation (see e.g. Tan 2003) may be circumvented in a cluster-based, coalescence-type scenario (Stahler, Palla & Ho 2000; Bonnell, Bate & Zinnecker 1998). Coalescence does require physical conditions that are as yet unobserved (but see Bally & Zinnecker 2005). On the other hand the formation of a high-mass star from a collapsing massive turbulent core under high external pressure (McKee & Tan 2003) and subsequent mass build up through an accretion disk (Yorke & Sonnhalter 2001; Krumholz, McKee & Klein 2005) is mildly supported by various observations in the IR and mm wavelengths of high-mass molecular cores, rotating CS-disks or disk-like structures and outflow signatures (see the various contributions on these topics in this volume). However the competing formation schemes make a common prediction, i.e. that a high-mass star forms inside a star cluster. Here we give account of some observational considerations regarding the isolated O-type stars in the Galactic field.

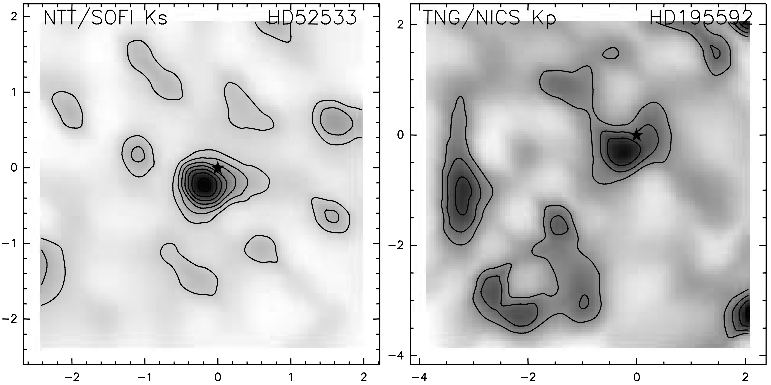

Figure 1. Clusters detected near the O-type field stars HD 52533 and HD 195592. The stellar density maps have been constructed from K-band imaging and probe masses down to a tenth of a solar mass. The contours are 1σ spaced deviations from the average stellar density value in the field of view. Location of the target star is indicated by an asterisk. The ordinates are in arcminutes and correspond roughly to a few parsecs. The clusters have radial sizes of ~0.25 pc.

2. The Galactic field population of spectral type O

Some 70% of the O-type stars in the Galaxy are found in clusters or OB-associations, ~10% are OB-runaway stars, and ~20% are field O stars (see Gies 1987; Mason *et al.* 1998; Maíz-Apellániz *et al.* 2004). Whether all Galactic O-type stars actually *form* in clusters is a recurring question the answer to which has remained the same over the years: "We may thus say that the great majority (if not all) O stars are formed and are still present in clusters and associations", was the conclusion by Roberts (1957).

The actual number of field O stars has declined since the publication of the "Catalog of O type Stars" (Garmany *et al.* 1982). Herein nearly half the O-type stars (with $V < 8^{m}$, roughly corresponding to a maximum distance of 2 kpc) could not be associated with OB-association or clusters. In a detailed study by Gies (1987), the fraction of field O stars had fallen to ~20% due to newly established membership. From 1987 onwards the field O star fraction has remained about 20%, despite discovery of new stellar groupings (e.g. Mel'Nik & Efrimov 1996).

In this contribution we aim to elucidate the origins of the O-type field star population in the solar neighbourhood. We report on an IR imaging campaign to search for clusters near field O stars in Sect. 3. The found low-detection rate of star clusters leads us to consider the OB-runaway star hypothesis in Sect. 4. Here we find that nearly half of the field O stars could plausibly be runaway objects. In the discussion (Sect. 5) we calculate the expected number of O stars formed in isolation from a statistical point of view and compare these results with the revised observed number.

3. Absence of clusters near field O stars

Some 43 field O stars with $V < 8^{m}$ catalogued by Mason *et al.* (1998) were selected to search for undetected stellar clusters centred on the sample stars (de Wit *et al.* 2004). High resolution stellar density maps were constructed from deep (down to fraction of a solar mass) K-band images taken with ESO's NTT and the Italian 4m telescope TNG on La Palma. The maps probe linear scales of ~0.25 pc. Lower resolution maps were constructed from 2MASS K-band covering tens of parsecs with a 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. 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. The two best examples are presented in Fig. 1, *viz.* the field O stars HD 52533 and HD 195592. Converting the detected density enhancements into volume densities, we obtain ∼1000 stars per cubic parsec. The radii of these clusters are measured to be 0.30 pc and 0.25 pc respectively. We note that these values are comparable those found near the early type Herbig AeBe stars (Testi *et al.* 1999). The imaging campaign revealed thus that ∼85% of the field O-type stars are in fact isolated.

4. Field O stars: a runaway history?

The low-detection rate of star clusters near field O stars lead us to consider the OB-runaway star hypothesis (de Wit *et al.* 2005). Within a 2 kpc radius from the Sun, the percentage of confirmed O-type runaway stars is ∼10%. They are characterized by high spatial velocities (presently or in the past) acquired from dynamical interactions in the centres of young dense stellar clusters or due to a binary supernova explosion (Blaauw 1961; Gies & Bolton 1986; Clarke & Pringle 1992; Hoogerwerf *et al.* 2001) . Evaluating a runaway nature for the field O stars, we re-examined their spatial velocity distribution using Hipparcos data, their spatial distribution with respect to the Galactic plane, and their proximity to known young clusters. The results can be summarized as follows:

• Peculiar space velocities for 35 field O stars are derived using Hipparcos (ESA 1997) proper motions and radial velocities from Gies (1987). The left panel of Fig. 2 demonstrates the identification of seven candidate runaway O stars by applying the traditional velocity limit of 40 km s^{-1}. Some are known candidate runaways (for references see de Wit *et al.* 2005). Apart from the double line spectroscopic binary HD 15137, each star is both optically and spectroscopically a single object.

• Massive star formation is confined to a distance of ∼200 pc from the Galactic plane. This is exemplified in the right panel of Fig. 2. It shows the spatial distribution of OB associations within 3 kpc of the Sun (Mel'Nik & Efremov 1995). Field O stars have an average peculiar radial velocity of 6.4 km s^{-1} (Gies 1987) and, moving ballistically, may wander ∼65 pc in an average lifetime of 10^7 yr. We apply therefore a maximum allowed distance of 250 pc from the Galactic plane, as the present location of a field O star. This leads to the identification of eleven field O stars as runaway candidate stars, three of which (HD 15137, HD 91452, HD 201345) were also found to have large spatial velocities. Among the stars, again the large majority is found to be single.

• The location of a young (< 10 Myr) stellar cluster in the proximity of a field O star suggests a possible physical connection between two such young objects. In seven cases such a cluster is observed within the wander distance of 65 pc. As far as these clusters have been studied, their nature supports a history of dynamical interactions among its constituents and the possible ejection of high-mass stars (e.g. Stock 16, Dokuchaev & Ozernoi 1981).

In conclusion, the search for candidate runaway stars among the O-type field stars (using more relaxing constraints than generally adopted in identifying runaways) yields 22 new candidate runaway O stars. It reflects the importance of dynamical interactions for massive stars in young clusters. Ultimately, we thus find a fraction of 4 ± 2% of all O-type stars that is not associated with a cluster/OB association. In the next section we speculate on the possibility of a formation in the Galactic field for these massive objects.

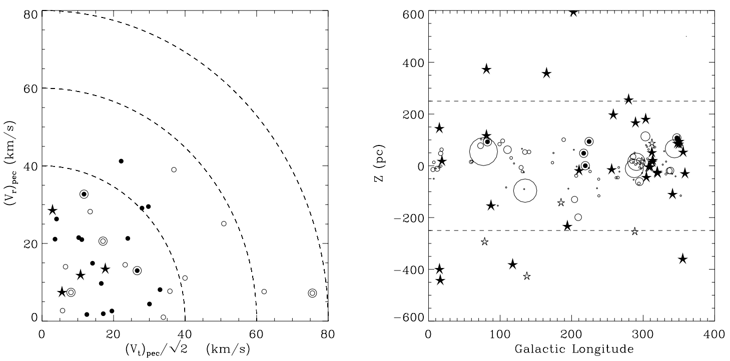

Figure 2. *Left:* The peculiar space velocity for 35 O-type field stars from Hipparcos proper motion measurements. Symbols are as follows: asterisks indicate a peculiar space velocity with an absolute error less than 10km s^{-1}, filled circles an error between 10-20 km s^{-1}, and empty circles errors >20km s^{-1}. Encircled symbols indicate stars that are found to reside in small scale clusters, as depicted in Fig. 1. Some field O stars have space velocities not different from the bulk of the Galactic field. Note that not all field O stars have Hipparcos proper motions.
Right: The location of O stars projected perpendicular to the Galactic plane. The open circles show OB-associations within 3 kpc of the Sun from Mel'Nik & Efremov (1995). The size of the circle is proportional to the estimated stellar richness of each association. Filled encircled dots correspond to field O stars found to reside in small scale clusters. The remaining field O stars are all indicated by asterisks: open asterisks for those that have peculiar spatial velocities larger than 40 km s^{-1}, otherwise filled asterisks.

5. Discussion

In a number of studies it is shown that a strong radiation field is able to the destroy the CO molecules in molecular clouds. The clouds are then described by a stiff equation of state. It would prevent a collapsing cloud from fragmenting and may produce single high-mass objects (see Spaans & Silk 2000; Li, Klessen & Mac Low 2003). In the following we estimate the probability of forming a massive star in isolation. To this end we assume that all stars form in clusters that are distributed in size according to a power law (e.g. Zhang & Fall 1999; Harris & Pudritz 1994; Elmegreen & Efremov 1997; Oey, King & Parker 2004) down to "clusters" consisting of a single member. Each synthetic cluster is subsequently populated according to an IMF.

The results of the calculations are presented as cumulative distributions in Fig. 3. Each distribution corresponds to a run comprising 0.5×10^6 clusters. Each panel shows the cumulative distribution of two different parameters as indicated on the x axis, namely (1) the total number of stars per cluster when the most massive cluster member is at least of O-type† represented by the two *lower* full curves in each panel. And (2) the two *upper* full curves in each panel represent the cumulative distribution of the total number of O-type stars per cluster. The upper and lower full curves are represented twice, corresponding to calculations with different shape of the stellar IMF, *viz.* a Salpeter (1955) and Kroupa (2002).

The upper two full curves in the left panel thus show that for a CMF with slope −2 that about 60% of the O-type stars are expected to be in clusters containing only 1 O-type star. The observed distribution (Mason *et al.* 1998) shows the somewhat lower fraction of ∼40%. Moreover the observed distribution is also found to be steeper than the calculated one. The model with power slope −2 also predicts that about 10% of the

† an O-type star in this case would be a star more massive than 17.5 $M_\odot$.

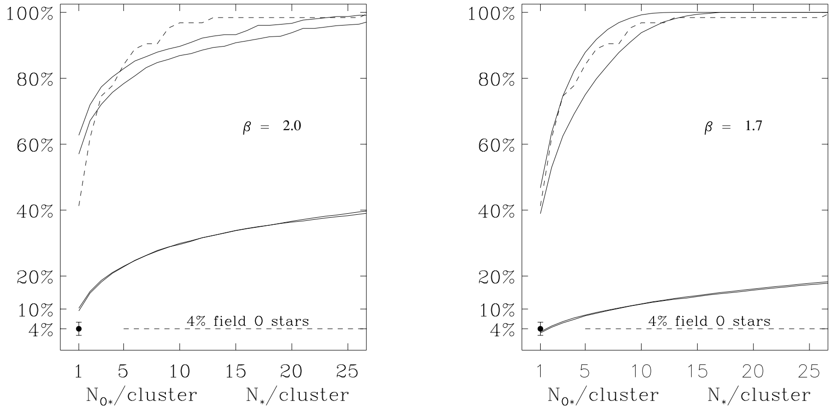

Figure 3. Both panels show the cumulative distribution of (1) the number of O stars per cluster (two upper full lines) and (2) the number of stars per cluster that have at least 1 O star (two lower full lines). The left and right display the same quantities for two different slopes of the cluster distribution. The dashed curve is the observed distribution of O-type stars per OB-association (Mason *et al.* 1998). Indicated by the dashed horizontal line is the percentage of Galactic field O-type stars, as revised in this contribution.

O-type stars are single stars (left panel, lower curves). This prediction is nearly independent of the adopted stellar IMF and somewhat higher than the observed ∼4% of field O stars. A CMF with power −2 therefore predicts too many single O-type stars and too many clusters with only one O-type star. The right panel shows the results for actually fitting the observations. The Galactic data for O-type stars is best fitted with a value of −1.7 for the CMF power index. It reproduced both the observed distribution of O stars per OB-association and the number of isolated O stars. Interestingly, a similar slope for the CMF is also preferred by Bonnell & Clarke (1999) in their interpretation of the cluster richness of HAeBe clusters (Testi *et al.* 1999) due to IMF and CMF sampling.

We thus see that although the number of field O stars in the Galaxy is small, such a small fraction is actually expected if clusters follow a cluster size distribution function with a power index of −1.7. This result is reasonably independent of the shape of the stellar IMF.

6. Summary and conclusions

With the aim to clarify the origin of Galactic O-type field star population, we presented deep near infrared imaging of these 43 stars in a search for their membership of yet unknown host clusters. In 5 cases we have found the evidence of the existence of such clusters. The large majority of the field O stars is isolated. Evaluating a possible runaway nature for the field O, we identified 22 field O stars to be candidate runaway stars by plausibly relaxing the criteria for the identification of such stars.

Effectively our study of the Galactic field O stars shows that only 12 stars cannot be associated with a cluster, near some of these objects we find evidence for recent star formation. Among them only one confirmed spectroscopic binary exists and two suspected visual binaries. Thus unlike the majority of O-stars that are part of binary/multiple systems, this would indicate a further peculiarity in the their formation process. If one would adopt the assumption that all stars are formed in clusters, and clusters are distributed in size according to a power law with a slope of −1.7, all the way down to clusters with a single member, one finds a number of field O-type stars that is consistent with the revised statistics of field O stars and with the observed number of O stars per Galactic OB associations. This may therefore indicate that the Galaxy is able to form a single high-mass star without the requirement of a stellar cluster.

Acknowledgements

WJDW acknowledges financial support from the French Centre National de Recherche et des Sciences. This research has made use of the Simbad database, operated at the Centre de Donnees Astronomiques de Strasbourg (CDS), andof NASA's Astrophysics Data System Bibliographic Services (ADS). This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

References

Bally J., Zinnecker H., 2005, AJ 129, 2281
Blaauw A., 1961, Bull. Astr. Inst. Neth. 15, 265
Bonnell I. A., Bate M. R., Zinnecker H., 1998, MNRAS 298, 93
Bonnell I. A., Clarke C. J., 1999, MNRAS 309, 461
Clarke C. J., Pringle J. E., 1992, MNRAS 255, 423
de Wit W. J., Testi L., Palla F., Vanzi L., Zinnecker H., 2004, A&A 425, 937
de Wit W. J., Testi L., Palla F., Zinnecker H., 2005, astro–ph/0503337
Dokuchaev V. I., Ozernoi L. M., 1981, Soviet Astronomy Letters 7, 52
Elmegreen B. G., Efremov Y. N., 1997, ApJ 480, 235
ESA, 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA) 1239
Garmany C. D., Conti P. S., Chiosi C., 1982, ApJ 263, 777
Gies D. R., 1987, ApJS 64, 545
Gies D. R., Bolton C. T., 1986, ApJS 61, 419
Harris W. E., Pudritz R. E., 1994, ApJ 429, 177
Hoogerwerf R., de Bruijne J. H. J., de Zeeuw P. T., 2001, A&A 365, 49
Kroupa P., 2002, Science 295, 82
Krumholz M. R., McKee C. F., Klein R. I., 2005, ApJ 618, L33
Larson R. B., 1990, in ASSL Vol. 162: Physical Processes in Fragmentation and Star Formation, p. 389
Li Y., Klessen R. S., Mac Low M., 2003, ApJ 592, 975
Maíz-Apellániz J., Walborn N. R., Galué H. Á., Wei L. H., 2004, ApJS 151, 103
Mason B. D., Gies D. R., Hartkopf W. I., Bagnuolo W. G., Brummelaar T. T., McAlister H. A., 1998, AJ 115, 821
McKee C. F., Tan J. C., 2003, ApJ 585, 850
Mel'Nik A. M., Efremov Y. N., 1995, Astronomy Letters 21, 10
Oey M. S., King N. L., Parker J. W., 2004, AJ 127, 1632
Roberts M. S., 1957, PASP 69, 59
Salpeter E. E., 1955, ApJ 121, 161
Spaans M., Silk J., 2000, ApJ 538, 115
Stahler S. W., Palla F., Ho P. T. P., 2000, Protostars and Planets IV 327–+
Tan J. C., 2003, in ASP Conf. Ser. 287: Galactic Star Formation Across the Stellar Mass Spectrum, p. 207
Testi L., Palla F., Natta A., 1999, A&A 342, 515
Yorke H. W., Sonnhalter C., 2002, ApJ 569, 846
Zhang Q., Fall S. M., 1999, ApJ 527, L81