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Spectroscopic Binaries in Young Open Clusters

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Abstract. We have analysed the binarity and multiplicity characteristics of 120 O-type stars in 22 very young open clusters and found marked differences between the "rich" (N $\geq$ 6 O-type stars and primaries) and "poor" (N = 1) clusters. In the rich clusters, the binary frequencies vary between 14% (1 SB among 7 stars) and 80% (8 SBs among 10 stars). Multiple systems seem not to be frequent and stars are spread all over the cluster area. In poor clusters, the binary frequency of the O-type objects is nearly 100%, with orbital periods around 3 days. Several binaries are also eclipsing. Additional companions are always present. They form either hierarchical multiple stars or trapezium systems. These massive multiple systems are generally found close to the cluster center, although there are exceptions.

1. Introduction

For various reasons, the attention of observers has been mostly focused, in the past years, on the duplicity of solar-type stars in nearby star-forming regions. However, duplicity of massive stars in very young open clusters and associations also contains important information for the understanding of star- and cluster formation as the present work will demonstrate.

Gies (1987) and Mason et al. (1998) have found, on the basis of speckle interferometry and adaptive optics observations of O-type stars brighter than V = 8, that the binary frequency and multiplicity are higher in open clusters and associations than in the field. The survey of B2-B5 field stars (Abt et al. 1990) also resulted in a high binarity rate. If one also takes into account spectroscopic studies of several very young open clusters, these observational evidences reveal that the multiplicity of O-type stars in open clusters is very frequently equal or larger than 2, i.e. O-type stars are quite often observed in binary or multiple systems. In addition, as will be shown here, the binary frequency seems to be variable from cluster to cluster.

The present investigation confirms that the duplicity or higher multiplicity is quite high among O-type stars, and finds a different behaviour between two groups of open clusters: the so-called **rich**, normal clusters, and the **poor** clusters, with stars clustered around one massive multiple object.

2. NGC 6231

In the context of the present investigation, NGC 6231 is a remarkable cluster because it is outside its parent cloud and contains fourteen O-type stars. The most remarkable property is the high binary rate among these O-type stars, 11 among 14, as shown by Table 1, adapted from García & Mermilliod (2000) who determined new orbital elements. In addition, all periods but one are shorter than 9 days. In Table 1, the stars are ordered by increasing V magnitudes (not reproduced). "P" is the orbital period, in days. The numbering systems (S and Sung) are from Seggewiss (1968) and Sung et al. (1998), respectively.

Table 1. Fundamental data for the O-type stars in NGC 6231

HD/DM	S	Sung	$V \sin i$	Sp.T.	P	Notes
152234	290	855	150	B0 Iab	54.4605	SB2O
152248	291	856	100	O7 Ib:(f) +	5.7533	SB2O, EB
			80	O6.5:((f))		
152249	293	857	105	O9 Ib		Cst
152233	306	858	130	O6 III (f)	4.1500	SB1O
152270	220	854		WC6 + O	8.8930	SB2O
326331	338	571		O8 III	6.2420	SB2O, M?
152218	2	853	140	O9 IV	4.8925	SB2O
152219	254	234	160	O9.5 III	4.0696	SB2O
152314	161	615	65	O8.5 III		SB2, triple?
-41.11037	323	862	55	O9 III	5.7497	SB1O
-41.11042	224	505	130	O9 IV	2.4531	SB2O
-41.11029	309	350	160	O9.5 V		
152200	266	206	210	O9.5 V(n)		SB2
326329	292	434	85	O9.5 V		SB?

3. Binary Frequency of O-Type Stars in Galactic Open Clusters

3.1. "Rich" Clusters ($N_O > 5$)

Based on the data and notes presently included in the open-cluster database (WEBDA, http://obswww.unige.ch/webda/), a compilation of the binary frequency of O-type stars in 8 very young open clusters for which extensive radial-velocity surveys have been conducted shows that the binary frequency is variable (Table 2). It reaches values as high as 80% in clusters like IC 1805 (8 SBs among 10 O-type stars) and NGC 6231 (11 SBs among 14 O-type stars), and as low as

14% in Trumpler 14 (1 SB among 7 O-type stars). In the latter cluster, extensive radial-velocity observations of the seven O3-O9 stars by several groups, the latest have been obtained by García et al. (1998), resulted in the identification of only one spectroscopic binary, with a period of $5\overset{d}{.}03$ (Levato et al. 2000).

In these "rich" clusters, i.e. with a number of O-type stars equal to or larger than 6 (these figures count only the primaries), the O stars have characteristics similar to those of the other main sequence stars: (1) they appear to be single or double, (2) the rate of multiple systems is low, (3) they are spread over most of the cluster area. In addition, there is no evident dependence in function of the number of O-type stars, taken as a meaure of the richness of the clusters, nor in function of the position within the Galaxy. There are clusters located in all three spiral arms. No immediate correlation is noticed with the IMF slope (Γ) tabulated by Massey (1998) and reproduced in the last column of Table 2.

Table 2. Binary frequency of clusters $N_{\mathrm{O\ star}} > 5$.

Cluster	Number of O-stars	Number of SBs	Frequency	Γ
IC 1805	10	8	0.80	-1.3
NGC 6231	14	11	0.79	
NGC 2244	6	3	0.50	-0.8
IC 2944	16	7	0.44	
NGC 6611	12	5	0.42	-0.7
Tr 16	20	7	0.35	-1.0
Cr 228	21	5	0.24	
Tr 14	7	1	0.14	-1.0

From the list of clusters collected in Table 4, we can see that only 4 other clusters with 6 and 7 O-type stars could be added to this sample. Thus, there is little hope to produce a more statistically significant sample to base these conclusions on a firmer basis. But further radial-velocity observations would be extremely useful to determine orbital periods and confirm the predominence of short periods. Presently, most available orbits, in NGC 6231 (Hill et al. 1974; García & Mermilliod 2000) and in Trumpler 16 (Levato et al. 1991), are shorter than 10 days.

3.2. "Poor" Clusters ($N_O \sim 1-2$)

In contrast to "rich" clusters which have several O-type stars, a number of open clusters seem to have only one object classified as an O-type star. They can be called "poor" clusters, because they contain few massive stars, although some of them may contain many low-mass stars, like in the Orion Trapezium cluster. All show however interesting common properties.

Indeed, it appears that these O-type stars are in fact double-lined, often eclipsing, spectroscopic binaries, with a binary frequency of nearly 100%, Θ^1 Ori

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C being the only exception. Sometimes they even have a third O star companion. Furthermore, these massive binaries have additional, fainter companions or are hosted in trapezium systems. The multiplicity is generally equal to or higher than 3.

Table 3. Properties of O-type stars in binary or multiple systems

Cluster	Binarity	Period	Visual	N_*	N_O	Multiplicity
NGC 2362	SBE SB1O	1.3 154.9	Aa 0"15	4	2	Quadruple
NGC 7380	SB2OE	2.1		2	2	SB2
NGC 6193	SB2O SB2?	2.7	AB 1"6	4	3	Quadruple
NGC 1502	SB2OE SB1O	3.1 2.8	Ba 0"07 AB 17"9, Aa 6"0	6	1	Multiple
NGC 6604	Cst SB2E	 3.3		3	3	Triple, A B: SB2
NGC 6383	SB2OE	3.4	Aa 0"27	3	2	Triple
Tr 37	SB2O	3.7	Aa 0"09, AB 1"6	4	1	Quadruple
Tr 24	SB1O	3.9	Aa 0"23	3	1	Triple
NGC 6871	SB2O	112.4	AB 6"6	3	2	Triple
NGC 2264	SB1O	23.6y	AB 2"91	3	2	Triple
NGC 1976	Cst		Cc 0"037	>8	1	Trapezium
	SB1E	65.4	Aa 0"22			
NGC 6823				>5	2	Trapezium
IC 1848	SB2?		AG 23"7 Gg 0"3	4	2	Multiple
IC 1590			AB 1"5, AC 3"9 AD 8"9	4	3	Triple

The second striking feature is the accumulation of orbital periods around the value of 3.3 days for 8 clusters among 11, as shown by Table 3. With such short periods, several systems are eclipsing binaries, with WUMa-type light curves indicating that the stars nearly fill their Roche lobes. Additional eclipsing binaries may be discovered either among the present sample of 120 O-type stars or in O-type stars located in other "poor" open clusters with one or two O stars listed in Table 4.

No information on periods are unfortunately available for the O-type stars in the three clusters listed at the bottom of Table 3, namely NGC 6823, IC 1590 and IC 1848. Further otherwise well studied open clusters have not been included in Table 3 because of the lack of information on binarity and multiplicity of their O-type stars (Tr 27, St 16, NGC 6514, NGC 6618). They are however included in Table 4.

In some clusters (NGC 1976, 2362, 6383, 6604, 6871) the massive multiple systems are close or very close to the cluster centers (as estimated by inspection of the apparent distribution of the brighter stars), but in other cases (NGC 1502, 2264, 6193, 7380) the multiple systems are not at the geometric center of the stars forming the open clusters. More quantitative estimates of the distance of the massive systems to their parent-cluster center would be useful to decide if these sytems are born as such close to the center, or if they moved to the center after the early dynamical evolution phase.

4. Other Clusters with O-Type Stars

Table 4 collects a list of galactic open clusters which contain between 1 and 7 O-type stars, with the exception of NGC 3603 which has 23 (Moffat et al. 1994; Drissen et al. 1995). But it is far away, as are the Arches (Nagata et al. 1995) and Quintet (Nagata et al. 1990, Okuda et al. 1990) clusters located in the very central part of our Galaxy. The columns give successively the cluster designation, the number of O-type stars, the earliest spectral type, the distance modulus and the $E(B-V)$ colour excess.

Investigations, with various methods, of the multiplicity of the O-type stars is highly desirable. Photometric search for eclipses may be the easiest way to prove the duplicity and determine the periods. High-resolution spectroscopy is necessary to resolve the line profiles of the rotating O-type stars and recognize the double-lined character of the stars, as shown by the example of star S291 in NGC 6231 (Fig. 1) adapted from García & Mermilliod (2000). With the large telescopes and new spectrographs now in operation, it should be possible to observe many of these clusters. The results on the massive-star multiplicity would be very valuable to constrain and improve the models of cloud fragmentation and of star- and cluster formation.

5. Conclusions

The investigation of the multiplicity of 120 O-type stars in 22 galactic open clusters has revealed striking differences in function of the number of stars in the parent clusters. We can summarize our conclusions as follows:
In "rich" clusters with several (N > 6 primaries) O-type stars :

1. The O stars are distributed over the cluster areas, but preferently within the central parts of the cluster;

2. They "non single" O type are mostly in the form of binary systems, with short periods;

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Table 4. Further open clusters with O-type stars

Cluster	N_O	Early Sp.T	m-M	E(B-V)
NGC 3603	23	O3 V	18.86	1.44
NGC 1893	7	O6 V((f))	14.51	0.49
NGC 6618	7	O5 V	15.40	1.51
HM 1	6	O4 f	18.23	1.85
Wes 2	6	O6 V	20.06	1.59
Bo 15	5	O7 e	14.64	0.55
Pis 20	5	O9.5 Vn	16.41	1.20
Tr 15	5	O9 V	12.19	0.40
NGC 6530	4	O4 V ((f))	12.05	0.35
NGC 6913	4	O9 V	12.20	0.53
Be 86	3	O9.5 V	12.93	0.88
Bo 2	3	O8 V	15.65	0.86
Haf 18	3	O6	15.94	0.64
NGC 6514	3	O7.5 III	10.59	0.21
NGC 6910	3	O5	14.25	1.05
Tr 27	3	O9 III	14.86	1.30
Cr 232	2	O3 V((f))	14.08	0.52
Ho 22	2	O7 e	13.11	0.66
NGC 3324	2	O6.5 V(n)	14.02	0.46
NGC 6322	2	O9.5 II	12.29	0.61
NGC 6604	2	O7	15.14	1.02
NGC 7822	2	O7		
Bo 1	1	O7.5 V	14.94	0.55
Ho 10	1	O5.5 III(f)	13.10	0.47
IC 1795	1	O8		
Ma 38	1	O9.5 III	12.01	0.40
NGC 1624	1	O7 f		
NGC 2175	1	O6.5 V	13.31	0.60
NGC 2353	1	O9.7 Ib	10.46	0.12
NGC 2384	1	O8 V	12.95	0.28
NGC 2483	1	O9 V	12.08	0.31
NGC 3572	1	O7.5 III(f)	13.74	0.48
NGC 5281	1	O9 e	11.19	0.28
NGC 6167	1	O7 V	12.59	0.79
NGC 6169	1	O9.5 Ib		
Sher 1	1	O8: I		
St 16	1	O7.5 III((f))	12.94	0.48
Tr 18	1	O8	12.08	0.35

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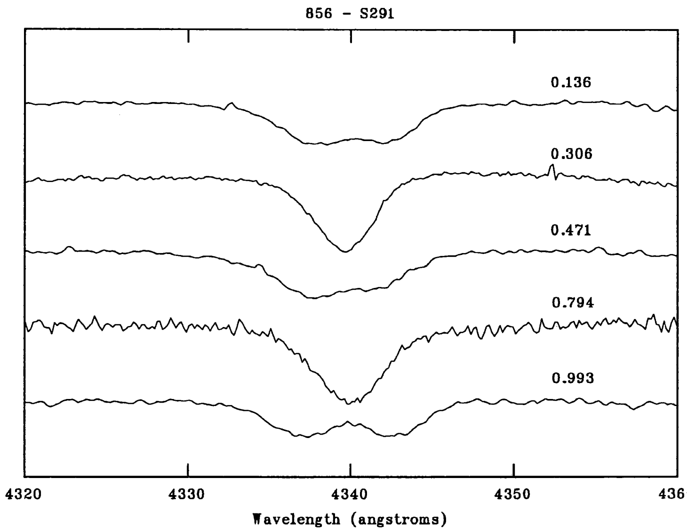

Figure 1. H_γ profiles at various phases for S291 in NGC 6231.

3. The binary frequency is variable between the clusters, but no evident correlation with specific properties has been found.
   The duplicity of the O-type stars in the clusters with the maximum (IC 1805, NGC 6231) and minimum values (Tr 14) is well documented, and therefore the differences are not due to observational biases.

In "poor" clusters, with almost one apparent O star :

1. The O stars are generally located at the very center of the cluster, with some exceptions;

2. The O stars form close binary systems, double-lined, often eclipsing, with mass ratios larger than 0.9;

3. There may be a third O-type companion;

4. The multiplicity is mostly higher than 3:
   Among 11 clusters, there are 1 SB2, 5 triples, 3 quadruples, and 2 systems with a multiplicity larger than 5;

5. The periods of the SBs are clustering around 3 $\pm$ 1 day.

The characteristics are well marked and different because we have compared, as a consequence of the available observational data, clusters mainly illustrating the two extreme situations. It would be interesting to observe additional clusters

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to add more information. Table 4 contains 16 open clusters with one O-type star identified.

If rich clusters appear to be well behaved, i.e. their characteristics, star radial distribution, binary frequency are resembling those of other, older, clusters, the case of the poor clusters is quite different. The main question is whether the observed situation results from the initial conditions, namely the stars are born near the cluster center in a multiple system, or it has been driven to the cluster center, as would be suggested by the simulations performed by Bonnell & Kroupa (1998) or Bonnell & Davies (1998), or whether it results from dynamical evolution and stellar merging (Portegies Zwart et al. 1999; Portegies Zwart et al. 2000).

In conclusion, the observational description of the binarity and multiplicity of massive stars in very young open clusters offers as many surprises and challenges as the low-mass stars in nearby star-forming regions do. It however concerns not only the theory of star- and binary formation, but also the understanding of early dynamical evolution of medium-size stellar systems in widely differing environments.

References

Abt, H. A., Gomez, A. E., Levy, S. G. 1990, ApJS, 74, 551

Bonnell, I. A., Davies, M. B. 1998, MNRAS, 295, 691

Bonnell, I., Kroupa, P. 1998, astro-ph/9802306

Drissen, L., Moffat, A. F. J., Walborn, N. R., Shara, M. M. 1995, AJ, 110, 2235

García, B., Malaroda, S., Levato, H., Morrell, N., Grosso, M. 1998, PASP, 110, 53

García, B., Mermilliod, J.-C. 2000, A&A, (submitted)

Gies, D. R. 1987, ApJS, 64, 545

Hill, G., Crawford, D. G., Barnes, J. V. 1974, AJ, 79, 1271

Levato, H., Malaroda, S., Morrell, N., García, B., Hernandez, C. 1991, ApJS, 75, 869

Mason, B. D., Gies, D. R., Hartkopf, W. I., Bagnuolo, W. G. Jr., Ten Brummelar, T., McAlister, H. A. 1998, AJ, 115, 821

Massey, P. 1998, in ASP Conf. Ser. 142, The Stellar Initial Mass Function, ed. G. Gilmore & D. Howell, 17

Moffat, A. F. J., Drissen, L., Shara, M. M. 1994, ApJ, 436, 183

Nakata, T., Woodward, C. E., Shure, M., Pipher, J. L., Okuda, H. 1990 ApJ 351, 83

Nakata, T., Woodward, C. E., Shure, M., Kobayashi, N. 1995, AJ 109, 1676

Portegies Zwart, S., Makino, J., McMillan, S. L. W., Hut, P. 1999, A&A 348, 117

Portegies Zwart, S., McMillan, S. L. W., Hut, P., Makino, J. 2000, MNRAS, (in press) astro-ph/0005248

Seggewiss, W. 1968, Veröff. Astr. Univ. Bonn, No. 79

Sung, H., Bessell, M. S., Lee, S.-W. 1998, AJ, 115, 734