The kinematic characteristics of magnetic O-type stars

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Although magnetic fields have been discovered in ten massive O-type stars during the last years, the origin of their magnetic fields remains unknown. Among the magnetic O-type stars, two stars, HD 36879 and HD 57682, were identified as candidate runaway stars in the past, and θ^1 Ori C was reported to move rapidly away from its host cluster. We search for an explanation for the occurrence of magnetic fields in O-type stars by examining the assumption of their runaway status. We use the currently best available astrometric, spectroscopic, and photometric data to calculate the kinematical status of seven magnetic O-type stars with previously unknown space velocities. The results of the calculations of space velocities suggest that five out of the seven magnetic O-type stars can be considered as candidate runaway stars. Only two stars, HD 155806 and HD 164794, with the lowest space velocities, are likely members of Sco OB4 and NGC 6530, respectively. However, the non-thermal radio emitter HD 164794 is a binary system with colliding winds, for which the detected magnetic field has probably a different origin in comparison to other magnetic O-type stars.

1 Introduction

Only in the last years, magnetic fields have been detected in a number of O and early B-type stars. To date, ten O-type stars have published magnetic fields: θ^1 Ori C (Donati et al. 2002), HD 191612 (Donati et al. 2006), HD 155806 (Hubrig et al. 2007), ζ Ori A (Bouret et al. 2008), HD 36879, HD 148937, HR 6272, 9 Sgr (Hubrig et al. 2008), HD 57682 (Grunhut et al. 2009), and HD 108 (Martins et al. 2010, Hubrig et al. 2010). However, theories on the origin of magnetic fields in O-type stars are still poorly developed. This is due to the fact that the distribution of magnetic field strengths in massive stars from the ZAMS to more evolved stages, which would shed light on the origin of the magnetic field, has not yet been studied. A number of magnetic O-type stars seem to be slow rotators and exhibit an excess of nitrogen (e.g., Walborn et al. 2003, Nazé et al. 2008a, 2008b). Note that massive stars with such characteristics are only very rarely found in clusters (Trundle et al. 2007), contrary to field stars, which frequently show slower rotation speed and nitrogen enrichment (Gies & Lambert 1992). Wolff et al. (2007) suggested that locking of accretion disks to proto-stars results in slowly rotating stars and these disks are longer lived in the field population than in clusters. Clearly, to understand the origin of magnetic fields in massive stars, it is important to build trustworthy statistics on their occurrence. About 10% of main-sequence A and B stars are slowly rotating, chemically peculiar, magnetic Ap and Bp stars, and among their descendants, the

white dwarfs, 10% have strong magnetic fields. The magnetic fields in magnetic white dwarfs could be fossil remnants from the main-sequence phase, consistent with magnetic flux conservation (Ferrario & Wickramasinghe 2005). If we assume that magnetic fields of massive stars behave like Ap and Bp stars, then we would expect a magnetic field probability of 10%.

The catalogue of Galactic O-stars (GOSV2; Sota et al. 2008) contains about 370 O-type stars. 105 O-stars (28%) in the subset of this catalogue are considered as field stars since they could not be identified as present or former members of recognised clusters or OB associations. Seventy-three of these 105 stars were recently back-traced to nearby associations and young open clusters (Schilbach & Röser 2008). Remarkably, almost one third of the star sample studied by Schilbach & Röser (2008; corresponding to ∼10% of the total number of O-stars in the GOSV2 catalogue) appeared to have rather long travel times after their ejection from their parent open clusters, longer by up to 60% than the expected lifetime of O-type stars. We suggest that one of the possible explanations for the long lifetime of these runaway stars could be the presence of magnetic fields. To test the proposition that magnetic O-type stars are frequently runaway stars, we carried out a study of the kinematical status of O-type stars with detected magnetic fields.

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2 Massive stars in the field and characteristics of runaway stars

It is generally accepted that the majority of massive stars form in star clusters or associations. To explain the origin of massive stars in the field, two mechanisms were discussed in the literature. In one scenario, close multibody interactions in a dense cluster environment cause one or more stars to be scattered out of the region (e.g. Leonard & Duncan 1990). For this mechanism, runaways are ejected in dynamical three- or four-body interactions and the model predicts that most runaways will be single stars, although some close binaries can be expected under exceptional circumstances. An alternative mechanism involves a supernova explosion within a close binary, ejecting the secondary due to the conservation of momentum (Zwicky 1957, Blaauw 1961). The resulting neutron star may remain bound to the secondary if not enough mass is lost during the explosion. The production of runaway massive binaries is expected to be rather low: Portegies Zwart (2000) predicted a binary fraction of 20%–40% among runaways that are ejected by a binary supernova scenario using binary population synthesis calculations. The observed fraction of binaries among runaways seems to be consistent with either scenario (5%—26% in Mason et al. 1998).

Schilbach & Röser (2008) followed the dynamic history of field O-type stars, calculating the path of stars and clusters back in time in the Galactic potential. For this study they used the positions and proper motions from the PPMX catalogue (Röser et al. 2008), and the radial velocities from the CRVAD-2 catalogue (Kharchenko et al. 2007). The major source of specific information on open clusters and O-type stars were the catalogues of Kharchenko et al. (2005a, 2005b). Acceptable solutions for the trajectories through the Galaxy were achieved for 73 O-type stars, indicating that the present-day data are consistent with the assumption that the major part of O-type field stars were ejected from young open clusters or protoclusters over the past 10 Myr. Since one third of the studied stars appear to have rather long travel times since their ejection from different open clusters, one of the possible explanations for the long lifetime of these runaway stars could be their rejuvenation by mass transfer just prior to the supernova explosion, which would reset their effective zero-age times to an epoch just prior to ejection. Another explanation could be that these stars are overluminous for their mass in the same way as some massive X-ray binaries (Kaper 2001), or they are all rapid rotators, where fast rotation helps to mix gas and extend their main-sequence life. The rapid rotation, however, cannot be considered as a major characteristics of runaway stars, since rather long rotation periods and low $v \sin i$-values were determined for a few runaway stars in individual studies (e.g. Grunhut et al. 2009).

In our view, the paradox between the long travel distance and the apparent young age of these stars could possibly be explained if runaway stars did undergo a rejuvenation in tight massive binary systems, where two stars merge at the end of their interaction and somehow acquire a magnetic field during this process. As Pflamm-Altenburg & Kroupa (2010) showed, only a small fraction of runaway O-type stars (1–4%) can be produced by the combined effect of massive binary ejection from star clusters and a second acceleration of a massive star during a subsequent supernova explosion. We note, however, that the current parameters in observable massive binaries are insufficient to pin down the many uncertainties about the mass-transfer process (e.g. Dray & Tout 2007), and how the rejuvenated star becomes magnetic. Maeder & Meynet (2005) showed that the presence of a magnetic field enlarges the main-sequence lifetime by $\sim$10% for a 15 $M_\odot$ star. However, no estimations were ever made for more massive stars.

3 Kinematical properties of O-type stars with published magnetic fields

Among the sample of magnetic O-type stars, two stars, HD 36879 and HD 57682, were already identified as candidate runaway stars (e.g., de Wit et al. 2004, 2005, Comeron et al. 1998). The space motion of the star θ^1 Ori C was studied by van Altena et al. (1988), who reported that θ^1 Ori C is moving at 4.8 ± 0.5 km s^{-1} towards position angle 142° and that this velocity is significantly larger that the dispersion value of 1.5 ± 0.5 km s^{-1} found for the other cluster members. The results of the radial velocity study of Stahl et al. (2008) indicate that this star is moving rapidly away from the Orion Molecular Cloud and its host cluster.

Using available data on stellar positions, proper motions, Hipparcos parallaxes, radial velocities, photometry, and cluster catalogues, we investigated the kinematical status for the remaining seven O-type stars with detected magnetic fields. The values for the stellar positions, proper motions, radial velocities, parallaxes, and B and V magnitudes in the Johnson system are presented in Table 1. They have been retrieved from the All-Sky Compiled Catalogue of 2 501 313 stars (ASCC-2.5; Kharchenko & Röser 2009) and from Kharchenko et al. (2007). If available, the values for radial velocities and spectral classification were taken from the following individual studies: from Humphreys (1978) and Martin (2010) for HD 108, Bouret et al. (2008) for HD 37742, Nazé et al. (2008a) for HD 148937, Conti et al. (1977a) for HD 152408, Conti et al. (1977b) for HD 155806, Nazé et al. (2010) for HD 164794, and Howarth et al. (2007) for HD 191612. An uncertainty of 5 km s^{-1} was assumed for the radial velocity determinations.

The calculated space velocities and their Galactic rectangular components are presented in Table 2. Apart from the parallax value for HD 37742, no accurate parallaxes have been measured for the other stars. For this reason, we used the method of indirect estimates of distances through the photometric approach, which was previously used by Kharchenko et al. (2005a). Spectral types, corresponding absolute visual magnitudes and $(B-V)_0$ on the ZAMS are

Table 1 HD numbers, stellar positions, proper motions, radial velocities, parallaxes, and magnitudes of magnetic O-type stars.

HD number	l [deg]	b [deg]	PMx [mas/yr]	PMy [mas/yr]	RV [km s^{-1}]	π [mas]	B [mag]	V [mag]
108	117.9221	1.2470	-5.12 ± 1.11	-1.15 ± 0.93	-62.0	-0.01 ± 0.64	7.505 ± 0.007	7.375 ± 0.007
37742	206.4522	-16.5852	3.99 ± 0.74	2.52 ± 0.40	45.5	3.99 ± 0.79	1.798 ± 0.005	1.898 ± 0.004
148937	336.3614	-0.2124	0.60 ± 1.42	-5.12 ± 1.15	-33.1	0.82 ± 1.30	7.038 ± 0.010	6.757 ± 0.009
152408	344.0789	1.4969	-1.21 ± 1.11	-2.28 ± 0.82	-56.5	0.33 ± 0.73	5.946 ± 0.004	5.807 ± 0.008
155806	352.5859	2.8683	0.33 ± 1.00	-2.02 ± 0.50	10.9	0.65 ± 0.76	5.559 ± 0.004	5.613 ± 0.005
164794	6.0090	-1.2050	1.92 ± 1.19	-0.40 ± 0.99	-12.0	0.66 ± 1.00	5.940 ± 0.005	5.933 ± 0.005
191612	72.9871	$+1.4365$	-3.26 ± 0.96	-6.65 ± 1.02	-5.2	0.18 ± 0.74	8.035 ± 0.009	7.821 ± 0.009

Table 2 Space velocities with respect to the Galactic open clusters system (SV$_C$) and the corresponding Galactic velocity components.

HD number	Spectral Type	M$_V$ [mag]	(B$-$V)$_0$ [mag]	dist [pc]	X [pc]	Y [pc]	Z [pc]	SV$_C$ [km s^{-1}]	U [km s^{-1}]	V [km s^{-1}]	W [km s^{-1}]
108	O6.5 V	-5.3	-0.32	2510	-1175	2217	74	94 ± 19	93 ± 12	-13 ± 7	2 ± 12
37742	O9.7 Iab	-6.5	-0.24	391	-335	-167	-91	32 ± 6	-31 ± 5	-7 ± 2	2 ± 1
148937	O6 V	-5.4	-0.32	1144	1048	-458	15	32 ± 13	-26 ± 5	8 ± 7	-13 ± 7
152408	O8 Iab	-6.7	-0.30	1694	1629	-464	64	50 ± 13	-50 ± 6	7 ± 8	1 ± 8
155806	O7.5 III	-5.7	-0.32	1251	1239	-161	82	19 ± 9	19 ± 6	1 ± 5	0 ± 4
164794	O5 I	-7.2	-0.33	2615	2600	273	-35	24 ± 21	-3 ± 6	17 ± 14	-15 ± 14
191612	O7 V	-5.2	-0.32	1874	548	1792	67	71 ± 14	70 ± 10	-11 ± 5	0 ± 9

listed in Cols. 2 to 4. The spectral class–colour–absolute magnitude calibration was based on Straizys (1992). The errors in M$_V$ and (B$-$V)$_0$ were assumed as 0.5 and 0.01 mag, respectively. The distances and rectangular galactic coordinates X, Y, and Z with respect to the Galactic plane are shown in Cols. 5–8. Space velocities with respect to the Galactic open cluster system and the corresponding Galactic velocity components are listed in Cols. 9 to 12. Solar motion parameters derived with open cluster system, ((U,V,W)$_\odot$ = (9.44, 11.90, 7.20)), Oort's constants and Z, which stand for the distance of the Sun from the Galactic plane, $Z_\odot = 20$ pc, have been determined by Piskunov et al. (2006).

In this paper we discuss runaway magnetic O-type stars, which originated in open clusters and OB-associations. For this reason, we consider their motions with respect to the Galactic open cluster system. Nowadays there is an increasing number of evidence that the open cluster system is very close in its kinematics to the local standard rest (LSR). Recently, Schönrich et al. (2010) re-examined the stellar kinematics of the Solar neighbourhood in terms of the velocity of the Sun with respect to the LSR. They obtained Solar motion parameters ((U,V,W)$_\odot$ = (11.1, 12.24, 7.25)), which are very close to those derived with open clusters.

Blaauw (1961) assigned the stellar runaway status to stars with space velocities larger than $40 \, \text{km s}^{-1}$. On the other hand, Stone (1979) and Tetzlaff et al. (2010) specified the velocity cutoff at $28 \, \text{km s}^{-1}$. This velocity cutoff is adopted in the following discussion of the obtained results. The errors in the determination of space velocities in the most distant stars are rather large because of proper motion errors. For this reason, we refrain from calling the stud-

ied stars bona fide runaways, but rather candidate runaway stars.

From the membership studies of Galactic open clusters and associations, two O-type stars, HD 155806 and HD 164794, with the lowest space velocities, are likely members of Sco OB4 and NGC 6530, respectively (Kharchenko et al. 2004). No other star in the sample is known to belong to an open cluster or an OB association. HD 155806 is also classified as an Oe star, possibly representing the higher mass analogues of classical Be stars (e.g. Walborn 1973). Only six members are suggested to belong to this group of stars (e.g. Negueruela et al. 2004). The star HD 164794 is a spectroscopic double-lined system with an orbital period of 2.4 yr, known as emitting non-thermal radio-emission, probably associated with colliding winds (Nazé et al. 2010). There are only about a dozen of non-thermal radio emitting O-type stars known (e.g. De Becker 2007) and the study of magnetic fields in such stars is especially difficult due to their broad and very variable line profiles caused by wind-wind collision.

The Of?p star HD 148937 possesses a space velocity of $32 \, \text{km s}^{-1}$ with respect to the Galactic open cluster system, with the velocity component $U=-26$ directed opposite from the Galactic center and the velocity component $W=-13$ directed from the Galactic plane. These rather large velocities indicate that this star can be considered as a candidate runaway star. HD 148937 is surrounded by the circumstellar nebula NGC 6164-65, expanding, with a projected velocity of about $30 \, \text{km s}^{-1}$ and it is assumed that this nebula has been ejected during an LBV-like event (Leitherer & Chavarria 1987). Among the remaining four stars, HD 108, HD 37742 (ζ Orionis A), HD 152408, and HD 191612, the

O-type supergiant ζ Orionis A, with the weakest magnetic field in our sample of magnetic O-type stars, shows the lowest space velocity with respect to the Galactic open clusters: $SV_{\rm C}{=}32{\pm}6\,{\rm km\,s^{-1}}$. The longitudinal magnetic field of ζ Orionis A is of the order of a few tens of G, while for all other stars, the longitudinal magnetic field is of the order of hundreds of G. The other three stars, the well known Of?p stars HD 108 and HD 191612, and the supergiant HD 152408, are moving with higher space velocities, from $50\,{\rm km\,s^{-1}}$ for HD 152408 up to $94\,{\rm km\,s^{-1}}$ for HD 108, suggesting that all of them can be considered as candidate runaway stars.

4 Discussion

The results of our kinematical analysis seem to indicate that the presence of a magnetic field is more frequently detected in candidate runaway stars than in stars belonging to clusters or associations. The peculiar velocities of three magnetic O-type stars were already mentioned in the literature, and our results of the calculations of space velocities suggest that five of the remaining seven magnetic O-type stars can be considered as candidate runaway stars. We note, however, that the sample of stars with magnetic field detections is still very small and a study of a larger sample is urgently needed to confirm the detected trend. Unfortunately, no dedicated magnetic field surveys of O stars in clusters/associations and in the field were carried out so far. In the sample of magnetic O-type stars, the two stars HD 155806 and HD 164794, with the lowest space velocities, are most probably members of Sco OB4 and NGC 6530, respectively (Kharchenko et al. 2004). However, the non-thermal radio emitter HD 164794 is a binary system with colliding winds, for which the detected magnetic field has probably a different origin in comparison to other magnetic O-type stars.

According to several studies (e.g., Gies 1987, Mason et al. 1998, Sota et al. 2008), about 70% of the massive O-type stars in the Galaxy are observed to be associated with stellar clusters and/or OB-associations. At least one third of the remaining 30% of the O-type stars, i.e. about 10%, are runaway stars, and may therefore also have formed in a cluster, where O stars can acquire high spatial velocities after dynamical interactions or after supernova explosions in binary systems. This percentage of runaways stars is similar to the percentage of Ap and Bp stars among main-sequence A and B stars. Possible paths for the formation of Ap and Bp stars were recently analysed with modern theories for the evolution of single and binary stars by Tutukov & Fedorova (2010), suggesting that merging of close binaries is the main channel for their formation. The low binary frequency of Ap and Bp stars of about 20% (e.g. Abt & Snowden 1973) and a strong deficit of SB2 binaries seem to support such a formation scenario. Similarly, the observed binary fraction of runaway O-type stars is of the order of 5% to 26% (Mason et al. 1998), i.e. roughly the same as that of magnetic Ap and Bp stars. Based on this line of arguments, it is quite possible that a significant fraction of the runaway stars possesses magnetic fields acquired during the ejection from their parent clusters or protoclusters.

Another aspect, which may hint at the presence of a magnetic field in runaway stars is that a number of individual abundance studies indicate nitrogen enrichment in the atmospheres of runaway stars (e.g. Boyajian et al. 2005). Among the magnetic O-type stars in our sample, three stars, HD 108, HD 148937, and HD 191612, were analysed by Nazé et al. (2008a, 2008b), who demonstrated a possible nitrogen enhancement in these stars too. The link between the anomalous abundances and the presence of magnetic fields was recently discovered also in massive early B-type stars. The observations collected by Morel et al. (2008) highlight a higher incidence of magnetic fields in hot B-type stars with nitrogen excess and boron depletion.

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