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Magnetic OB–Type Stars in Open Clusters and in the Field

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Abstract. Important effects induced by magnetic fields in massive stars are suggested by recent models and observations. However, the origin of these magnetic fields remains unknown. At present, only very few magnetic O–type stars are known to belong to clusters, whereas the other magnetic O–type stars are field stars. Surprisingly, a kinematical study of the field O–type stars with detected magnetic fields indicates that some of them can be considered as runaway star candidates. Since this indication could in some way be related to the origin of magnetic fields in massive stars, we carried out the calculations of space velocities of the O–type stars with previously published magnetic fields. We report here on our recent spectropolarimetric and kinematic studies of the OB–type stars in clusters and in the field.

Key words: astrometry – stars: early–type – stars: magnetic field – stars: kinematics and dynamics – open clusters and associations: general

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, the 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 the 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 the protostars results in slowly rotating stars, and these disks live longer 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. Among their descendants, the white dwarfs, 10% have strong magnetic fields. 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%.

2 Observations

Our spectropolarimetric studies of a sample of massive O and B–type stars in clusters and in the field were carried out over the last two years using the FORS2 installed at the VLT and the SOFIN echelle spectropolarimeter at the 2.56m Nordic Optical Telescope. Using a slit width of $0\farcs4$, the achieved spectral resolving power of the FORS2 obtained with the GRISM 600B was about 2000. A detailed description of the assessment of the longitudinal magnetic field measurements using the FORS2 is presented in our previous papers (e. g., Hubrig et al., 2004a, 2004b), and references therein. The SOFIN (Tuominen et al., 1999) is a high–resolution echelle spectrograph mounted at the Cassegrain focus of the NOT and equipped with three optical cameras providing different resolving powers of 30 000, 80 000, and 160 000. The stars were observed with the low–resolution camera with $R = \lambda/\Delta\lambda \approx 30\,000$. We used the 2K Loral CCD detector to register 40 echelle orders partially covering the range from 3500 to 10 000 Å with the spectral order lengths of about 140 Å.

The major goal of the study was to build trustworthy statistics on the occurrence of magnetic fields in massive stars. This is critical to answer the principal question of the possible origin of such fields.

3 Magnetic Field Measurements

During the observations with the FORS2, we were able to detect among the studied 35 massive OB–type stars nine stars with mean longitudinal magnetic fields in the range from 80 to 400 Gauss. Among the stars with magnetic field detections, five stars are members of open clusters, which are tracing the Sagittarius–Carina arm, and four stars are field stars. The ages of clusters containing magnetic O–type stars range from $\log t = 6.70$ to $\log t = 7.17$ (Kharchenko et al., 2005a). New high–resolution SOFIN observations confirmed the presence of magnetic fields in the massive O–type stars HD 36879, 15 Mon, and 9 Sgr, previously detected with the low–resolution FORS2 observations. Further, the magnetic field measurements using the SOFIN spectrograph confirmed the magnetic nature of HD 108 and HD 191612. Our measurements of HD 191612 using eight spectral lines resulted in $\langle B_z \rangle = +450 \pm 153\,\mathrm{G}$ and a crossover of $+16446 \pm 8031\,\mathrm{km\,s^{-1}\,G}$ at rotation phase 0.43. The difference in the phase between the measurement of Donati et al. (2006) and our measurement is about 0.19. Thus, we observe a change of polarity over ~ 100 days (Hubrig et al., 2010). Interestingly, to achieve magnetic field detections in HD 108 for the years 2007, 2008, and 2009, Martins et al. (2010) had to combine all the observations from each observing season, up to 23 observing nights in 2009. Their individual observations did not reveal any clear Zeeman feature and only the average over multiple observations allowed the authors to detect the presence of a magnetic field. Further spectropolarimetric monitoring studies are urgently needed to derive the exact geometry of their magnetic fields. No definite crossover effect at a 3σ level was detected in HD 108 and HD 191612. Both stars are the members of the Of?p class, which in our Galaxy further includes HD 148937, NGC 1624–2, and CPD −28 2561. The latter, CPD −28 2561, was recently observed with the FORS2 in spectropolarimetric mode, revealing the presence of a mean longitudinal magnetic field of the order of a few hundred Gauss (Hubrig et al., in preparation). Obviously, the results of current magnetic studies confirm the tight link between the peculiar properties of Of?p stars and the presence of a magnetic field.

Our surveys of the massive B–type stars in the last years revealed the presence of magnetic fields in about two dozens of β Cephei and Slowly Pulsating B stars. In 2006, using low–resolution

Table 1: Space velocities with respect to the Galactic open cluster systems ($\mathrm{SV_C}$) and the corresponding Galactic velocity components

HD number	Spectral Type	M_V	$(\mathrm{B-V})_0$	dist	X	Y	Z	$\mathrm{SV_C}$	U	V	W
		[mag]		[pc]				[km/s]			
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

FORS1 polarimetric spectra, we announced that the star ξ^1 CMa possesses the strongest magnetic field among the β Cephei stars (Hubrig et al., 2006, 2009). The slight variability of the field was also recently confirmed by the SOFIN observations separated by one year $\langle B_z \rangle = 386 \pm 39$ G in 2008 September and $\langle B_z \rangle = 297 \pm 26$ G in 2010 January. A few months ago additional FORS2 observations obtained in service mode allowed us to determine the rotation period and the magnetic field geometry of this star (Hubrig et al., 2011).

4 Kinematical Status

Surprisingly, kinematical studies of O–type stars with detected magnetic fields indicate that some of them can be considered as candidate runaway stars. Since this indication can be in some way related to the origin of magnetic fields in massive stars, we carried out calculations of space velocities of O–type stars with previously published magnetic fields. Blaauw (1961) assigned the stellar runaway status to stars with space velocities larger than 40 km/s. On the other hand, Stone (1979) and Tetzlaff et al. (2010) specified the velocity cutoff at 28 km/s. This velocity cutoff is adopted in the following discussion of the obtained results. The errors in the estimation of space velocities in the most distant stars are rather large because of the proper motion errors. For this reason, we refrain from calling the studied stars bona fide runaways, but rather candidate runaway stars.

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 towards the position angle 142° and that this velocity is significantly larger than the dispersion value of 1.5 ± 0.5 km/s, found for the other cluster members. The results of the radial velocity study of Stahl et al. (2008) indicate that this star is rapidly moving away from the Orion Molecular Cloud and its host cluster.

The calculated space velocities with respect to the Galactic open cluster systems $\mathrm{SV_C}$ and their Galactic rectangular components for the remaining seven stars are presented in Table 1. 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. (2005b). Spectral types, corresponding absolute visual magnitudes and $(\mathrm{B-V})_0$ on the ZAMS are listed in Columns 2 to 4. The spectral class–colour–absolute magnitude calibration was based on Straizys (1992). The errors in M_V and $(\mathrm{B-V})_0$ 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 Columns 5−8. Space velocities with respect to the Galactic open cluster system and the corresponding Galactic velocity

Table 2: Space velocities with respect to the LSR (SV_{LSR}) and the Sun (SV_S), and the corresponding velocity components.

HD	SV_{LSR}	U	V	W	SV_S	U	V	W
number	[km/s]				[km/s]			
108	96 ± 18	95 ± 11	-13 ± 7	3 ± 12	87 ± 18	84 ± 11	-25 ± 7	-4 ± 12
37742	31 ± 5	-30 ± 4	-7 ± 2	2 ± 1	45 ± 5	-41 ± 4	-19 ± 2	-4 ± 1
148937	31 ± 11	-26 ± 5	8 ± 7	-13 ± 7	43 ± 11	-37 ± 5	-3 ± 6	-21 ± 7
152408	49 ± 12	-48 ± 5	8 ± 8	1 ± 8	60 ± 12	-59 ± 5	-4 ± 7	-5 ± 8
155806	21 ± 8	21 ± 5	2 ± 5	0 ± 4	16 ± 8	10 ± 4	-9 ± 4	-7 ± 4
164794	24 ± 20	-2 ± 5	18 ± 14	-15 ± 14	27 ± 20	-13 ± 5	5 ± 13	-22 ± 13
191612	73 ± 14	72 ± 9	-11 ± 5	0 ± 9	65 ± 13	61 ± 8	-23 ± 5	-7 ± 9

components are listed in Columns 9 to 12. Solar motion parameters derived with respect to the open cluster system, ($(U,V,W)_\odot = (9.44,\ 11.90,\ 7.20)$), Oort's constants and $Z_\odot$, which stands for the distance of the Sun from the Galactic plane, $Z_\odot = 20$ pc, have been determined by Piskunov et al. (2006).

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 local standard rest (LSR). They obtained the Solar motion parameters ($(U,V,W)_\odot = (11.1,\ 12.24,\ 7.25)$), which are very close to those, derived with open clusters. To examine our results for the possible differences, we also used the parameters from Schönrich et al. (2010) to recalculate the space velocities for the stars in our sample. The results of these calculations, as well as the space velocities with respect to the Sun (SV_S) are presented in Table 2. The difference between the space velocities calculated with respect to the Galactic open cluster system, and those obtained using the LSR from Schönrich et al. (2010) is always below 2 km/s.

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 the 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 to emit non–thermal radio–emission, probably associated with colliding winds (Nazé et al., 2010). There are only about a dozen non–thermal radio emitting O–type stars known to date (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 the wind–wind collision.

The Of?p star HD 148937 possesses a space velocity of 32 km/s 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 km/s, and it is assumed that this nebula has been ejected during an LBV–like event (Leitherer & Chavarria, 1987).

Among the four remaining 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: $SV_C = 32 \pm 6$ km/s.

The longitudinal magnetic field of ζ Orionis A is on the order of a few tens of G, while for all other stars, the longitudinal magnetic field is around 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 km/s for HD 152408 up to 94 km/s for HD 108, suggesting that all of them can be considered as runaway star candidates.

5 Discussion

The results of our kinematical study seem to indicate that the presence of a magnetic field is more frequently detected in runaway star candidates 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 probably has a different origin in comparison to other magnetic O–type stars. The first kinematical assessment of massive B–type stars with magnetic fields shows that most of them are field stars, and only very few magnetic B–type stars belong to clusters or associations.

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 analyzed 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 in massive early B–type stars as well. The observations collected by Morel et al. (2008) highlight a higher incidence of magnetic fields in hot B–type stars with the nitrogen excess and boron depletion. We note, however, that the sample of stars with detected magnetic fields is still rather small, and a study of a larger sample is urgently needed to confirm the low occurrence rate of massive magnetic stars in clusters and associations.

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