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Magnetic fields in intermediate- and high-mass binary systems with short periods

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Abstract. Most stars of the upper HRD live in multiple systems. When the separation is small, interactions may occur, affecting the stellar evolution and feedback. The presence of magnetic fields here opens the door to phenomena beyond the "usual" ones (mass transfer, wind collisions, tidal interactions,...) but it also put strong constraints on models of stellar evolution and magnetic field generation. This is why surveys of intermediate- and high-mass binaries with short periods have been undertaken. We will review results in this domain, including the properties of the (rare) detected cases such as Plaskett's star.

Key words: stars: magnetic field – stars: massive – binaries: general

1. Introduction

While a few detections were made in the 20th century, the magnetism of the most massive stars has only begun to be investigated in detail in the last decade, thanks to the advent of sensitive spectropolarimeters. Survey results indicate that magnetic stars share similar properties from spectral types A to O: the incidence rate is low (7% for OB, Fossati et al., 2015b; Grunhut et al., 2017, and 1–10% for Ap stars, depending on their masses, see Sikora et al. in these proceedings); the fields are generally strong (typically a few kG, though some very weak fields were also detected - see Blazère et al. (2015, 2016); Fossati et al. (2015a)), stable, and large-scale (with a strong dipolar component).

These magnetic fields are thought to be fossil. Indeed, the same magnetism incidence rate is found in HAeBe stars (Alecian et al., 2013; Hubrig et al., 2013) and the intermediate- and high-mass stars lack the convective envelopes responsible for the presence of magnetic fields in lower-mass stars. Three scenarios have then been invoked to explain the presence of such fields. First, the magnetism could be directly inherited from the primordial cloud. In this case, since strong magnetism is expected to inhibit cloud fragmentation, few magnetic binaries are expected; besides, in those rare cases, since close binaries are formed from the same material, both components would share the same magnetic properties (e.g., Moss, 2001). Second, the magnetism could relax from a convective dynamo taking place at a very early stage of the star formation. The reason why this process would only occur in some stars still needs to be ascertained. Finally, the magnetism could arise from the strong shear associated to merging events (Ferrario et al., 2009; Schneider et al., 2016). This latter mechanism would naturally explain the low incidence rate since, from stellar evolution considerations, de Mink et al. (2014) predict that about 8% of massive stars are merger products (note that the field generation then needs to produce a stable field for every merging event, which is not ascertained). Such merging could occur in the PMS or MS stage but, since incidence rates are similar for PMS and MS stars, some decaying process is needed to avoid increasing rates. Theoretically, a MS merging leaves several signatures: rejuvenation (the magnetic stars should appear younger than surrounding cluster members), presence of ejecta (material ejected during the event should form a circumstellar nebula), rapid rotation and abundance anomalies (Schneider et al., 2016). Observationally, these properties are found, but are not universally shared, amongst magnetic intermediate- and high-mass stars: rejuvenation may have been detected for τ Sco and HR 2948, ejecta surround HD 148937, and rapid rotation or abundance anomalies have been found in some cases - but not all. Besides, if merging occurred, no close companion remains hence the resulting star should appear single or in a long-period binary (which could even form after the event by dynamical capture, for example).

The magnetic properties of intermediate- and high-mass binaries, especially the shortest-period ones, thus represent a crucial test for models of stellar evolution or of magnetism generation. Besides, such systems possess several advantages: the stellar properties can be derived with a high precision (masses, radii,...) and the age and composition should be the same for both stars. However, a good coverage of both the orbital and rotational periods is required, which represent a substantial investment of observing time. Finally, the presence of two stars opens the door to additional, interesting but still poorly known, phenomena, such as tidal interactions, magnetospheric interactions, or wind-wind collisions.

2. Results

Because multiplicity is widespread in massive stars, many of the magnetic detections actually occurred in binaries. For example, the first magnetic field detected in an O-star was found in θ^1 Ori C, which has a companion. However, the vast majority of these binaries have long periods, and cannot serve as a probing tool for the objectives previously mentioned. The first detection of magnetism in a close OBA binary occurred in 1958, for the intermediate-mass system HD 98088 (Babcock, 1958). The detailed study of Ap stars then revealed that their overall binary fraction was similar to, though maybe slightly smaller than, that of “normal” A stars (Abt & Snowden, 1973), and there seems to be an almost complete lack of binaries with periods shorter than 3d (Carrier et al., 2002). Recent surveys (general ones like MiMeS Grunhut et al. (2017) or BOB Schöller et al.

(2017), or ones specific to close binaries like BinaMIcS Alecian et al. (2015)) refined the picture and enlarged it to OB stars. They found few detections in close binaries composed of two hot stars, with an incidence rate limited to 2%. It is also important to underline that, in all but one case, only one of the two components is found to be magnetic.

Table 1 lists the dozen detections achieved up to now, with the main orbital/stellar/magnetic parameters. As a complement, we may note that (1) two other Ap+Am systems were proposed in the past but recently dismissed (Folsom et al., 2013b) and (2) HD 34736 was first thought to have $P_{orb} \sim 0.3$d (Semenko et al., 2014) but actually has $P_{orb} \sim 83$d (Semenko et al., in prep.) – the large excentricity of the system may lead to interactions at periastron, though. In addition, there are also two triple systems where a magnetic B star is associated to a close A+A binary: HD 35502 (Sikora et al., 2016) and HD 164492C (González et al., 2017; Wade et al., 2017). Those are not *per se* cases of magnetic objects in close binaries but these systems have an interesting configuration which may also sensitively test theoretical models.

2.1. Plaskett's star

This massive binary system harbours two late-type O-stars in a tight, 14.4 d orbit. It displays several peculiarities: the secondary is a fast rotator, there is a mismatch between dynamical and spectroscopic masses, as well as abundance anomalies (He enrichment of both stars, N depletion in the secondary, N enrichment and C depletion in the primary). This has led Bagnuolo et al. (1992) and Linder et al. (2008) to conclude that Plaskett's star actually is a post-mass transfer binary. In addition, the Doppler mapping of the Hα and He II 4686 emissions suggested a flattened wind region around the equator of the secondary (Linder et al., 2008). Grunhut et al. (2013) detected a magnetic signature in Stokes-V spanning the radial velocity interval covered by the fast-rotating secondary. The flattened wind region was then interpreted as magnetically confined winds. Since both stars have strong stellar winds, the interactions are complex in the system: preliminary MHD modelling suggests the simultaneous presence of a confined secondary wind and a wind-wind collision (ud-Doula, private communication). This may be reflected in the high-energy properties of the system, which is brighter at these wavelengths than other magnetic O-stars (Nazé et al., 2014). While X-ray variations are known from ROSAT, XMM, and Chandra data, their study could not definitely identify the recurrence timescale(s) (Linder et al., 2006, and Leutenegger et al., in prep.) and much remain to be done to characterize this unique wind interaction.

Plaskett's secondary is a fast rotator, and it is the sole fast-rotating magnetic O-star. This is puzzling since magnetic braking is supposed to play an important role in those stars. This led to question the origin of the field: could it be different from that of other magnetic massive stars? Because of its past interaction, Plaskett's secondary is obviously not a merging product (the companion being still there!) but the shear generated by the mass-transfer event could here have been the magnetic trigger. In other words, could Plaskett's secondary be the prototype of a new category of magnetic massive stars, or is it simply amongst the 2% of magnetic stars in close massive binaries, its fast rotation being a coincidence? This was tested by observing with FORS2, ESPaDOnS or Narval a set of 15 short-period massive binaries known to undergo or to have undergone similar interactions (Nazé et al., 2017). The campaign resulted only in non-detections, with an overall limit of $B_d \sim 200\,\mathrm{G}$ for the whole sample (considering all stars to share similar properties). In addition, the incidence rate after adding Plaskett's detection appears compatible with survey results. This finding strongly limits the putative role of binary interactions in the generation of magnetic fields in massive stars.

2.2. ϵ Lupi

This system comprises two B-type stars, both likely pulsating, in a short eccentric orbit ($P_{orb} = 4.6\,\mathrm{d}$, $e = 0.27$, Uytterhoeven et al., 2005). Magnetic signatures were detected in the system in the last decade (Hubrig et al., 2009; Shultz et al., 2012), and subsequent monitoring revealed that *both* components were actually magnetic. ϵ Lupi thus is the only known case of a doubly magnetic massive binary. This leads to an interesting phenomenon: because of the combination of strong fields and small separation, the two magnetospheres should interact – moreover, this interaction should vary with time, as the system is eccentric. The search for the signature of this unique interaction is ongoing, and will certainly unveil a wealth of new phenomena.

2.3. Others

Since we are dealing with close binaries, tidal interactions are supposed to take place. This may lead to alignment of orbital and rotational axes, synchronization of the orbital and rotational periods, and orbit circularization. In the sample of close magnetic binaries (Table 1), a few systems have achieved synchronization, about half of the systems have circularized, but nearly all have reached alignment (when the inclination information is known). This is in line with the timescale expectations of these phenomena. In this context, it is interesting to note that in BD–19°5044L, the synchronization is not complete (i.e. $P_{orb} \neq P_{rot}$) but the orbital and rotational angular velocities agree at periastron (Landstreet et al., 2017).

There are two interesting additional pieces of information: (1) the two components of HD 98088 have been found to display similar ages, an argument in favour of coevality; (2) the obliquity of the detected magnetic fields is generally large (the exceptions are the weaker fields of ϵ Lupi and HD 5550, and that of HD 36485).

3. Conclusion

Sensitive spectropolarimetric measurements have showed that magnetic stars do exist in close OBA binaries, and with field strengths similar to what is found in single stars or wide binaries of similar spectral types. Their mere existence seems incompatible with a merger scenario (even more so for the case of ϵ Lupi, the sole doubly magnetic massive binary). In this context, the non-detection of magnetism associated to blue stragglers (Grunhut et al., in prep.) is also a strong argument against the merger scenario. Furthermore, magnetism is even rarer in short-period binaries than in long-period systems or in single objects (2% vs. 7% for OB stars - the situation appears less clear-cut for Ap stars). This suggests that whatever generated magnetic fields in massive stars is somewhat inhibited when binaries form, placing strong constraints on their origin. This result could be compatible with the simulations showing that intense fields inhibit cloud fragmentation, if the fields are inherited from the primordial cloud. However, in all but one system, only one of the companions is detected to be magnetic, not both. Since both stars are formed from the same (piece of) cloud, one would rather expect to observe the contrary in case the stellar magnetic field originates from a field in the primordial, interstellar material.

A specific survey also demonstrated that interacting or post-interacting massive systems are not predominantly magnetic – there is only one case, the fast-rotating secondary in Plaskett's star. Therefore, binary interactions appear to play little role in the magnetic field generation. Plaskett's secondary is "just" one of the few examples of magnetic massive stars in binaries, not the prototype of a new class of magnetic objects.

Moreover, as expected for such close systems, some magnetic intermediate- and high-mass binaries are presenting signatures of tidal interactions, with stellar rotation synchronized and/or aligned with the orbital motion, and/or circularized orbits detected in more than half of the systems. In addition, two systems appear particularly exceptional: Plaskett's star combines magnetically confined winds and wind-wind collision, while ϵ Lupi should harbour (variable) magnetospheric interactions. These two systems therefore will continue to be monitored in detail, especially at high energies, to pinpoint the characteristics of these new phenomena.

Finally, the detected fields usually present a large obliquity, which is certainly linked to their origin. All these elements (incidence rate, obliquity,...) thus place strong constraints on the origin of the magnetism in intermediate- and high-mass stars but, while important results have already been achieved, much work remain to be done (notably refining models and enlarging observational samples) before fully understanding these "massive" magnetic phenomena.

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References

Abt, H. A. & Snowden, M. S. 1973, *Astrophys. J., Suppl. Ser.*, **25**, 137

Alecian, E., Kochukhov, O., Petit, V., et al. 2014, *Astron. Astrophys.*, **567**, A28

Alecian, E., Neiner, C., Wade, G. A., et al. 2015, in IAU Symposium, Vol. **307**, *New Windows on Massive Stars*, ed. G. Meynet, C. Georgy, J. Groh, & P. Stee, 330–335

Alecian, E., Tkachenko, A., Neiner, C., Folsom, C. P., & Leroy, B. 2016, *Astron. Astrophys.*, **589**, A47

Alecian, E., Wade, G. A., Catala, C., et al. 2013, *Mon. Not. R. Astron. Soc.*, **429**, 1001

Babcock, H. W. 1958, *Astrophys. J., Suppl. Ser.*, **3**, 141

Bagnulo, S., Fossati, L., Landstreet, J. D., & Izzo, C. 2015, *Astron. Astrophys.*, **583**, A115

Bagnuolo, Jr., W. G., Gies, D. R., & Wiggs, M. S. 1992, *Astrophys. J.*, **385**, 708

Blazère, A., Neiner, C., & Petit, P. 2016, *Mon. Not. R. Astron. Soc.*, **459**, L81

Blazère, A., Neiner, C., Tkachenko, A., Bouret, J.-C., & Rivinius, T. 2015, *Astron. Astrophys.*, **582**, A110

Borra, E. F. & Landstreet, J. D. 1979, *Astrophys. J.*, **228**, 809

Carrier, F., North, P., Udry, S., & Babel, J. 2002, *Astron. Astrophys.*, **394**, 151

de Mink, S. E., Sana, H., Langer, N., Izzard, R. G., & Schneider, F. R. N. 2014, *Astrophys. J.*, **782**, 7

Ferrario, L., Pringle, J. E., Tout, C. A., & Wickramasinghe, D. T. 2009, *Mon. Not. R. Astron. Soc.*, **400**, L71

Folsom, C. P., Likuski, K., Wade, G. A., et al. 2013a, *Mon. Not. R. Astron. Soc.*, **431**, 1513

Folsom, C. P., Wade, G. A., & Johnson, N. M. 2013b, *Mon. Not. R. Astron. Soc.*, **433**, 3336

Fossati, L., Castro, N., Morel, T., et al. 2015a, *Astron. Astrophys.*, **574**, A20

Fossati, L., Castro, N., Schöller, M., et al. 2015b, *Astron. Astrophys.*, **582**, A45

González, J. F., Hubrig, S., Przybilla, N., et al. 2017, *Mon. Not. R. Astron. Soc.*, **467**, 437

Grunhut, J. H., Wade, G. A., Leutenegger, M., et al. 2013, *Mon. Not. R. Astron. Soc.*, **428**, 1686

Grunhut, J. H., Wade, G. A., Neiner, C., et al. 2017, *Mon. Not. R. Astron. Soc.*, **465**, 2432

Hubrig, S., Briquet, M., De Cat, P., et al. 2009, *Astron. Nachr.*, **330**, 317

Hubrig, S., Carroll, T. A., González, J. F., et al. 2014, *Mon. Not. R. Astron. Soc.*, **440**, L6

Hubrig, S., Ilyin, I., Schöller, M., & Lo Curto, G. 2013, *Astron. Nachr.*, **334**, 1093

Landstreet, J. D., Kochukhov, O., Alecian, E., et al. 2017, *Astron. Astrophys.*, **601**, A129

Leone, F., Bohlender, D. A., Bolton, C. T., et al. 2010, *Mon. Not. R. Astron. Soc.*, **401**, 2739

Linder, N., Rauw, G., Martins, F., et al. 2008, *Astron. Astrophys.*, **489**, 713

Linder, N., Rauw, G., Pollock, A. M. T., & Stevens, I. R. 2006, *Mon. Not. R. Astron. Soc.*, **370**, 1623

Moss, D. 2001, in ASP Conf. Ser., Vol. **248**, *Magnetic Fields Across the Hertzsprung-Russell Diagram*, ed. G. Mathys, S. K. Solanki, & D. T. Wickramasinghe, 305

Nazé, Y., Neiner, C., Grunhut, J., et al. 2017, *Mon. Not. R. Astron. Soc.*, **467**, 501

Nazé, Y., Petit, V., Rinbrand, M., et al. 2014, *Astrophys. J., Suppl. Ser.*, **215**, 10, (+erratum in ApJS, 224, 13)

Neiner, C., Tkachenko, A., & MiMeS Collaboration. 2014, *Astron. Astrophys.*, **563**, L7

Petit, V., Wade, G. A., Drissen, L., Montmerle, T., & Alecian, E. 2008, *Mon. Not. R. Astron. Soc.*, **387**, L23

Schneider, F. R. N., Podsiadlowski, P., Langer, N., Castro, N., & Fossati, L. 2016, *Mon. Not. R. Astron. Soc.*, **457**, 2355

Schöller, M., Hubrig, S., Fossati, L., et al. 2017, *Astron. Astrophys.*, **599**, A66

Semenko, E. A., Romanyuk, I. I., Kudryavtsev, D. O., & Yakunin, I. A. 2014, *Astrophysical Bulletin*, **69**, 191

Shultz, M. 2016, The rotational evolution and magnetospheric emission of the magnetic early B-type stars, PhD thesis, Queen's University (Canada)

Shultz, M., Wade, G. A., Alecian, E., & BinaMIcS Collaboration. 2015, *Mon. Not. R. Astron. Soc.*, **454**, L1

Shultz, M., Wade, G. A., Grunhut, J., et al. 2012, *Astrophys. J.*, **750**, 2

Sikora, J., Wade, G. A., Bohlender, D. A., et al. 2016, *Mon. Not. R. Astron. Soc.*, **460**, 1811

Uytterhoeven, K., Harmanec, P., Telting, J. H., & Aerts, C. 2005, *Astron. Astrophys.*, **440**, 249

Wade, G. A., Shultz, M., Sikora, J., et al. 2017, *Mon. Not. R. Astron. Soc.*, **465**, 2517

Table 1. Properties of the detected magnetic stars in close ($P < 30$d) hot binaries (i.e. both objects being intermediate- or high-mass objects).

Name	sp. types	P_{orb}(d)	e	$P_{orb} = P_{rot}$?	$i_{orb} = i_{rot}$?	β(°)	B_d(kG)	Ref.
Magnetic O-star in a close binary system								
Plaskett's star	O8III+O7.5III	14.4	0	no		>>	∼2.0	1, 2
Magnetic B-stars in close binary systems								
BD–19°5044L	Bp+Am	17.6	0.474	at peri.	yes	26	1.4	3
HD 1976	B5IVp+?+?	25-28	0.1-0.2					4
HD 36485	B3p+A	30.0	0.32	no	yes	<52	7–12	5
HD 37017	B2V+?	18.7	0.47	no	yes	63	6.5	6, 7
HD 149277	B2IV/V+?	11.5	0.24	no	yes	72	9.8	7, 8
HD 156324A	B2V+?+?	1.6	<0.03	yes	∼yes	69	12.3	7, 9
NU Ori	B0.5V+?+?	14.3	<0.07	no	∼yes	56	1.8	7, 10
ϵ Lupi	B2V+B3V	4.6	0.27	no	∼yes	36	0.8	7, 11
						5	0.5	
Magnetic A-stars in close binary systems								
HD 161701	B9+Ap	12.5	0.004	∼yes		>>		12
HD 5550	Ap+Am	6.8	0.006	yes		–24	0.065	13
HD 98088	Ap+Am	5.9	0.18	yes	yes	75	3.85	14

References: 1: Grunhut et al. (2013), 2: Grunhut et al., in prep., 3: Landstreet et al. (2017), 4: Neiner et al. (2014), 5: Leone et al. (2010), 6: Borra & Landstreet (1979), 7: Shultz (2016), 8: Bagnulo et al. (2015), 9: Alecian et al. (2014), 10: Petit et al. (2008), 11: Shultz et al. (2015), 12: Hubrig et al. (2014), 13: Alecian et al. (2016), 14: Folsom et al. (2013a)