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The origin of magnetic fields in hot stars

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Abstract. Observations of stable mainly dipolar magnetic fields at the surface of ∼7% of single hot stars indicate that these fields are of fossil origin, i.e. they descend from the seed field in the molecular clouds from which the stars were formed. The recent results confirm this theory. First, theoretical work and numerical simulations confirm that the properties of the observed fields correspond to those expected from fossil fields. They also showed that rapid rotation does not modify the surface dipolar magnetic configurations, but hinders the stability of fossil fields. This explains the lack of correlation between the magnetic field properties and stellar properties in massive stars. It may also explain the lack of detections of magnetic fields in Be stars, which rotate close to their break-up velocity. In addition, observations by the BinaMIcS collaboration of hot stars in binary systems show that the fraction of those hosting detectable magnetic fields is much smaller than for single hot stars. This could be related to results obtained in simulations of massive star formation, which show that the stronger the magnetic field in the original molecular cloud, the more difficult it is to fragment massive cores to form several stars. Therefore, more and more arguments support the fossil field theory.

Keywords. stars: magnetic fields, stars: rotation, stars: formation, stars: early-type

1. Introduction

The MiMeS (Magnetism in Massive Stars) project showed that about 7% of single OB stars are magnetic (Neiner *et al.* 2011; Wade *et al.* 2014a). In addition, a similar proportion of A stars are known to be magnetic (Wolff 1968; Power 2007). The magnetic fields of OBA stars have simple configurations, stable mainly oblique dipoles, and their strengths range from ∼100 to ∼30000 G. More details on the properties of magnetic fields in hot stars are presented in Grunhut et al. (these proceedings). Therefore, there seems to be a common origin of magnetic fields in all hot (OBA) stars. This origin, however, has remained unknown for a long time.

In cool stars, including the Sun, magnetic fields are generated and sustained by a dynamo in the convective envelope (e.g., Charbonneau 2010; Brun *et al.* 2004). As a consequence, the magnetic fields of cool stars are highly dynamic, and exhibit variability on a very wide range of timescales. The internal structure of the star, its rotation, and its accretion state can strongly influence the dynamo, and ultimately set the broad properties of the magnetic field. The dynamo-generated magnetic field, in turn, drives the mass loss and angular momentum loss through magnetised winds and coronal mass ejection processes (e.g., Matt *et al.* 2012; Réville *et al.* 2015). Therefore, a complex interplay exists between magnetic fields and rotation of cool stars during their whole evolution.

These properties are not observed in hot stars. They do not have a thick outer convective envelope and a Sun-like dynamo can thus not develop. The origin of their magnetic field must be found elsewhere.

2. Dynamo fields?

2.1. *Dynamo field in the convective core*

A hot star consists of a convective core, a radiative envelope, and a very thin convective layer just below the surface. Like in the external convective envelope of low-mass and solar-type stars, a dynamo takes place in the convective core of intermediate-mass and massive stars. It generates and sustains a magnetic field, because of the combined action of differential rotation and turbulent helical flows (i.e., an $\alpha - \Omega$ dynamo action; e.g., Brun *et al.* 2005). However, the time needed for this field to reach the surface and become visible is longer than the lifetime of the star (Charbonneau & MacGregor 2001; MacGregor & Cassinelli 2003). Moreover, an $\alpha - \Omega$ dynamo would lead to a correlation between the magnetic field properties and stellar rotation, which is not observed. Therefore, even if such a core dynamo field exists, it is not the one that we observe at the surface of hot stars.

2.2. *Dynamo field in the radiative envelope*

Over the last decade, various groups investigated the possibility of creating a dynamo in the radiative envelope of hot stars (e.g., Spruit 2002; Zahn *et al.* 2007; Arlt & Rüdiger 2011; Rüdiger *et al.* 2012; Jouve *et al.* 2015). Like in convective regions, the Ω effect, i.e., differential rotation, transforms an initial axisymmetric poloidal field into an axisymmetric toroidal field. Tayler's and other MHD instabilities, that can develop in radiation regions, then transform this field into a field with a non-axisymmetric component (Tayler 1973; Markey & Tayler 1973; Brun 2007). To maintain the magnetic field, it is then necessary to close the dynamo loop, by regenerating an axisymmetric field from the non-axisymmetric field. Spruit (2002) proposed to regenerate the axisymmetric toroidal field, while Braithwaite (2006) proposed to regenerate the poloidal field. For this, both used the shear, but Zahn *et al.* (2007) showed that axisymmetric fields cannot be regenerated by the shear alone. Instead, Zahn *et al.* (2007) proposed to close the loop thanks to the electromotive force of the instability (see also Rüdiger *et al.* 2012). While this seems to work theoretically, numerical simulations have shown that this dynamo is not excited or maintained.

Moreover, if an $\alpha - \Omega$ dynamo existed in the radiative envelope, a correlation would exist between the rotation and the magnetic field properties. Such a correlation is not observed in OB stars (Wade *et al.* 2014a). Consequently, the possible production of a dynamo field in the radiative envelope of hot stars must be rejected.

2.3. *Dynamo field in the sub-surface convection layer*

Hot stars have a very thin convective layer just below their surface. Cantiello & Braithwaite (2011) showed that a dynamo may develop in this layer. However, the fields produced this way are of the order of 5 to 50 G for B stars, which is much weaker than the magnetic fields observed at the surface of these stars. Moreover, a magnetic field produced by sub-surface convection would likely have a small-scale and time-dependent structure, while the observed fields are mostly dipolar and stable. As a result, even if such a sub-surface dynamo field may exist, it does not correspond to the ones observed at the surface of the hot stars.

3. Fossil fields

3.1. *Fossil origin of magnetism in hot stars*

During the formation of a hot star, the magnetic field present in the molecular cloud can get trapped in the star as the cloud collapses. Fossil magnetic fields are descendants from this seed field (Mestel 1999). During the early stage of the life of the star, when it is fully convective, this seed field can get enhanced and sustained by a dynamo. As the radiative core forms and the convective turbulence disappears in the center of the star, this dynamo field relaxes onto a large-scale mixed (poloidal+toroidal) stable (possibly oblique) dipole. Such relaxation processes have been observed in numerical simulations (Braithwaite & Spruit 2004; Braithwaite & Nordlund 2006). Moreover, theoretical work demonstrated that this mechanism results from a selective decay of the energy of the system and of ideal MHD invariants such as magnetic helicity (Duez & Mathis 2010). Finally, to stay stable on long timescale, the field must have a given ratio of the relative energies contained in its toroidal and poloidal components (Braithwaite 2009; Duez *et al.* 2010). The external convection zone then disappears and the star becomes fully radiative with the dipolar fossil field emerging at its surface. It is possible that the appearance of the convective core, just before reaching the ZAMS, produces a (extra) tilt of the dipole and explains why oblique dipoles are observed in basically all hot stars. Indeed, from ASH 3D MHD simulations, Featherstone *et al.* (2009) showed that the interaction of a core dynamo with a fossil field in the envelope produces several effects: it strengthens the core field, it makes the rotation of the envelope more rigid, and it changes the orientation of the fossil field in the envelope. Figure 1 shows a diagram of the evolution of fossil fields.

In addition, Alecian *et al.* (2013) showed that Herbig Ae/Be stars, which are the precursors of the magnetic Ap/Bp stars, host magnetic fields with a similar occurence rate and configuration to main sequence hot stars. This indicates that the fields observed in hot stars are already present at the PMS phase.

Therefore, it is now well established that the magnetic fields of hot stars are of fossil origin. However, the exact details of the creation and evolution of these fields, from the molecular cloud to the main sequence, require further investigations, in particular on the influence of rotation and stellar formation conditions.

3.2. *Impact of rotation on a fossil field*

Recent theoretical calculations showed that rotation modifies the internal distribution of the magnetic flux and the stability of fossil magnetic fields, while it does not modify their surface geometric configuration. Indeed, fossil fields relax onto mixed dipolar configurations, no matter how fast the star rotates (Emeriau & Mathis 2015). However, as demonstrated by Braithwaite & Cantiello (2013), the time needed to reach equilibrium increases with rotation. Therefore, it is probably more difficult for a rapidly rotating star to reach a stable dipolar configuration.

This would explain, in particular, why magnetic fields have not been directly detected in classical Be stars, which rotate close to their breakup velocity (see Wade *et al.* 2014b). However, rapidly rotating magnetic hot stars do exist. This is the case, for example, of HR 7355 (Oksala *et al.* 2010) and HR 5907 (Grunhut *et al.* 2012). More investigations on the impact of rapid rotation are thus needed.

When equilibrium is not reached, the star can still host a magnetic field, but this field will most likely be very weak and on small scales (Aurière *et al.* 2007; Lignières *et al.*

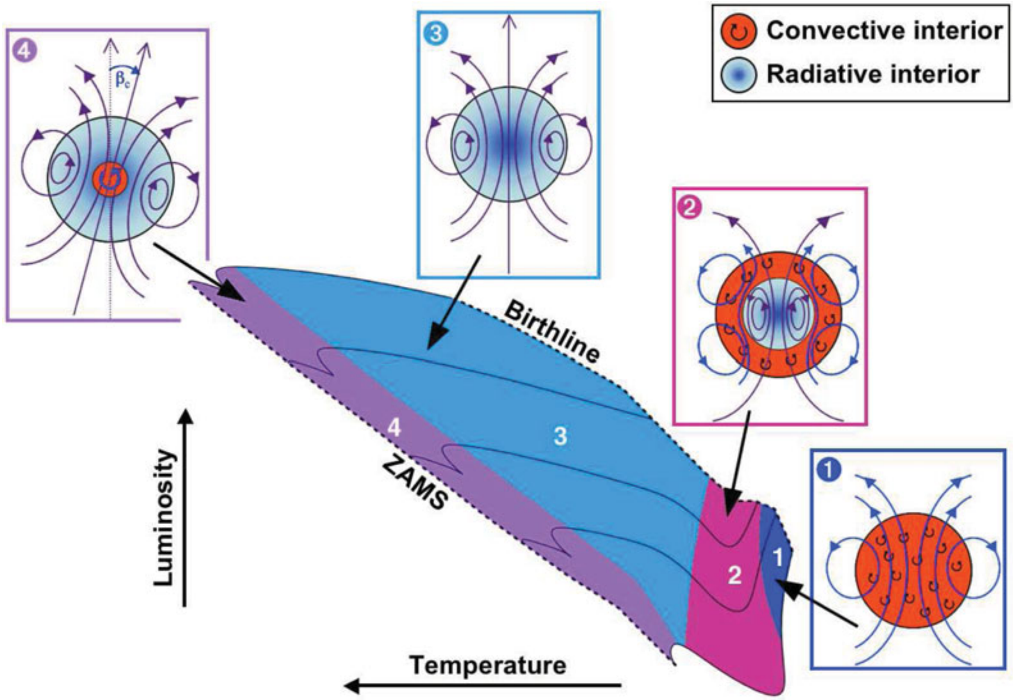

Figure 1. Diagram showing the pre-main sequence (PMS) from the birthline to the ZAMS, with various evolutionary tracks from 1.2 to 8 $M_\odot$ shown with black solid lines. The PMS is divided in 4 parts indicated with different grey shades (color version in on-line copy of this figure), showing 4 stages of the evolution of the structure of the stars and of their fossil magnetic field.

2014; Braithwaite & Cantiello 2013). This kind of ultra-weak field has been observed in Vega (Lignières *et al.* 2009; Petit *et al.* 2010) and in a few Am stars (e.g., Petit *et al.* 2011, see also Blazere *et al.*, these proceedings).

4. Lack of magnetic fields in hot binaries

BinaMIcS (Binarity and Magnetic Interactions in various classes of Stars, Neiner *et al.* 2013; Alecian *et al.* 2015) is an ongoing project that exploits binarity to yield new constraints on the physical processes at work in hot and cool magnetic stars. It rests on two large programs of observations with the ESPaDOnS spectropolarimeter at CFHT in Hawaii and its twin Narval at TBL in France. BinaMIcS aims at studying the role of magnetism during stellar formation, magnetospheric star-star (and star-planet) interactions, the impact of tidal flows on fossil and dynamo fields, its impact on mass and angular momentum transfer, etc.

In the frame of BinaMIcS, a large survey of magnetism in hot spectroscopic binary systems with 2 spectra (SB2) has been undertaken. Out of ~200 observed SB2, including at least one star (and most of the time two stars) with spectral type O, B or A in each system, none were found to host a magnetic field, while the detection threshold was similar to the one used in the MiMeS project on single hot stars. This lack of detections in ~400 stars with BinaMIcS, compared to the ~7% detection rate in ~500 single stars with MiMeS, is thus statistically significant: magnetism is less present in hot binaries than in single hot stars.

This lack of magnetic stars in hot binaries might be related to results obtained from simulations of star formation by Commerçon *et al.* (2011). They found that the more magnetic the medium is, the less fragmentation of dense cores there is. In other words, when the medium is magnetic, it is more difficult to form binaries. As a consequence, forming a binary with a fossil field is unlikely.

Nevertheless, 6 SB2 systems hosting a magnetic OBA star are known to exist. These are HD 5550, HD 37017, HD 37061 (NU Ori), HD 47129 (Plaskett's star), HD 98088, and HD 136504 (ϵ Lup). It is possible that magnetic hot binaries still form sometimes. However, for these 6 systems, only one of the two components is known to be magnetic, which is puzzling if the stars were formed simultaneously. A possible explanation is that these binaries were formed in a later stage of stellar evolution, e.g., by capture, from a magnetic single hot star and non-magnetic hot star.

5. Conclusions

The magnetic fields of single hot stars is of fossil origin, i.e. they are the descendants of the seed field from the molecular cloud from which the stars were formed. They are found in ∼7% of all single OBA stars and are mainly dipolar. Rapid rotation makes it more difficult for fossil fields to reach this dipolar equilibrium, and this may explain the lack of field detections in classical Be stars, even though a few examples of rapidly rotating magnetic hot stars exist.

A few magnetic hot binaries also exist, but magnetism is much less present in hot binaries than in single hot stars. This might be related to stellar formation issues: it is more difficult to fragment dense cores when the medium is magnetic.

These results provide constraints and challenges for formation theories and simulations to understand the magnetic properties of upper-main sequence stars, which are very different from those of low-mass and solar-type stars.

References

Alecian, E., Neiner, C., Wade, G. A., *et al.* 2015, in: *New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry*, Vol. 307 of *IAU Symposium*, p. 330
Alecian, E., Wade, G. A., Catala, C., *et al.* 2013, *MNRAS* 429, 1001
Arlt, R. & Rüdiger, G. 2011, *MNRAS* 412, 107
Aurière, M., Wade, G. A., Silvester, J., *et al.* 2007, *A&A* 475, 1053
Braithwaite, J. 2006, *A&A* 449, 451
Braithwaite, J. 2009, *MNRAS* 397, 763
Braithwaite, J. & Cantiello, M. 2013, *MNRAS* 428, 2789
Braithwaite, J. & Nordlund, Å. 2006, *A&A* 450, 1077
Braithwaite, J. & Spruit, H. C. 2004, *Nature* 431, 819
Brun, A. S. 2007, *AN* 328, 1137
Brun, A. S., Browning, M. K., & Toomre, J. 2005, *ApJ* 629, 461
Brun, A. S., Miesch, M. S., & Toomre, J. 2004, *ApJ* 614, 1073
Cantiello, M. & Braithwaite, J. 2011, *A&A* 534, A140
Charbonneau, P. 2010, *Living Reviews in Solar Physics* 7, 3
Charbonneau, P. & MacGregor, K. B. 2001, *ApJ* 559, 1094
Commerçon, B., Hennebelle, P., & Henning, T. 2011, *Ap. Lett.* 742, L9
Duez, V., Braithwaite, J., & Mathis, S. 2010, *Ap. Lett.* 724, L34
Duez, V. & Mathis, S. 2010, *A&A* 517, A58
Emeriau, C. & Mathis, S. 2015, in: *New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry*, Vol. 307 of *IAU Symposium*, p. 373
Featherstone, N. A., Browning, M. K., Brun, A. S., & Toomre, J. 2009, *ApJ* 705, 1000

Grunhut, J. H., Rivinius, T., Wade, G. A., *et al.* 2012, *MNRAS* 419, 1610

Jouve, L., Gastine, T., & Lignières, F. 2015, *A&A* 575, A106

Lignières, F., Petit, P., Aurière, M., Wade, G. A., & Böhm, T. 2014, in: *Magnetic Fields throughout Stellar Evolution*, Vol. 302 of *IAU Symposium*, p. 338

Lignières, F., Petit, P., Böhm, T., & Aurière, M. 2009, *Astron. Lett.* 500, L41

MacGregor, K. B. & Cassinelli, J. P. 2003, *ApJ* 586, 480

Markey, P. & Tayler, R. J. 1973, *MNRAS* 163, 77

Matt, S. P., MacGregor, K. B., Pinsonneault, M. H., & Greene, T. P. 2012, *Ap. Lett.* 754, L26

Mestel, L. 1999, *Stellar magnetism*, Oxford: Clarendon; International series of monographs on physics

Neiner, C., Alecian, E., & Mathis, S. 2011, in: G. Alecian, K. Belkacem, R. Samadi, & D. Valls-Gabaud (eds.), *SF2A-2011: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, p. 509

Neiner, C. & Alecian, E., the BinaMIcS collaboration 2013, in: K. Pavlovski, A. Tkachenko, & G. Torres (eds.), *Setting a New Standard in the Analysis of Binary Stars*, Vol. 64 of *EAS Publications Series*, p. 75

Oksala, M. E., Wade, G. A., Marcolino, W. L. F., *et al.* 2010, *MNRAS* 405, L51

Petit, P., Lignières, F., Aurière, M., *et al.* 2011, *Astron. Lett.* 532, L13

Petit, P., Lignières, F., Wade, G. A., *et al.* 2010, *A&A* 523, A41

Power, J. 2007, *Master's thesis*, Queen's University, Canada

Réville, V., Brun, A. S., Matt, S. P., Strugarek, A., & Pinto, R. F. 2015, *ApJ* 798, 116

Rüdiger, G., Kitchatinov, L. L., & Elstner, D. 2012, *MNRAS* 425, 2267

Spruit, H. C. 2002, *A&A* 381, 923

Tayler, R. J. 1973, *MNRAS* 161, 365

Wade, G. A., Grunhut, J., Alecian, E., *et al.* 2014a, in: *Magnetic Fields throughout Stellar Evolution*, Vol. 302 of *IAU Symposium*, p. 265

Wade, G. A., Petit, V., Grunhut, J., & Neiner, C. 2014b, *ArXiv e-prints 1411.6165*

Wolff, S. C. 1968, *PASP* 80, 281

Zahn, J.-P., Brun, A. S., & Mathis, S. 2007, *A&A* 474, 145