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PROGRESS ON MAGNETISM IN MASSIVE STARS (MIMES)

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Abstract. We present the MiMeS project, which aims at studying all aspects of magnetism in massive stars to understand their characteristics, origin, incidence, evolution, and impact on other physical processes. We show examples of recent observational results obtained within this project on pulsating B stars (β Cephei and SPB stars) as well as Herbig Ae/Be stars. Recent theoretical progress obtained within MiMeS on the configuration and stability of magnetic fields is also summarized.

Keywords: stars: early-type, stars: magnetic fields

1 The MiMeS project

The Magnetism in Massive Stars (MiMeS) project represents a comprehensive, multidisciplinary strategy to address the big questions related to the complex and puzzling magnetism of massive stars.

MiMeS has been awarded "Large Program" status with the high resolution spectropolarimeters Espadons at the CFHT (Hawaii), Narval at TBL (France), and HarpsPol at ESO (Chile), resulting in a total of ~1500 hours of allocated observing time from late 2008 through early 2013. This large amount of time is being used to acquire an immense database of sensitive measurements of polarized and unpolarized spectra of massive stars, providing magnetic fields measurements for hundreds of massive stars. This database is combined with a wealth of new and archival complementary data (e.g. optical photometry, UV and X-ray spectroscopy) as well as theoretical work, and applied to address the 4 main scientific objectives of the MiMeS project:

- to identify and model the physical processes responsible for the generation of magnetic fields in massive stars
- to study the physics of atmospheres, winds, envelopes, and magnetospheres of massive stars
- to identify the role of magnetic field in the rotational evolution of massive stars
- to understand the impact of magnetic fields on the evolution of massive stars and origin of the magnetic fields of neutron stars and magnetars

The MiMeS collaboration includes over 60 scientists from all around the world and in particular from France and Canada. To address the general problems expressed by the MiMeS science drivers, we have devised a two-component observing program that allows us to obtain basic statistical information about the magnetic properties of the overall population of massive stars (the Survey Component), while simultaneously providing detailed information about the magnetic fields and related physics of individual objects (the Targeted Component). See more details in Wade & the MiMeS Collaboration (2010). In addition, theoretical work and simulations are being developed to interprete the data.

2 Recent observational results

Observational results have been obtained within the MiMeS project on all types of massive stars: OB stars, Of?p stars, β Cephei stars, Slowly Pulsating B (SPB) stars, Be stars, Herbig Ae/Be stars,... Here we concentrate on recent results obtained for pulsating B stars and Herbig Ae/Be stars.

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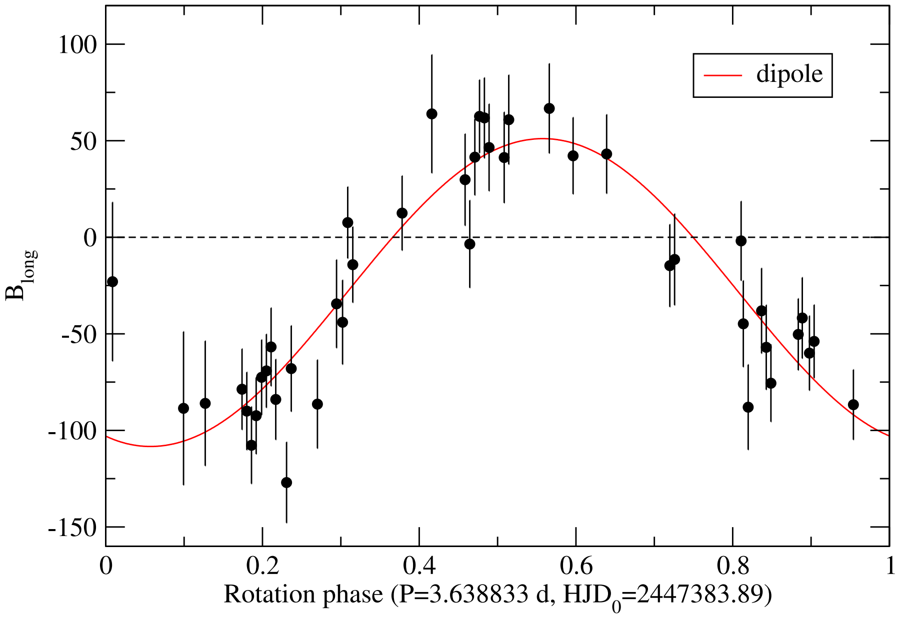

Fig. 1. Longitudinal magnetic field curve of the β Cephei star V2052 Oph obtained from Narval measurements within the MiMeS project. A dipole fit is superimposed. Adapted from Neiner et al. (2011).

2.1 Pulsating B stars

Before MiMeS, a direct magnetic signature had been detected in only very few pulsating stars of β Cephei or SPB type. β Cep itself was the first β Cephei star for which a Zeeman signature had been directly detected (Henrichs et al. 2000). Direct signatures had also been reported for ζ Cas (Neiner et al. 2003a) and ξ^1 CMa (Silvester et al. 2009; Fourtune-Ravard et al. 2011). Other magnetic β Cep or SPB stars have been suggested (e.g. Hubrig et al. 2009) but further observations rejected those possible detections (e.g. Silvester et al. 2009).

Within MiMeS a direct magnetic signature has been observed for 3 new magnetic pulsating B stars: 16 Peg (Henrichs et al. 2009), σ Lup (Henrichs et al. 2011), and V2052 Oph (Neiner et al. 2011). Note that V2052 Oph was already considered magnetic thanks to indirect evidences (Neiner et al. 2003b) but no direct signature had been detected until recently. Its longitudinal field curve folded in phase with the stellar rotation period is shown in Fig. 1.

The few detections and statistical results obtained within MiMeS show that magnetic fields do exist in pulsating B stars but are present in only ~16% of these stars (Grunhut et al. 2011) at the level of detection that can currently be reached. The fields are usually dipolar with an intensity $B_{\rm pol}$ of a few hundreds of Gauss. Some of the magnetic pulsating B stars also show spots of enhanced chemical abundance at their surface (e.g., V2052 Oph, see Neiner et al. 2011).

2.2 Herbig Ae/Be stars

Many indirect evidences of magnetic fields are observed in Herbig Ae/Be (HAeBe) stars. Highly ionised species, such as NV or OVI, are observed in emission in the spectra of HAeBe stars, and rotational modulation of the UV wind lines has been observed in some HAeBe stars (e.g. Catala et al. 1991). Moreover, X-ray emission has also been reported in HAeBe stars and are believed to come from very high-temperature regions close to the stellar surface, such as hot corona or chromosphere. Finally, non-thermal radio observations of a few HAeBe stars have also been reported (Skinner et al. 1993) suggesting a magnetic origin.

For all these reasons, HAeBe stars have been assumed to host magnetic fields. Until recently, however, only one marginal detection in HD 104237 had been reported (Donati et al. 1997). It is only with the emergence of the new generation of spectropolarimeters ESPaDOnS and Narval that a large survey of HAeBe stars could be performed, leading to the detection of 8 additional magnetic stars, i.e, an incidence of ~6% of magnetic HAeBe stars (e.g. Alecian et al. 2009). Following the survey, one more magnetic HAeBe star has been discovered,

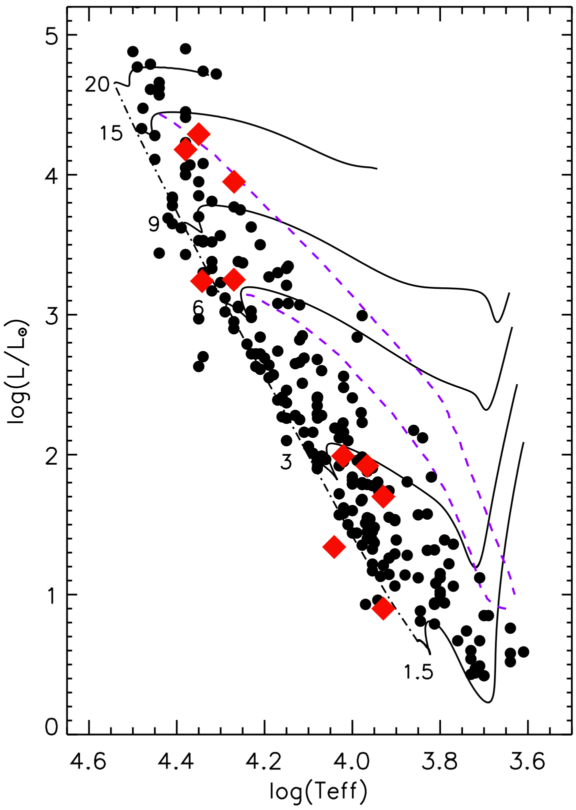

Fig. 2. Hertzsprung-Russell diagram of the Herbig Ae/Be stars for which the magnetic field was measured. Red diamonds indicate the 10 known magnetic HAeBe stars. Evolutionary tracks are superimposed (solid black lines). Purple dotted lines are the birthlines. Taken from Alecian et al. (2012).

bringing the total to 10 (see their position in the HR diagram in Fig. 2).

The incidence of magnetic field in HAeBe stars should be compared with the ∼5% of main sequence A/B stars that possess strong magnetic fields, organised on large scales, and stable over many years (Donati & Landstreet 2009). The spectropolarimetric survey of HAeBe stars has thus brought very strong arguments in favour of the fossil origin of the magnetic field in A/B stars, by discovering that their progenitors also possess strong magnetic fields organised on large scales, stable on many years and with the same incidence. A fossil link has therefore been established between the PMS and the MS phases of intermediate- and high-mass stars.

3 Recent theoretical work

The physics of magnetic fields in massive stars is not well understood. However, since observed fields have large-scale, quasi-static, stable configurations, which are not correlated with the star's characteristics such as rotation, the favored hypothesis is a fossil origin. Three main theoretical questions have to be addressed: i) what are the configurations of such fields and how are they born? ii) what are the necessary conditions to achieve large-scale organized stable magnetic configurations as observed in massive stars and how can one explain the dichotomy observed in the stellar population (some stars are magnetic and the others not)? iii) how are fossil fields coupled with other dynamical processes in massive star interiors such as differential rotation and what is their impact on stellar evolution? Until now, the MiMeS collaboration has mainly focused on the first two questions which constitute the first step to tackle the third question.

First, fossil fields are believed to originate from the trapping of the interstellar magnetic field flux during stellar formation. If the initial field is a small-scale turbulent field, we have to understand how it is converted into large-scale organized stable configurations as those observed at the surface of massive stars. This problem is related to the turbulent MHD relaxation processes, in which a turbulent magnetic field is converted into a large-scale one due to a selective decay (with different time-scales) of the ideal MHD invariants (the magnetic

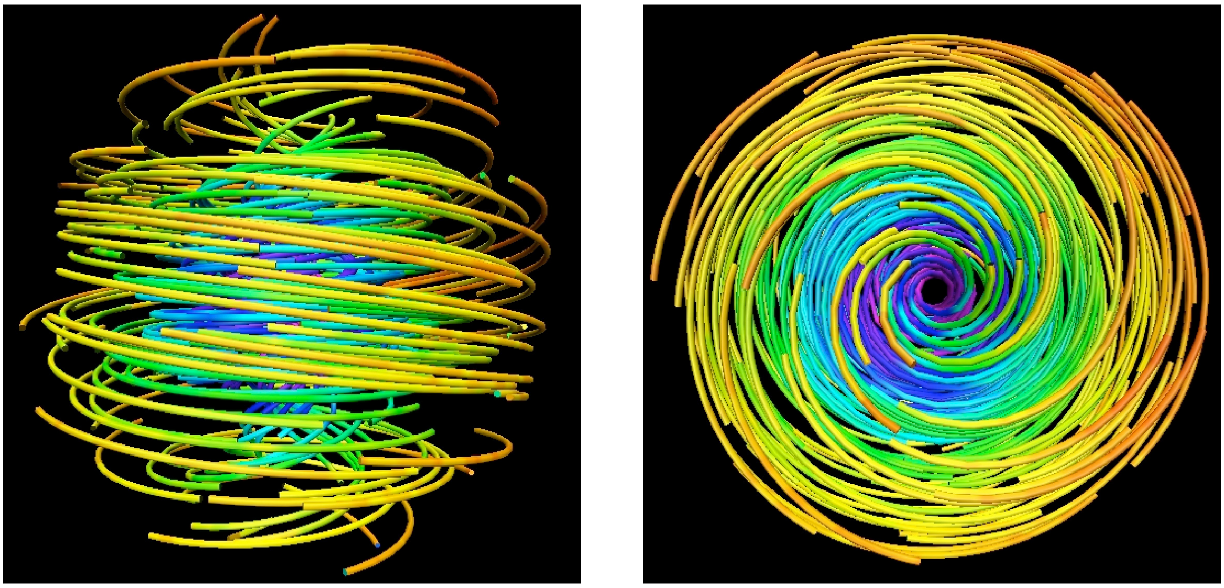

Fig. 3. Semi-analytical stable relaxed axisymmetric magnetic configuration seen from the equator (left panel) and from the pole (right panel). Colors scale with the density. Taken from Duez et al. (2010) (courtesy ApJ).

energy and the magnetic helicity). These processes have been first studied in experimental plasma physics where resulting relaxed states are those of minimum magnetic energy for a given magnetic helicity (Taylor 1954). Then, the case of high-β stellar radiation zone plasmas has been studied both theoretically (Duez & Mathis 2010) and numerically (Braithwaite & Spruit 2004; Braithwaite & Nordlund 2006; Braithwaite 2008). Resulting non force-free relaxed states are more complex and minimize the total energy for a given magnetic helicity and fluid invariants due to the stable stratification of stellar radiation zones. Moreover, roughly axisymmetric dipolar twisted configurations are obtained if the initial magnetic energy is confined near the stellar center (Braithwaite & Nordlund 2006; Duez & Mathis 2010) whereas one obtains non-axisymmetric fields when it is distributed in the whole radiation zone (Braithwaite 2008). The field is then organized on large-scale, mixed (poloidal and toroidal), stable, non force-free configurations, which are in magnetohydrostatic equilibrium. The study of the impact of rotation on such relaxation mechanisms is ongoing (see Duez, Braithwaite & Mathis, these proceedings).

Once relaxed magnetic configurations are obtained, one has to test their stability. It has been demonstrated in the 70's that purely poloidal or toroidal magnetic configurations are unstable (Tayler 1973; Markey & Tayler 1973). These theoretical results have recently been verified using 3-D MHD numerical simulations (see e.g., Brun 2007). Thus, stable magnetic configurations should be of mixed type (Tayler 1980; Braithwaite 2009) thanks to the stabilization of each component by the other; this is precisely the case of known relaxed configurations. To study the stability of relaxed mixed configurations we use direct 3-D MHD numerical simulations in which the obtained configurations are submitted to general perturbations. This numerical method is used because of the lack of general results by the analytical method, which is very efficient to demonstrate instability but not stability. This type of simulations applied to axisymmetric relaxed configurations obtained by numerical simulations (Braithwaite & Nordlund 2006) and by theoretical studies (Duez & Mathis 2010) concluded on the stability of those configurations (Braithwaite 2009; Duez et al. 2010), a major result for the magnetism of massive stars (see Fig. 3) that should be extended to other and more general configurations.

Theoretical results are then used to understand observed magnetic topologies. Moreover, these constitute a strong basis to get a coherent picture of magnetic massive stars internal dynamical processes and evolution (Mathis & Zahn 2005). Finally, these will be used in 3-D MHD modelling of massive stars environment by MiMeS collaborators (Townsend et al. 2007).

4 Conclusions

The MiMeS project allows to obtain rapid progress on the study of magnetic fields in massive stars. The new observations provide critical constraints on the configuration, strength, and incidence of magnetic fields in massive stars. This allows for the development and testing of new models and theories.

Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii, as well as on observations obtained using the Narval spectropolarimeter at the Observatoire du Pic du Midi (France), which is operated by the Institut National des Sciences de l'Univers (INSU). We thank the Programme National de Physique Stellaire (PNPS) for their support to MiMeS.

References

Alecian, E., Wade, G. A., Catala, C., et al. 2009, MNRAS, 400, 354

Alecian, E., Wade, G. A., Catala, C., et al. 2012, MNRAS, to be submitted

Braithwaite, J. 2008, MNRAS, 386, 1947

Braithwaite, J. 2009, MNRAS, 397, 763

Braithwaite, J. & Nordlund, Å. 2006, A&A, 450, 1077

Braithwaite, J. & Spruit, H. C. 2004, Nature, 431, 819

Brun, A. S. 2007, Astronomische Nachrichten, 328, 1137

Catala, C., Czarny, J., Felenbok, P., Talavera, A., & The, P. S. 1991, A&A, 244, 166

Donati, J.-F. & Landstreet, J. D. 2009, ARA&A, 47, 333

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658

Duez, V., Braithwaite, J., & Mathis, S. 2010, ApJ, 724, L34

Duez, V. & Mathis, S. 2010, A&A, 517, A58

Fourtune-Ravard, C., Wade, G. A., Marcolino, W. L. F., et al. 2011, in IAU Symposium 272, ed. C. Neiner, G. Wade, G. Meynet, & G. Peters, 180

Grunhut, J. H., Wade, G. A., & the MiMeS Collaboration. 2011, ArXiv e-prints 1108.2673

Henrichs, H. F., de Jong, J. A., Donati, D.-F., et al. 2000, in Magnetic Fields of Chemically Peculiar and Related Stars, ed. Y. V. Glagolevskij & I. I. Romanyuk, 57

Henrichs, H. F., Kolenberg, K., Plaggenborg, B., et al. 2011, in IAU Symposium 272, ed. C. Neiner, G. Wade, G. Meynet, & G. Peters, 192

Henrichs, H. F., Neiner, C., Schnerr, R. S., et al. 2009, in IAU Symposium 259, 393

Hubrig, S., Briquet, M., De Cat, P., et al. 2009, Astronomische Nachrichten, 330, 317

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

Mathis, S. & Zahn, J.-P. 2005, A&A, 440, 653

Neiner, C., Alecian, E., Briquet, M., et al. 2011, A&A, submitted

Neiner, C., Geers, V. C., Henrichs, H. F., et al. 2003a, A&A, 406, 1019

Neiner, C., Henrichs, H. F., Floquet, M., et al. 2003b, A&A, 411, 565

Silvester, J., Neiner, C., Henrichs, H. F., et al. 2009, MNRAS, 398, 1505

Skinner, S. L., Brown, A., & Stewart, R. T. 1993, ApJS, 87, 217

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

Tayler, R. J. 1980, MNRAS, 191, 151

Taylor, R. L. 1954, Science, 119, 780

Townsend, R. H. D., Owocki, S. P., & Ud-Doula, A. 2007, MNRAS, 382, 139

Wade, G. A. & the MiMeS Collaboration. 2010, ArXiv e-prints 1012.2925