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Magnetism of hot stars

G. A. Wade[1] **and C. Neiner**[2]

[1] *Department of Physics & Space Science, Royal Military College of Canada, P.O. Box 17000, Station Forces, Kingston, Ontario, Canada, K7K 7B4*

[2] *LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France*

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Abstract. Strong, stable, and organised magnetic fields are present at the surfaces of a small fraction of OBA stars. These "fossil fields" exhibit uniform characteristics in stars over a tremendous range of stellar mass, age, temperature, and rotation rate. In hot O- and B-type stars, these magnetic fields couple efficiently to the stellar radiatively driven winds, strongly influencing stellar mass loss and rotation. In this article we review the characteristics of the known magnetic hot stars, discuss recent discoveries and insights, and describe recent theoretical progress toward understanding basic field properties and the influence of magnetic fields on hot star evolution.

Key words: stars: magnetic fields – stars: evolution – stars: winds, outflows – stars: rotation

1. Introduction

Recent large surveys (Wade et al., 2016a; Grunhut et al., 2017; Fossati et al., 2015; Schöller et al., 2017) have investigated the properties of surface magnetism of stars having radiative envelopes, i.e. stars of spectral types A, B and O ranging in effective temperature from roughly 7 000–50 000 K. The largest of these surveys - the Magnetism in Massive Stars (or MiMeS) project (Wade et al., 2016a) - obtained magnetic measurements of over 550 bright stars of spectral types B and O. Based on these data, they reported that organized magnetic fields stronger than a few hundred gauss are present at the surfaces of approximately 7% of such stars (e.g. Grunhut et al., 2017). Their surface dipolar field components range in strength from less than 100 G to well over 10 kG (e.g. Briquet et al., 2016; Wade et al., 2012; Petit et al., 2013; Shultz, 2016). Like their lower-mass A-type cousins, their magnetic fields are not symmetric about the stellar rotation axis, leading to rotational modulation of the measured line-of-sight magnetic field and other photospheric and wind diagnostics, phenomena explained by the Oblique Rotator Model (Stibbs, 1950).

The essential characteristics of these magnetic fields (their organized topologies, their large range of strengths, their stability on timescales of at least decades, and their lack of correlation with basic stellar parameters such as mass

and rotation rate) are identical to those of cooler, lower-mass A-type stars, but stand in strong contrast to those of the dynamo-generated fields of cool stars. On the other hand, they bear a number of similarities to the fields of white dwarfs and neutrons stars. These fields are thought to be "fossils", i.e. the slowly-evolving remnants of magnetic fields generated or accumulated during an earlier phase of stellar evolution. That the properties of these fields remain essentially unchanged in stars ranging in mass from 1.5 to about 60 times that of the Sun (Wade et al., 2014; Wade & MiMeS Collaboration, 2015), notwithstanding the important differences in stellar structure that occur over this enormous range of mass, suggests a basic underlying commonality of the formation or evolution of their magnetic fields. Understanding this remarkable observational fact is a key challenge of modern stellar astrophysics.

1.1. The physics of fossil magnetism

A major breakthrough of the first decades of the 21st century has been to establish that stochastic initial seed magnetic fields in stellar radiative zones relax naturally to long-lived stable configurations with mixed poloidal/toroidal configurations organized on large scales. Numerical and semi-analytic calculations (Braithwaite & Spruit, 2004; Duez & Mathis, 2010; Duez et al., 2010) have shown that the characteristics of the fields predicted at the stellar surface by these models are in good qualitative agreement with those observed in real magnetic O, B and A-type stars (also see Kochukhov, these proceedings). In the stellar interior, the toroidal fields are predicted to be very strong, and they may have important consequences for chemical and angular momentum transport throughout the radiative envelope.

This breakthrough has provided the first quantitative physical model for the interpretation and study of fossil stellar magnetism, with the consequence that there now exists a theoretical context for the interpretation of the magnetic fields observed at the surfaces of main sequence (MS) and evolved A, B and O stars, in white dwarfs (Braithwaite & Spruit, 2004), and in neutron stars (Braithwaite & Spruit, 2006). It has even spawned the first theoretical speculations aimed at understanding why only a minority (about 10%) of MS stars exhibit detectable surface magnetism, and to explain the puzzling "magnetic field desert" phenomenon (Aurière et al., 2007; Braithwaite & Cantiello, 2013).

Notwithstanding this important progress, the origins of the seed fields that give rise to the observed fossil fields remain unknown and poorly constrained (Neiner et al., 2015). Currently, there exist three principal hypotheses: conservation of magnetic flux from the interstellar medium (ISM) during star formation, convective dynamos operating during protostellar or pre-MS phases that could enhance the ISM field (e.g. Hussain & Alecian, 2014), and stellar mergers early in the formative history (e.g. Ferrario et al., 2009; Langer, 2014).

2. Observed properties of magnetic B- and O-type stars

To date, about 70 early-type magnetic stars with spectral types earlier than B5 or effective temperatures above 15 000 K have been confidently identified. Most are relatively bright stars. Petit et al. (2013), Wade & MiMeS Collaboration (2015), and Shultz (2016) provide summaries.

2.1. Fundamental characteristics

Fossil magnetic fields are observed without any significant change in their general characteristics in stars ranging in spectral type from mid-F to early O. The earliest magnetic stars have spectral types of about O4, although their spectral classification changes somewhat due to the periodic variability of their spectra (Walborn, 1972; Howarth et al., 2007). These most massive magnetic stars have inferred masses of 40–60 $M_{\odot}$. However, because the field characteristics of magnetic O stars are poorly sampled (only about one dozen are known), this does not represent a confident upper limit and higher-mass magnetic stars could exist.

The HR diagram of the known magnetic hot stars (Shultz, 2016) shows that the lion's share of the known magnetic A, B and O stars are MS objects. A small number of pre-MS magnetic B-type stars (see e.g. Alecian et al., 2013) and post-MS magnetic O, B and high-mass A stars (see Martin, these proceedings, Neiner et al., 2017; Martin et al., 2017) are also known.

2.2. Spectral properties

The properties of stellar spectra at visible wavelengths change significantly from the early B stars to the mid-O stars. While some of this change is attributable to the evolving radiation field, changing ionization balance and the importance of non-LTE effects, it is also in large part due to the growing influence of the stellar wind.

As is discussed later in Sect. 3, a key impact of a magnetic field at the surface of a hot star is the channeling of its outflowing wind. This phenomenon results in the presence of a large quantity of relatively dense magnetically-confined plasma typically located within a few stellar radii of the stellar surface. The presence of this plasma weakly modifies the optical spectra of magnetic B stars, but can fundamentally alter the spectra of magnetic O stars (see e.g. Petit et al., 2013; Wade & MiMeS Collaboration, 2015) by introducing many periodically-variable emission lines. At radio wavelengths, magnetic B and O stars exhibit non-thermal emission, likely due to the gyrosynchrotron mechanism (e.g. Trigilio et al., 2004; Kurapati et al., 2017). At shorter wavelengths, X-ray emission diagnoses the hot plasma produced as a consequence of the large-scale shocks caused by channelling of the supersonic wind (ud-Doula & Nazé, 2016).

In addition to wind channeling effects, the magnetic field may also influence transport processes in the photosphere, producing large-scale chemical abundance inhomogeneities (e.g. Oksala et al., 2015). This chemical spots, which are prevalent for magnetic stars cooler than about 25 000 K, are responsible for periodic modulation of the profiles of many photospheric spectral lines.

2.3. Magnetic field strengths and topologies

Shultz (2016) (see also Shultz et al., these proceedings) performed a homogeneous study of the physical, rotational, magnetic and magnetospheric properties of the known magnetic B-type stars. The properties of the known magnetic O stars are summarized by Wade & MiMeS Collaboration (2015). Apart from a small number of well-known exceptions (e.g. the B stars τ Sco and HD 37776), the magnetic field toplogies of hot stars appear to be qualitatively identical to those of their lower-mass Ap star cousins: they contain most of their magnetic energy in the dipole mode, their dipole axes are inclined significantly relative to their rotation axes, and their magnetic configurations are stable on long timescales (years to decades, corresponding to hundreds or even thousands of stellar rotations). The distributions of surface dipole magnetic field strengths are very similar for O, B and A stars: they range from a few times 10^1 to a few times 10^4 G, and peak at a few times 10^3 G.

A key characteristics of the distribution of magnetic fields strengths of Ap stars is the so-called "magnetic desert", characterized by a "critical dipole field strength" of about 300 G below which essentially no magnetic stars are detected (Aurière et al., 2007). The characteristics of this 'desert' for more massive stars remains to be established, as several clear examples of stars with field strengths below 300 G have already been discovered (e.g. Briquet et al., 2016).

While the magnetic properties of the hot pre-MS magnetic stars are similar to those of the MS population, the evolved post-MS magnetic stars generally have much weaker fields (Neiner et al., 2017), as would be expected from magnetic flux conservation (e.g. Keszthelyi et al., 2017). Those evolved stars thus often appear in the magnetic desert, and explain, at least to some extent, the hot stars that reside there.

2.4. Rotation

Magnetic hot stars generally exhibit rotation rates below those of "normal", non-magnetic stars of similar spectral types. The magnetic field impacts the stellar rotation by coupling to the outflowing wind, enhancing angular momentum loss and rapidly braking the star. Nevertheless, several examples of magnetic hot stars exhibiting rapid rotation have been discovered (e.g. Oksala et al., 2010; Grunhut et al., 2012).

Classical Be stars exhibit the most rapid rotation of any class of B-type stars. As of today, no magnetic field has been directly detected in any classical

Be star, notwithstanding extensive searches (Wade et al., 2016a,b). However, indirect evidence of the presence of a magnetic field, i.e. rotationally modulated observables, seems to be have been found in the classical Be star ω Ori (Neiner et al., 2003, 2012).

2.5. Binarity

Magnetic fields in binary systems may be strongly affected by, and may also strongly affect, the transfer of energy, mass and angular momentum between the components.

Although binary systems containing hot stars are extremely common, binaries with orbital periods shorter than $\sim$ 60 days containing magnetic hot stars are very rare. At the conclusion of the MiMeS survey, less than one dozen SB2 systems containing magnetic A, B or O stars were known. Of these, less than one-half contained a hot primary star. The Binarity and Magnetic Interactions in various classes of Stars (BinaMIcS, e.g. Neiner et al., 2015) project has studied this issue further in short-period spectroscpic binaries and indeed confirms that the occurence of magnetic fields in hot stars in those binaries is lower than in single hot stars. A possible explanation for this dearth of magnetic fields in hot binary systems may lie in stellar formation processes. For example, Commerçon et al. (2011) showed in their simulations that fragmentation of dense stellar cores is inhibited when the medium is magnetic. This could make binary system more difficult to form in the presence of a seed field.

Similar discrepancies between incidence rates of strong magnetic fields in cataclysmic variables (CV) vs. single white dwarfs led Tout et al. (2008) to conclude that the formation of white dwarf magnetic fields was initimately tied to the physics of CV formation, in particular the mass transfer and merger processes. Others (e.g. Langer, 2014) have speculated about a similar connection between binarity and the origin of the fossil magnetic fields of non-degenerate hot stars. The binarity of magnetic hot stars is discussed in greater detail by Nazé and Alecian (these proceedings).

3. Stellar wind-magnetic field interactions

Magnetic stars of spectral types A to moderately early B (often called Ap and Bp stars) exhibit strong, characteristic spectral line strength anomalies and variability. These phenomena - diagnostic of complex, large-scale distributions of abundance enhancement and depletion of various chemical elements - result from the interaction of the magnetic field with photospheric atoms diffusing under the competitive effects of gravity and radiative levitation (e.g. Alecian & Stift, 2017). These structures are able to form and subsist because, at the effective temperatures of these stars, the radiative and gravitational forces on some ions are of similar orders of magnitude. At earlier spectral types, the strong growth of the UV radiation field leads to radiative accelerations that

rapidly overwhelm gravity, leading to the appearance of radiatively driven stellar winds. (The disappearance of evidence of systematic photospheric chemical peculiarities and abundance structures at about the temperature at which winds become significant is thereby naturally explained.)

Systematic MHD studies of the interaction of these outflowing winds with dipolar magnetic fields have been carried out during the past 15 years (e.g. ud-Doula & Owocki, 2002; Ud-Doula et al., 2008, 2009; Petit et al., 2013). A basic conclusion of these investigations is that two physical quantities are capable of describing the general behaviour of the wind of a hot star under the influence of a magnetic field and stellar rotation (Petit et al., 2013): the *wind magnetic confinement parameter* (ud-Doula & Owocki, 2002), which determines the *Alfvén radius* $R_{\rm A}$, and the *rotation parameter* (Ud-Doula et al., 2008), which determined the Kepler co-rotation radius $R_{\rm K}$.

In the case of a rapidly-rotating star, the Kepler radius is located relatively close to the stellar surface, and for sufficiently strong magnetic fields is located inside the Alfvén radius. In this scenario, plasma in the region between $R_{\rm K}$ and $R_{\rm A}$ is forced (by the magnetic field) to orbit at greater than the local Keplerian speed, and hence experiences an unbalanced (outward) net force. In such a "centrifugal magnetosphere" (CM), wind plasma is trapped in this region by the combined effects of magnetic field and rotation. In the case of a slowly-rotating star, the Kepler radius is located far from the stellar surface. The net gravitational + centrifugal force is always directed toward the star. In such a "dynamical magnetosphere" (DM) scenario, plasma driven up the field lines ultimately cools and falls back to the stellar surface. The material in the DM is thus frequently renewed (i.e. on the dynamical timescale).

Centrifugal and dynamical magnetospheres can be observationally distinguished in several ways. First, broad emission features, often found at high velocities, are observed in optical spectra of stars hosting a CM, while stars with DMs show narrower emission if any (see, e.g. Grunhut & Neiner, 2015). DM emission is mostly observed for O stars, since the winds of B stars are too weak to feed the magnetosphere at a sufficient rate to produce significant emission. Rotationally-modulated variability of the magnetospheric emission can be used to reconstruct the circumstellar plasma distribution, especially for stars with CMs (e.g. Grunhut et al., 2013). The magnetospheres of hot stars can be comparatively classified using the *rotation-confinement diagram* (Petit et al., 2013).

4. The influence of magnetic fields on stellar evolution

Current 2D and 3D MHD models can effectively compute the short-term evolution of the wind under such conditions, and have provided a sound theoretical basis for understanding the general observational behaviour of hot magnetic stars. In particular, they demonstrate that the surface field interaction with the

wind results in two effects that are predicted to significantly influence the evolution of hot stars. *Mass-loss quenching* (e.g. ud-Doula & Owocki, 2002) refers to the net reduction in the mass loss rate of a star through the top of its magnetosphere as a consequence of magnetic wind trapping. *Magnetic braking* (e.g. Ud-Doula et al., 2009) refers to the enhanced loss of angular momentum through the wind resulting principally from Maxwell stresses imparted by the magnetic field. Recent efforts have sought to incorporate the effects of these two important phenomena into models of stellar evolution. Meynet et al. (2011) performed first calculations that showed the potential evolutionary impact of magnetic braking. Keszthelyi et al. (these proceedings) have developed more complete and realistic models, and demonstrate that mass-loss quenching also yields an important evolutionary impact. Petit et al. (2017) and Georgy et al. (2017) have recently exploited these new modeling capabilities to provide potential explanations of the appearance of high-mass stellar black holes and pair-instability supernovae in high (∼Galactic) metallicity environments. Moreover, recent identification of candidate magnetic stars in the Magellanic Clouds (e.g. Nazé et al., 2015; Walborn et al., 2015) provides the potential to explore the properties and evolution of magnetic stars in environments very different from those occurring in the Milky Way.

In addition to these predicted (and observed) large scale poloidal surface fields, models of relaxed fossil fields predict very strong, predominantly toroidal fields throughout the stellar radiative zone. The extent to which these fields are modified or modify internal circulation currents and differential rotation, including coupling of the rotation of the core to the envelope, is of great current interest (Langer, 2014) and is beginning to become amenable to observational verification (Briquet et al., 2012).

5. Transformation of fields on evolutionary timescales

As magnetic fields influence stellar evolution, so are magnetic fields expected to transform in response to changes in the structure of the stars in which they are embedded. The evolution of surface magnetic fields of MS stars has been investigated by e.g. Landstreet et al. (2007), and more recently by Fossati et al. (2016). These studies suggest that magnetic flux conservation - a basic assumption in models attempting to connect fossil magnetism through different phases of stellar evolution - is poorly supported by observations of main sequence stars.

Extensive surveys of magnetic fields in cool giants and supergiants (the evolutionary descendants of hot MS stars) show that these stars exhibit magnetic fields powered by dynamos (e.g. Grunhut et al., 2010; Aurière et al., 2015). Although a small population of red giants show evidence of surviving fossil fields from the MS (and the unique interactions between the post-MS dynamo and the pre-existing fossil field; e.g. Aurière et al., 2008), the growth of the deep convective envelope generally appears to erase evidence of their earlier magnetic

characteristics. However, because hot OBA supergiants retain the radiative envelopes they had on the MS, these stars provide a capability to directly extend the studies of MS objects to more advanced evolutionary phases and a much greater range of stellar structural changes (e.g. Blazère et al., 2015; Neiner et al., 2017). The Large Impact of magnetic Fields on the Evolution of hot stars (LIFE) project aims at detecting and characterizing magnetic evolved hot stars at various phases of the post-MS evolution. This project and magnetic fields of evolved stars are discussed in more detail by Martin (these proceedings).

References

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

Alecian, G. & Stift, M. J. 2017, *Mon. Not. R. Astron. Soc.*, **468**, 1023

Aurière, M., Konstantinova-Antova, R., Charbonnel, C., et al. 2015, *Astron. Astrophys.*, **574**, A90

Aurière, M., Konstantinova-Antova, R., Petit, P., et al. 2008, *Astron. Astrophys.*, **491**, 499

Aurière, M., Wade, G. A., Silvester, J., et al. 2007, *Astron. Astrophys.*, **475**, 1053

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

Braithwaite, J. & Cantiello, M. 2013, *Mon. Not. R. Astron. Soc.*, **428**, 2789

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

Braithwaite, J. & Spruit, H. C. 2006, *Astron. Astrophys.*, **450**, 1097

Briquet, M., Neiner, C., Aerts, C., et al. 2012, *Mon. Not. R. Astron. Soc.*, **427**, 483

Briquet, M., Neiner, C., Petit, P., Leroy, B., & de Batz, B. 2016, *Astron. Astrophys.*, **587**, A126

Commerçon, B., Hennebelle, P., & Henning, T. 2011, *Astrophys. J., Lett.*, **742**, L9

Duez, V., Braithwaite, J., & Mathis, S. 2010, *Astrophys. J., Lett.*, **724**, L34

Duez, V. & Mathis, S. 2010, *Astron. Astrophys.*, **517**, A58

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

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

Fossati, L., Schneider, F. R. N., Castro, N., et al. 2016, *Astron. Astrophys.*, **592**, A84

Georgy, C., Meynet, G., Ekström, S., et al. 2017, *Astron. Astrophys.*, **599**, L5

Grunhut, J., Townsend, R., & Wade, G. 2013, in Massive Stars: From alpha to Omega, 69

Grunhut, J. H. & Neiner, C. 2015, in IAU Symp., Vol. **305**, *Polarimetry*, ed. K. N. Nagendra, S. Bagnulo, R. Centeno, & M. Jesús Martínez González, 53–60

Grunhut, J. H., Rivinius, T., Wade, G. A., et al. 2012, *Mon. Not. R. Astron. Soc.*, **419**, 1610

Grunhut, J. H., Wade, G. A., Hanes, D. A., & Alecian, E. 2010, *Mon. Not. R. Astron. Soc.*, **408**, 2290

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

Howarth, I. D., Walborn, N. R., Lennon, D. J., et al. 2007, *Mon. Not. R. Astron. Soc.*, **381**, 433

Hussain, G. A. J. & Alecian, E. 2014, in IAU Symp., Vol. **302**, *Magnetic Fields throughout Stellar Evolution*, ed. P. Petit, M. Jardine, & H. C. Spruit, 25–37

Keszthelyi, Z., Wade, G. A., & Petit, V. 2017, in IAU Symp., Vol. **329**, *The Lives and Death-Throes of Massive Stars*, ed. J. J. Eldridge, J. C. Bray, L. A. S. McClelland, & L. Xiao, 250–254

Kurapati, S., Chandra, P., Wade, G., et al. 2017, *Mon. Not. R. Astron. Soc.*, **465**, 2160

Landstreet, J. D., Bagnulo, S., Andretta, V., et al. 2007, *Astron. Astrophys.*, **470**, 685

Langer, N. 2014, in IAU Symp., Vol. **302**, *Magnetic Fields throughout Stellar Evolution*, ed. P. Petit, M. Jardine, & H. C. Spruit, 1–9

Martin, A. J., Neiner, C., Oksala, M. E., et al. 2017, *ArXiv e-prints* [arXiv:1712.07403]

Meynet, G., Eggenberger, P., & Maeder, A. 2011, *Astron. Astrophys.*, **525**, L11

Nazé, Y., Walborn, N. R., Morrell, N., Wade, G. A., & Szymański, M. K. 2015, *Astron. Astrophys.*, **577**, A107

Neiner, C., Grunhut, J. H., Petit, V., et al. 2012, *Mon. Not. R. Astron. Soc.*, **426**, 2738

Neiner, C., Hubert, A.-M., Frémat, Y., et al. 2003, *Astron. Astrophys.*, **409**, 275

Neiner, C., Morin, J., & Alecian, E. 2015, in SF2A-2015: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. F. Martins, S. Boissier, V. Buat, L. Cambrésy, & P. Petit, 213–216

Neiner, C., Oksala, M. E., Georgy, C., et al. 2017, *Mon. Not. R. Astron. Soc.*, **471**, 1926

Oksala, M. E., Kochukhov, O., Krtička, J., et al. 2015, *Mon. Not. R. Astron. Soc.*, **451**, 2015

Oksala, M. E., Wade, G. A., Marcolino, W. L. F., et al. 2010, *Mon. Not. R. Astron. Soc.*, **405**, L51

Petit, V., Keszthelyi, Z., MacInnis, R., et al. 2017, *Mon. Not. R. Astron. Soc.*, **466**, 1052

Petit, V., Owocki, S. P., Wade, G. A., et al. 2013, *Mon. Not. R. Astron. Soc.*, **429**, 398

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

Shultz, M. 2016, PhD thesis, Queen's University (Canada)

Stibbs, D. W. N. 1950, *Mon. Not. R. Astron. Soc.*, **110**, 395

Tout, C. A., Wickramasinghe, D. T., Liebert, J., Ferrario, L., & Pringle, J. E. 2008, *Mon. Not. R. Astron. Soc.*, **387**, 897

Trigilio, C., Leto, P., Umana, G., Leone, F., & Buemi, C. S. 2004, *Astron. Astrophys.*, **418**, 593

ud-Doula, A. & Nazé, Y. 2016, *Adv. Space Res.*, **58**, 680

ud-Doula, A. & Owocki, S. P. 2002, *Astrophys. J.*, **576**, 413

Ud-Doula, A., Owocki, S. P., & Townsend, R. H. D. 2008, *Mon. Not. R. Astron. Soc.*, **385**, 97

Ud-Doula, A., Owocki, S. P., & Townsend, R. H. D. 2009, *Mon. Not. R. Astron. Soc.*, **392**, 1022

Wade, G. A., Grunhut, J., Alecian, E., et al. 2014, in IAU Symp., Vol. **302**, *Magnetic Fields throughout Stellar Evolution*, ed. P. Petit, M. Jardine, & H. C. Spruit, 265–269

Wade, G. A., Maíz Apellániz, J., Martins, F., et al. 2012, *Mon. Not. R. Astron. Soc.*, **425**, 1278

Wade, G. A. & MiMeS Collaboration. 2015, in ASP Conf. Ser., Vol. **494**, *Physics and Evolution of Magnetic and Related Stars*, ed. Y. Y. Balega, I. I. Romanyuk, & D. O. Kudryavtsev, 30

Wade, G. A., Neiner, C., Alecian, E., et al. 2016a, *Mon. Not. R. Astron. Soc.*, **456**, 2

Wade, G. A., Petit, V., Grunhut, J. H., Neiner, C., & MiMeS Collaboration. 2016b, in ASP Conf. Ser., Vol. **506**, *Bright Emissaries: Be Stars as Messengers of Star-Disk Physics*, ed. T. A. A. Sigut & C. E. Jones, 207

Walborn, N. R. 1972, *Astron. J.*, **77**, 312

Walborn, N. R., Morrell, N. I., Nazé, Y., et al. 2015, *Astron. J.*, **150**, 99