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Magnetic Fields across the Hertzsprung-Russell Diagram

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Abstract. The research area of stellar magnetism has entered a new era in the last few years with the considerable increase in the number of spectropolarimetric instruments in regular operation at various observatories and the spectacular improvement in their performance and sensitivity compared to the previous generation of such instruments. The observations made possible by these instrumental developments, combined with refined diagnostic and modelling techniques, have led to the discovery of magnetic fields with strengths down to a few Gauss in stars of a large number of types throughout the Hertzsprung-Russell diagram. An overview of the current knowledge of stellar magnetic fields is given, with emphasis on the stellar types that are particularly relevant for asteroseismology.

1. Introduction

The title of this talk is the same as that of an international workshop that took place in Santiago (Chile) in January 2001 (Mathys et al. 2001) – almost exactly 10 years ago. Since that time, progress in the area of stellar magnetic fields has accelerated to such an extent that the number of papers on this subject that have been published in the past decade exceeds the number of such publications that had appeared over the previous half-century – since Babcock's (1947) discovery of the first magnetic field in a star other than the Sun, the Ap star 78 Vir. Moreover, while the existence of such fields had for a long time been confirmed only in a very small number of stellar types (Ap stars, white dwarfs, and since the 1980's, cool solar-type stars), their occurrence has in recent years been convincingly established across an increasingly wide range of regions of the Hertzsprung-Russell (H-R) diagram.

These spectacular advances have been made possible in large part by the development of new and improved instruments. Observers now have at their disposal an unprecedented large number of high performance spectropolarimeters, most of which are offered as facility instruments in public observatories. They include:

- ESPaDOnS at the Canada-France-Hawaii Telescope (CFHT) in Mauna Kea (Hawaii, USA);
- its twin, NARVAL, at the Telescope Bernard Lyot (TBL) atop Pic-du-Midi (France);
- HARPS at the ESO 3.6-m telescope (La Silla, Chile), in its polarimetric mode;

- FORS-2 (originally FORS-1) in its spectropolarimetric mode, at one of the Unit Telescopes (currently UT1) of ESO's Very Large Telescope (VLT; Paranal, Chile);
- SOFIN at the Nordic Optical Telescope, at the Roque de los Muchachos Observatory on the La Palma island (Spain), in its polarimetric mode;
- the Semel polarimeter (SEMPOL) for UCLES at the Anglo-Australian Telescope (AAT) of the Australian Astronomical Observatory.

This list is not exhaustive, but it includes the instruments with which the vast majority of the results presented in this review have been obtained.

Another important factor contributing to progress in our knowledge of stellar magnetic fields has been the development of ever more sophisticated inversion techniques. These allow one to reconstruct to some extent the structure of the magnetic field at the surface of the studied stars from analysis of the profiles of their spectral lines recorded in circular and, possibly, linear polarisations. They come in slightly different flavours, such as Zeeman-Doppler Imaging (ZDI; Donati & Semel 1990) and Magnetic Doppler Imaging (MDI; Piskunov & Kochukhov 2002; Kochukhov & Piskunov 2002).

Full coverage of our current knowledge of stellar magnetic fields would vastly exceed the framework of this review. Here I shall only give an overview of this knowledge, with emphasis on recent results and on the stellar types that are particularly relevant for asteroseismology. I shall also refrain from discussing magnetism in pre-main-sequence stars – a vast topic in itself, extending well beyond the scope of this presentation. For more details, readers may refer e.g. to Donati & Landstreet's (2009) recent review.

The H-R diagram can be divided in two halves based on the dominant mechanism of heat transport in stellar outer layers. Indeed the envelopes of cool stars are predominantly convective and those of hot stars are (almost) fully radiative. On the main sequence, the dividing line between the two processes occurs around an effective temperature of 6500 K, roughly half-way through the F spectral type. This boundary shifts towards lower temperatures for more luminous stars and towards higher temperatures at lower luminosities. Properties of stellar magnetic fields change drastically across this line.

2. Stars with Convective Envelopes

2.1. Low-mass Stars

Magnetic fields are permanently generated by dynamo processes in the convective envelopes of cool stars. These fields have a complex, fractionated structure, and they are variable on a wide range of timescales. They are concentrated in active regions, spots or plages, covering a fraction $f < 1$ of the stellar surface. The magnetism of cool stars can be quantified by their magnetic flux, fB, where B is the average value of the magnetic field strength across the stellar surface. Except in the most active, fastest-rotating, coolest low-mass stars, B is approximately equal to the equipartition field, that is, such that the magnetic pressure is equal to the gas pressure. To first order, the magnetic flux is higher in faster-rotating stars. This correlation can be characterised by consideration of the Rossby number, $R_0 = P_{\rm rot}/\tau_{\rm conv}$, where $P_{\rm rot}$ is the rotation period of the star and $\tau_{\rm conv}$ is the convective turnover time, a mass-dependent parameter that can be determined theoretically or empirically [see e.g.,Kiraga & Stepien (2007)]. The convective

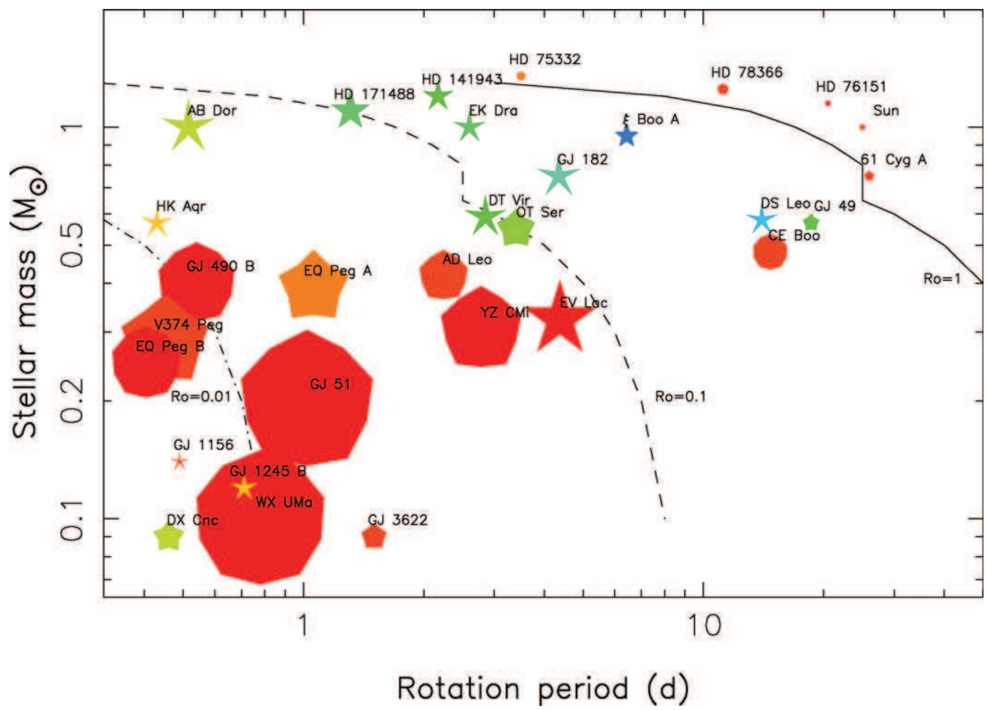

Figure 1. Basic properties of the large-scale magnetic topologies of low-mass stars, as a function of stellar mass and rotation rate. Symbol size indicates relative magnetic energy densities, symbol colour illustrates field configurations (blue and red for purely toroidal and purely poloidal fields respectively) while symbol shape depicts the degree of axisymmetry of the poloidal field component (decagon and stars for purely axisymmetric and purely non-axisymmetric poloidal fields respectively). The full, dashed and dashed-dotted lines respectively trace where the Rossby number R_0 equals 1, 0.1 and 0.01. The smallest and largest symbols correspond to mean large-scale field strengths of 3 G and 1.5 kG respectively. From Donati (2011).

turnover time varies little from star to star, so that the Rossby number is primarily a measurement of the stellar rotation rate. Reiners et al. (2009) showed that the magnetic flux varies linearly with the Rossby number for $R_0 > 0.1$, and that it is essentially constant (~ 3 kG) for $R_0 < 0.1$. This reflects the occurrence of a saturation of the magnetic flux in fast-rotating, fully convective M dwarfs. The latter corresponds to the transition from a regime in which the magnetic field has a mostly plage-like structure to one in which it occurs mainly in spots.

In recent years, Donati and his collaborators have been conducting a systematic spectropolarimetric survey of the large-scale magnetic topologies of low-mass stars. The results are summarised in Fig. 1. At $R_0 > 1$, fields are purely poloidal and axisymmetric. The magnetic fields of stars with $R_0 < 1$ and $M > 0.5\,M_\odot$ have a substantial, possibly predominant, toroidal component, and their poloidal components are in general non-axisymmetric. Most stars with $M < 0.5\,M_\odot$ tend to have strong poloidal axisymmetric fields, but some fast-rotating, very low mass stars have weak, non-axisymmetric fields.

Magnetic fields in cool stars are responsible for a wide variety of phenomena such as photospheric starspots, prominences, coronal loops, coronal emission throughout the electromagnetic spectrum (in radio, UV/optical, X-ray), and flares. These phenomena are known collectively as magnetic activity. The activity level varies with time, defining activity cycles qualitatively similar to the solar cycle. In particular, polarity reversals have been observed through ZDI mapping of spectropolarimetric observations obtained at different epochs (Fares et al. 2009). Flip-flop cycles, that is, quasi-periodic oscillations of the preferred longitudes of spot formation, have also been observed, both in young solar analogs and in active red giants such as RS CVn and FK Com stars [see e.g., Berdyugina (2007) and references therein].

2.2. Evolved Stars

Most late-type giants and supergiants that have evolved as single stars are slowly rotating, so that the magnetic fields that can be generated in these stars by rotation-driven dynamo processes are expected to be considerably weaker than in main-sequence and sub-giant stars. Indeed these fields have until very recently eluded observation. It is only in the past few years that measurements of sufficient accuracy have become feasible, allowing a number of detections to be achieved in evolved stars of spectral types G to M (Aurière et al. 2008, 2009, 2010a; Konstantinova-Antova et al. 2008, 2010; Lèbre et al. 2009). The detected fields are weak, with strengths ranging from a fraction of 1 G to a few 10 G. The measurements obtained until now are still too few and patchy to draw general conclusions. In most cases studied so far, the observational evidence is consistent with dynamo-induced magnetic fields. However, it must be noted that the majority of the stars in which fields have been detected, although slow rotators in absolute terms, have rotational velocities greater than average for their spectral type. On the other hand, the dynamo process responsible for the magnetic field of the M-type supergiant Betelgeuse appears more likely to be generated by a local dynamo due to large convection cells on its surface rather than by a solar-type dynamo (Aurière et al. 2010a). Finally, the magnetic topology of the G8 III-IV giant EK Eri is dominated by a single, large-scale dipole, reminiscent of the field structures of Ap stars (see Sect. 3.1). This field is more likely to be the fossil remnant of the field of the main-sequence progenitor of the star than to be generated by a contemporary dynamo, so that EK Eri appears to be the product of the post-main-sequence evolution of an Ap star (Aurière et al. 2011).

Much stronger magnetic fields are found in RS CVn and FK Com stars. The former are close detached binaries consisting of a G or K giant star and a sub-giant or dwarf companion of spectral types G to M. The primary rotates fast as a result of tidal effect (in most cases, the system is synchronised), it is extremely active and has a magnetic field of kG or sub-kG order (Petit et al. 2004; Carroll et al. 2007). FK Com stars are very active late-type single giants. The mean longitudinal field[1] of the prototype of the class was recently measured for the first time, and found to vary between ~ 60 and ~ 270 G at the epoch of observation (Korhonen et al. 2009). The origin of FK Com stars is not fully established, but the preferred scenario is that they result from the coalescence of the two solar-type components of a contact binary (W UMa system). This merging accounts for their high rotational velocity. In both RS CVn and FK Com giants, fast rotation is responsible for the presence of strong, dynamo-induced magnetic fields.

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[1]The mean longitudinal magnetic field, or longitudinal field in short, is defined as the average over the visible stellar disk of the component of the magnetic vector along the line of sight, weighted by the local emergent line intensity.

2.3. Magnetic Activity Diagnosis from Asteroseismology

Recently, using CoRoT observations, García et al. (2010) found that the amplitude and the frequency of the p-modes of the F5V star HD 49933, in which solar-like oscillations take place, showed variations correlated with the number of starspots on its surface. Further analysis by Salabert et al. (2011) showed that the observed frequency shifts increase with the frequency of the mode. This behaviour is similar to that observed in the Sun, where its relation with the varying level of magnetic activity through the solar cycle and the resulting changes in the solar outer layers is well established. This suggests that asteroseismological studies, with the unprecedented precision and detail achievable with CoRoT and *Kepler*, represent a new tool for the diagnosis of magnetic activity in late-type stars. As these studies also provide key information such as the depth of the convective zone or the sound speed within the star, they have the potential to allow new insight to be gained into the physics of the stellar dynamo processes.

3. Stars with Radiative Envelopes

3.1. Ap and Bp Stars

About 5% of the main-sequence stars between spectral types early-F and mid- to early-B display extreme anomalies of the surface abundance of a number of chemical elements, such as He, Si, Sr, Cr, and the rare earth elements. Over- or under-abundances of up to ~ 5 dex are observed. Furthermore, the distribution of some elements over the stellar surface is often inhomogeneous (with "spots" of over- or under-abundance), and there are vertical abundance gradients over the depth of the photosphere. More generally, the abundance anomalies of Ap/Bp stars are local: they result from segregation processes inside the star and across its surface, which create concentrations or deficiencies of selected elements in confined regions. Overall, these stars have a "normal" (essentially solar) chemical composition.

Historically, Ap/Bp stars occupy a special place in the landscape of stellar magnetism. The first star other than the Sun in which a magnetic field was detected, 78 Vir, was an Ap star (Babcock 1947), and for more than three decades following this breakthrough, Ap/Bp stars remained the only non-degenerate stars in which the presence of magnetic fields was definitely established.

Most Ap/Bp stars show periodic variations on timescales from days to years, of their brightness in various photometric bands, of the equivalent widths, shapes and radial velocities of their spectral lines, and of their magnetic field. All observables vary with the same period. These variations are due to the changing aspect of the visible hemisphere of the star as it rotates: to first order, its surface properties (brightness, abundances, magnetic field) are approximately symmetric about an axis that is, in general, inclined to the rotation axis. This Oblique Rotator Model (Deutsch 1956) has successfully withstood all observational tests to which it has been submitted over more than half a century.

Magnetic fields of Ap/Bp stars are large-scale organised fields covering their entire surface. Their structure generally resembles a large-scale dipole at the scale of the whole star, whose axis is inclined to the rotation axis: this is the above-mentioned axis of symmetry. No intrinsic variations of those magnetic fields have ever been observed. This represents a strong argument in support of the view that the magnetic fields of Ap/Bp stars are fossil fields, that is, fields acquired at early stages of the evolution of these stars, which have been retained until the present time. The exact way in which these fields were acquired during the star's formation and pre-main sequence evolution continues to be debated. Possible scenarios include the capture of the magnetic field of the interstellar medium from which the star contracts (Moss 2003), dynamo generation during pre-main sequence stages (Arlt & Rüdiger 2011), or the merging of the pre-main sequence components of a close binary (Ferrario et al. 2009; Tutukov & Fedorova 2010).

The rotation periods of Ap/Bp stars range from ~ 0.5 d to several decades – some may exceed one century: they rotate, on average, significantly slower than the rest of the A- and B-type main-sequence stars. The extremely slow rotation of some of them represents a challenge for the theories of stellar formation and evolution (Mathys 2004). Another intriguing feature of Ap/Bp stars is that almost none of them belongs to a short-period binary (Carrier et al. 2002).

The typical strength of the magnetic fields of Ap/Bp stars is of the order of a few hundred to a few thousand Gauss. More than 50 years after its discovery, the Bp star HD 215441 still has the strongest observed field: the average of its modulus over the stellar surface is 34 kG (Babcock 1960). At the other end of the field strength range, Aurière et al. (2007) inferred from spectropolarimetric observations that all Ap/Bp stars have a detectable magnetic field, which in none of them corresponds to a dipole strength much lower than 300 G. There is a certain parallel between this finding and the existence of a discontinuity around ~ 3 kG at the low end of the distribution of the mean magnetic field modulus of Ap stars with resolved lines (Mathys et al. 1997). However, more recent estimates of the mean modulus via modelling of differential magnetic line broadening in Ap stars that do not show magnetically resolved lines suggest that this discontinuity reflects the bimodal nature of the field strength distribution rather than a lower cutoff (Mathys & Hubrig 2006).

Simultaneous mapping of the magnetic field structure and of the surface abundance distribution of Ap stars via magnetic Doppler imaging shows that in some stars, considerable small-scale structure is superimposed on the large-scale, dipole-like field topology (e.g., Kochukhov & Wade 2010). However, other stars hardly show any significant departures from the latter (e.g., Lüftinger et al. 2010). On the other hand, the magnetic field of the B2p He-strong star HD 37776 does not seem to include any dipolar component, or even any higher-order axisymmetric multipole (Kochukhov et al. 2011a); its structure appears exceptionally complex. Nevertheless, when considering such analyses, one should also bear in mind Stift et al.'s (2011) caveat about the possible inference of spurious structures due to limitations of the observational data from which they are derived.

Of particular relevance for the participants of this seminar are the magnetic fields of rapidly oscillating Ap (roAp) stars. No specific properties that would distinguish their fields from those of non-oscillating Ap stars have been identified so far. The roAp star HD 154708 has been found a few years ago to be one the most strongly magnetic Ap stars, with a mean field modulus of 24.5 kG (Hubrig et al. 2009b), but many other roAp stars have weaker, albeit definitely detected, magnetic fields (Mathys 2003; Hubrig et al. 2004).

3.2. Am, HgMn and Superficially Normal A Stars

Early reports of detections of magnetic fields of kG order in Am stars (Mathys & Lanz 1990; Lanz & Mathys 1993) and in HgMn and superficially normal late-B stars (Hubrig et al. 1999; Hubrig & Castelli 2001) were based on the analysis of high-resolution spectra recorded in natural light. However, more recent spectropolarimetric studies (Aurière et al. 2010b; Makaganiuk et al. 2011) set very stringent constraints on the mean longitudinal magnetic field of Am and HgMn stars, of the order of a few G. If the early, non-polarimetric detections are not spurious, they can be reconciled with the polarimetric constraints only if the structure of the magnetic fields of Am and HgMn stars is sufficiently complex, with enough small-scale regions of opposite field polarities across the stellar surface, so that their contributions to the net, disk-integrated polarimetric signal mutually cancel out. This interpretation receives support from Hubrig et al.'s (2010) study of the HgMn primary of the eclipsing binary AR Aur, according to which different values of the longitudinal field are derived from the analysis of the lines of different chemical elements that have different distributions over the stellar surface. This may reflect the existence of correlations between the magnetic field structure and the abundance inhomogeneities. The latter may possibly account for the fact that apparently significant detections of the field are achieved in an element-by-element analysis, while no longitudinal field in excess of 100 G was found by Folsom et al. (2010) with a diagnostic combining lines of many different elements. Note also that the widespread occurrence of non-uniform distributions of chemical elements across the surfaces of HgMn stars is now well established (e.g., Hubrig et al. 2008). But while such inhomogeneities were originally thought to be indicative of the presence of magnetic fields in these stars, by similarity with Ap stars, this inference is now getting increasingly questioned (Kochukhov et al. 2011b).

Magnetic fields of superficially normal A stars also remained elusive in a couple of systematic spectropolarimetric searches of unprecedented accuracy. Shorlin et al. (2002) did not find any significant longitudinal field in 22 stars of spectral types B0.5 to F9, with a median 1σ uncertainty of 13 G. Bagnulo et al. (2006) studied 138 superficially normal A- and B-type open cluster members and did not achieve any field detection, with a mean error bar of 136 G.

However, in the past couple of years, the discoveries of sub-Gauss magnetic fields through spectropolarimetry in Vega (Lignières et al. 2009; Petit et al. 2010) and in Sirius A (Petit et al. 2011a) raised the intriguing possibility that a significant fraction of tepid stars may, to some degree, be magnetic. Nevertheless, it would be premature to draw definitive conclusions about the magnetism of superficially normal A stars from these two examples, especially considering that neither actually features "normal" abundances: Sirius A is well known to be a hot Am star, and it now appears well established that Vega is a λ Boo star [see Yoon et al. (2010) and references therein].

3.3. Slowly Pulsating B Stars and β Cephei Stars

The pioneering detections of magnetic fields in two β Cephei stars, β Cep itself (Henrichs et al. 2000) and V2052 Oph (Neiner et al. 2003b), and in the Slowly Pulsating B (SPB) star ζ Cas (Neiner et al. 2003a) triggered systematic searches for such fields in these two classes of B-type pulsating stars. The most comprehensive results of these efforts were reported by Silvester et al. (2009) and Hubrig et al. (2009a). The latter authors observed 13 β Cephei stars (B0–B2 stars, which pulsate in low-order pressure and gravity modes with periods ranging from ~ 2 to ~ 6 h), and found that 4 of them harboured magnetic fields. They also detected such fields in 16 of the 34 SPB stars (i.e., B3–B9 stars pulsating in high-order gravity mode with periods in the range ~ 0.5–3 d) that they studied. By contrast, Silvester et al. (2009) found non-zero longitudinal fields in only one β Cephei and one SPB star, out of samples of 8 and 12, respectively. Discrepancies between the two groups about detections in individual stars in common are in most cases of limited significance, as they often rest on single-epoch observations, hence ignore the variability of the longitudinal fields (which may at some phases be close to zero). But statistically, they leave open the question of the frequency of occurrence of magnetic fields in the considered classes of pulsating stars.

The mean longitudinal magnetic fields of β Cephei and SPB stars is typically of the order of a few hundred Gauss, with the largest extremum values observed so far close to 700 G in the SPB star HD 152511 (Hubrig et al. 2009a) and, recently, in the β Cephei star V1449 Aql (Hubrig et al. 2011a).

Hubrig et al. (2011a,b) obtained multi-epoch measurements of the mean longitudinal magnetic field of 3 β Cephei stars, 2 candidate β Cephei stars, and 2 SPB stars. They established the occurrence of periodic variations of this field moment in 5 of them, and interpreted them in terms of an oblique rotator model, with a magnetic field structure consistent with a centred dipole. The derived dipole field strengths range from ~ 0.5 to ~ 5 kG. The models unambiguously indicate that the angle between the dipole and rotation axes is large ($> 60°$) in all 5 studied stars, and that 3 of them are fairly fast-rotating stars (with rotation periods not exceeding 3.2 d) that are seen almost pole-on. Whether small inclination of the rotation axis to the line of sight is a generic property of the considered classes of pulsators is an intriguing question, which remains to be answered.

3.4. O Stars

The discovery 10 years ago of a magnetic field in the young O star θ^1 Ori C (Donati et al. 2002) prompted several groups to undertake systematic searches for such fields in these hot stars. Detections were achieved in only a fairly small fraction of the studied stars. At present, this fraction cannot be exactly quantified, in part because failed attempts may not all have been published and because the observed candidates were selected according to different, and not always stated, criteria. In addition, a significant number of detections are controversial, with different groups disagreeing about their reality. To which extent differences between the observation and analysis methods used by these different groups may account for their discrepant conclusions as to the presence or not of a detectable magnetic field in some O stars remains to be established. It may be worth keeping in mind that in the extended, highly dynamical photospheres of these hot stars, diagnostic lines of different chemical elements in different ionisation stages may sample considerably different depths, and that different mechanisms may contribute to their formation. The fact that combining multiple observations may be required to achieve significant detections (e.g., Martins et al. 2010) further muddles the interpretation of apparent discrepancies between the results of different groups. Notwithstanding these uncertainties, it appears safe to conclude that the occurrence of large-scale organised magnetic fields with strengths in excess of a few hundred Gauss is rare in O stars (Hubrig et al. 2011c).

There is also an emerging consensus about the probable existence of at least one sub-class of magnetic O stars, the Of?p stars (Wade et al. 2012). Whether the other O stars in which magnetic fields are present belong to specific sub-classes is unclear at present. On the other hand, Hubrig et al. (2011c) suggest that magnetic fields are predominantly found in field O stars (as opposed to cluster members), and that an unusually high fraction of the magnetic O stars are runaway stars. Further work is needed to confirm these intriguing possibilities.

Magnetic topologies in O stars are still poorly known. While Of?p stars (Wade et al. 2012, 2011) and the closely related θ^1 Ori C (Wade et al. 2006) are satisfactorily represented by oblique rotator models with a simple, centred dipole, the magnetic field of the faster rotating O supergiant ζ Ori A appears to have a considerably more complex structure, possibly questioning its fossil origin (Bouret et al. 2008). The magnetic field of the slow-rotating B0.2V star τ Sco, which is probably more closely related to that of O stars than of cooler B stars (including Bp, β Cephei and SPB stars) is possibly even more complex than that of ζ Ori A, but more likely of fossil origin (Donati et al. 2006). Petit et al. (2011b) recently identified two magnetic B0.5V stars that bear strong similarities with τ Sco; however, the structure of their magnetic fields has not been determined yet.

3.5. White Dwarfs and Their Progenitors

Historically, white dwarfs represent, after the Ap stars, the second class of stars in which the presence of magnetic fields has been definitely established, following the discovery of such a field in Grw +70°8247 by Kemp et al. (1970). For a long time, all the magnetic fields observed in white dwarfs had strengths of several MG to several hundred MG. It is only in the last decade, thanks in large parts to instrumentation progress, that the first kG-order fields were detected in this class of stars (Fabrika et al. 2003; Aznar Cuadrado et al. 2004).

About 10 to 15% of the white dwarfs have magnetic fields in the range of 1 to 10^3 MG. A similar fraction have fields of kG order (Jordan et al. 2007). The high-field (> 1 MG) magnetic white dwarfs are, on average, significantly more massive than white dwarfs in general (Liebert et al. 2003).

Magnetic white dwarfs are oblique rotators. However, the field topologies that have been derived in the last few years by application of Zeeman tomography to time series of phase-resolved spectra obtained throughout a rotation cycle appear considerably more complex than a simple dipole (Euchner et al. 2005, 2006; Beuermann et al. 2007)

It has long been hypothesised that magnetic white dwarfs are the descendants of the main-sequence magnetic Ap and Bp stars (Angel et al. 1981), whose magnetic flux is conserved throughout post-main-sequence evolutionary stages. However, Wickramasinghe & Ferrario (2005) showed that this channel alone is insufficient to explain the observed frequency of occurrence and mass distribution of the magnetic white dwarfs. They suggested instead that the progenitors of the high-field magnetic white dwarfs comprise not only the magnetic Ap and Bp stars, but also 40% of the main-sequence stars with masses in the range of 4.5 to 8 solar masses, which they assume to have magnetic fields of the order of 10 to 100 G. They also proposed that low-field magnetic white dwarfs could be the descendants of (weakly) magnetic main-sequence F stars, provided that the latter account for ~ 25% of all main-sequence F stars. The constraints on the magnetic properties of main-sequence stars that underlie Wickramasinghe & Ferrario's (2005) hypothesis are not incompatible with the observations of the latter that have been obtained so far.

Furthermore, magnetic fields have also been detected in a small number of stars at pre-white dwarf, late evolution stages: hot subdwarf B and O stars (O'Toole et al. 2005) and central stars of planetary nebulae (Jordan et al. 2005). These discoveries fit qualitatively with the view that the magnetic flux is conserved all the way through from the main sequence to the white dwarf stage, but some quantitative aspects of this scenario may need to be sorted out. However, the samples studied so far are too small to allow statistically significant conclusions to be drawn.

An alternative scenario for the origin of the magnetic fields of high field magnetic white dwarfs has been proposed more recently by Tout et al. (2008). It is based on the observation that while magnetic fields in excess of 1 MG are present in isolated single white dwarfs, and in cataclysmic variables (i.e., binaries consisting of a white dwarf and a close companion overflowing its Roche lobe), no white dwarf with a detached low-mass companion has been observed to have such a strong field. This suggests that the magnetic field is generated at the time of formation of the cataclysmic variable, when the orbit of the binary shrinks and the two components share a common envelope, in which differential rotation is responsible for the onset of a dynamo process. Eventually, the binary components may either merge or not, leading respectively to the formation of an isolated high field magnetic white dwarf or of a magnetic cataclysmic variable. In this scenario, Ap/Bp stars are not more likely than superficially normal A and B stars to be the progenitors of magnetic white dwarfs. On the contrary, given the deficiency of short-period binaries among Ap/Bp stars, the probability that they end up as magnetic white dwarfs may be lower than for other A and B-type stars.

4. Conclusion

Spectacular progress has been achieved in the area of stellar magnetism over the past decade. Many new types of magnetic stars have been discovered, including some with fields of the order of only a few Gauss, or even, in few cases, weaker than 1 G. The properties of stellar magnetic fields have been characterised with unprecedented detail. Field topologies of previously unobserved complexity have been derived through inversion of high-quality spectropolarimetric data, and in some cases, their evolution in time has been characterised.

Magnetic fields, and magnetic activity, both influence stellar pulsation processes and affect their observational manifestations. They need to be taken properly into account in asteroseismological studies, for which their detailed knowledge is therefore required. Conversely, CoRoT and *Kepler* asteroseismological observations can now be used to diagnose stellar magnetic activity, opening a new avenue for its study.

More generally, stellar magnetism and asteroseismology are becoming increasingly interconnected. They are also two of the areas of stellar astrophysics where the most significant progress has been made possible in the recent past, and will foreseeably continue to take place in the coming years, thanks to the advent of new instrumental capabilities, respectively ground-based and (mostly) space-based. One can but look forward to the new results to come.

References

Angel, J. R. P., Borra, E. F., & Landstreet, J. D. 1981, ApJS, 45, 457
Arlt, R., & Rüdiger, G. 2011, MNRAS, 412, 107
Aurière, M., Donati, J.-F., Konstantinova-Antova, R., Perrin, G., Petit, P., & Roudier, T. 2010a, A&A, 516, L2
Aurière, M., Konstantinova-Antova, R., Petit, P., et al. 2008, A&A, 491, 499

Aurière, M., Konstantinova-Antova, R., Petit, P., et al. 2011, A&A, 534, A139
Aurière, M., Wade, G. A., Konstantinova-Antova, R., et al. 2009, A&A, 504, 231
Aurière, M., Wade, G. A., Lignières, F., et al. 2010b, A&A, 523, A40
Aurière, M., Wade, G. A., Silvester, J., Lignières, F., Bagnulo, S., Bale, K., Dintrans, B., et al. 2007, A&A, 475, 1053
Aznar Cuadrado, R., Jordan, S., Napiwotzki, R., Schmid, H. M., Solanki, S. K., & Mathys, G. 2004, A&A, 423, 1081
Babcock, H. W. 1947, ApJ, 105, 105
— 1960, ApJ, 132, 521
Bagnulo, S., Landstreet, J. D., Mason, E., Andretta, V., Silaj, J., & Wade, G. A. 2006, A&A, 450, 777
Berdyugina, S. V. 2007, Mem. Soc. Astron. Italiana, 78, 242
Beuermann, K., Euchner, F., Reinsch, K., Jordan, S., & Gänsicke, B. T. 2007, A&A, 463, 647
Bouret, J.-C., Donati, J.-F., Martins, F., Escolano, C., Marcolino, W., Lanz, T., & Howarth, I. D. 2008, MNRAS, 389, 75
Carrier, F., North, P., Udry, S., & Babel, J. 2002, A&A, 394, 151
Carroll, T. A., Kopf, M., Ilyin, I., & Strassmeier, K. G. 2007, AN, 328, 1043
Deutsch, A. J. 1956, PASP, 68, 92
Donati, J.-F. 2011, in Astrophysical Dynamics: from Stars to Galaxies, IAU Symp. 271, 23
Donati, J.-F., Babel, J., Harries, T. J., Howarth, I. D., Petit, P., & Semel, M. 2002, MNRAS, 333, 55
Donati, J.-F., Howarth, I. D., Jardine, M. M., et al. 2006, MNRAS, 370, 629
Donati, J.-F., & Landstreet, J. D. 2009, ARA&A, 47, 333
Donati, J.-F., & Semel, M. 1990, Solar Phys., 128, 227
Euchner, F., Jordan, S., Beuermann, K., Reinsch, K., & Gänsicke, B. T. 2006, A&A, 451, 671
Euchner, F., Reinsch, K., Jordan, S., Beuermann, K., & Gänsicke, B. T. 2005, A&A, 442, 651
Fabrika, S. N., Valyavin, G. G., & Burlakova, T. E. 2003, Astronomy Letters, 29, 737
Fares, R., Donati, J.-F., Moutou, C., et al. 2009, MNRAS, 398, 1383
Ferrario, L., Pringle, J. E., Tout, C. A., & Wickramasinghe, D. T. 2009, MNRAS, 400, L71
Folsom, C. P., Kochukhov, O., Wade, G. A., Silvester, J., & Bagnulo, S. 2010, MNRAS, 407, 2383
García, R. A., Mathur, S., Salabert, D., Ballot, J., Régulo, C., Metcalfe, T. S., & Baglin, A. 2010, Science, 329, 1032
Henrichs, H. F., de Jong, J. A., Donati, J.-F., et al. 2000, in IAU Colloq. 175: The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat, ASP Conf. Ser., 214, 324
Hubrig, S., Briquet, M., De Cat, P., Schöller, M., Morel, T., & Ilyin, I. 2009a, AN, 330, 317
Hubrig, S., & Castelli, F. 2001, A&A, 375, 963
Hubrig, S., Castelli, F., & Wahlgren, G. M. 1999, A&A, 346, 139
Hubrig, S., González, J. F., & Arlt, R. 2008, Contri. Astron. Obs. Skalnate Pleso, 38, 415
Hubrig, S., Ilyin, I., Briquet, M., Schöller, M., González, J. F., Nuñez, N., De Cat, P., & Morel, T. 2011a, A&A, 531, L20
Hubrig, S., Ilyin, I., Schöller, M., Briquet, M., Morel, T., & De Cat, P. 2011b, ApJ, 726, L5
Hubrig, S., Mathys, G., Kurtz, D. W., Schöller, M., Elkin, V. G., & Henrichs, H. F. 2009b, MNRAS, 396, 1018
Hubrig, S., Savanov, I., Ilyin, I., et al. 2010, MNRAS, 408, L61
Hubrig, S., Schöller, M., Kharchenko, N. V., et al. 2011c, A&A, 528, A151
Hubrig, S., Szeifert, T., Schöller, M., Mathys, G., & Kurtz, D. W. 2004, A&A, 415, 685
Jordan, S., Aznar Cuadrado, R., Napiwotzki, R., Schmid, H. M., & Solanki, S. K. 2007, A&A, 462, 1097
Jordan, S., Werner, K., & O'Toole, S. J. 2005, A&A, 432, 273
Kemp, J. C., Swedlund, J. B., Landstreet, J. D., & Angel, J. R. P. 1970, ApJ, 161, L77
Kiraga, M., & Stepien, K. 2007, Acta Astron., 57, 149
Kochukhov, O., Lundin, A., Romanyuk, I., & Kudryavtsev, D. 2011a, ApJ, 726, 24
Kochukhov, O., Makaganiuk, V., Piskunov, N., et al. 2011b, A&A, 534, L13

Kochukhov, O., & Piskunov, N. 2002, A&A, 388, 868
Kochukhov, O., & Wade, G. A. 2010, A&A, 513, A13
Konstantinova-Antova, R., Aurière, M., Charbonnel, C., et al. 2010, A&A, 524, A57
Konstantinova-Antova, R., Aurière, M., Iliev, I. K., Cabanac, R., Donati, J.-F., Mouillet, D., & Petit, P. 2008, A&A, 480, 475
Korhonen, H., Hubrig, S., Berdyugina, S. V., Granzer, T., Hackman, T., Schöller, M., Strassmeier, K. G., & Weber, M. 2009, MNRAS, 395, 282
Lanz, T., & Mathys, G. 1993, A&A, 280, 486
Lèbre, A., Palacios, A., Do Nascimento, J. D., Jr., Konstantinova-Antova, R., Kolev, D., Aurière, M., de Laverny, P., & de Medeiros, J. R. 2009, A&A, 504, 1011
Liebert, J., Bergeron, P., & Holberg, J. B. 2003, AJ, 125, 348
Lignières, F., Petit, P., Böhm, T., & Aurière, M. 2009, A&A, 500, L41
Lüftinger, T., Kochukhov, O., Ryabchikova, T., Piskunov, N., Weiss, W. W., & Ilyin, I. 2010, A&A, 509, A71
Makaganiuk, V., Kochukhov, O., Piskunov, N., et al. 2011, A&A, 525, A97
Martins, F., Donati, J.-F., Marcolino, W. L. F., Bouret, J.-C., Wade, G. A., Escolano, C., Howarth, I. D., & Mimes Collaboration 2010, MNRAS, 407, 1423
Mathys, G. 2003, in Magnetic Fields in O, B and A Stars: Origin and Connection to Pulsation, Rotation, and Mass Loss, ed. L. A. Balona, H. F. Henrichs, & R. Medupe, ASP Conf. Ser., 305, 65
— 2004, in Stellar Rotation, ed. A. Maeder & P. Eenens, IAU Symp. 215, 270
Mathys, G., & Hubrig, S. 2006, A&A, 453, 699
Mathys, G., Hubrig, S., Landstreet, J. D., Lanz, T., & Manfroid, J. 1997, A&AS, 123, 353
Mathys, G., & Lanz, T. 1990, A&A, 230, L21
Mathys, G., Solanki, S. K., & Wickramasinghe, D. T. (eds.) 2001, Magnetic Fields Across the Hertzsprung-Russell Diagram, ASP Conf. Ser., 248
Moss, D. 2003, A&A, 403, 693
Neiner, C., Geers, V. C., Henrichs, H. F., Floquet, M., Frémat, Y., Hubert, A.-M., Preuss, O., & Wiersema, K. 2003a, A&A, 406, 1019
Neiner, C., Henrichs, H. F., Floquet, M., et al. 2003b, A&A, 411, 565
O'Toole, S. J., Jordan, S., Friedrich, S., & Heber, U. 2005, A&A, 437, 227
Petit, P., Donati, J.-F., Wade, G. A., et al. 2004, MNRAS, 348, 1175
Petit, P., Lignières, F., Aurière, M., et al. 2011a, A&A, 532, L13
Petit, P., Lignières, F., Wade, G. A., et al. 2010, A&A, 523, A41
Petit, V., Massa, D. L., Marcolino, W. L. F., Wade, G. A., Ignace, R., & Mimes Collaboration 2011b, MNRAS, 412, L45
Piskunov, N., & Kochukhov, O. 2002, A&A, 381, 736
Reiners, A., Basri, G., & Browning, M. 2009, ApJ, 692, 538
Salabert, D., Régulo, C., Ballot, J., García, R. A., & Mathur, S. 2011, A&A, 530, A127
Shorlin, S. L. S., Wade, G. A., Donati, J.-F., Landstreet, J. D., Petit, P., Sigut, T. A. A., & Strasser, S. 2002, A&A, 392, 637
Silvester, J., Neiner, C., Henrichs, H. F., et al. 2009, MNRAS, 398, 1505
Stift, M. J., Leone, F., & Cowley, C. R. 2011, MNRAS, 2025
Tout, C. A., Wickramasinghe, D. T., Liebert, J., Ferrario, L., & Pringle, J. E. 2008, MNRAS, 387, 897
Tutukov, A. V., & Fedorova, A. V. 2010, Astronomy Reports, 54, 156
Wade, G. A., Fullerton, A. W., Donati, J.-F., Landstreet, J. D., Petit, P., & Strasser, S. 2006, A&A, 451, 195
Wade, G. A., Grunhut, J., Gräfener, G., et al. 2012, MNRAS, 419, 2459
Wade, G. A., Howarth, I. D., Townsend, R. H. D., et al. 2011, MNRAS, 416, 3160
Wickramasinghe, D. T., & Ferrario, L. 2005, MNRAS, 356, 1576
Yoon, J., Peterson, D. M., Kurucz, R. L., & Zagarello, R. J. 2010, ApJ, 708, 71