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OBSERVING AND MODELLING STELLAR MAGNETIC FIELDS. 3. STRUCTURE AND EVOLUTION

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Abstract. We start by looking at some recent developments in field measurements in middle main sequence and pre-main sequence stars. Then we consider how other magnetic effects such as the Hanle effect and continuum polarisation may be used to detect fields in a variety of stellar environments such as the solar corona and white dwarf atmospheres. Finally we consider how the current body of observational knowledge about magnetic stars may be integrated into a roughly coherent, provisional scenario of field origin and evolution.

1 Introduction

In the previous two chapters we have discussed some methods of magnetic field measurement in stars, and have surveyed the basic nature of the fields found, particularly those in intermediate mass ("tepid") main sequence stars. We then looked in some detail at how spectrum synthesis allows us to recover a considerable amount of information about conditions in the atmospheres of magnetic stars. We now examine a wider range of magnetic measurements. First we will survey some recent advances in the study of magnetic fields and related phenomena in magnetic Ap stars, and then consider the fields of magnetic white dwarfs, and the possibility of studying weak fields in the outer layers of the Sun using the Hanle effect. Finally we will outline our current understanding of the nature and evolution of stellar magnetic fields.

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2 Recent advances in the study of magnetic fields in intermediate mass stars

2.1 A minimum field strength for Ap surface anomalies to develop

Michel Aurière and a cast of thousands of eager MuSiCoS observers have recently shown conclusively that the suite of chemical peculiarities associated with magnetic Ap stars are invariably the signature of a magnetic field (Aurière et al. 2007). They did this by selecting a sample of 28 stars in which the characteristic Ap star chemical peculiarities are clear, but in which fields have never previously been detected. Using the MuSiCoS spectropolarimeter, they showed that every one of these stars does indeed have a detectable magnetic field.

A particularly interesting result of this work came from simple models of the detected fields. Aurière et al. showed that in this sample of stars the minimum field strength in the atmosphere is of the order of 300 G; presumably this is the minimum field required to allow the Ap chemical peculiarities to develop. It may even be the minimum field capable of producing a simple detectable global magnetic field. In contrast, earlier studies (e.g. Shorlin et al. 2002) have shown that various types of A and late B stars that do not show the characteristic Ap chemical peculiarities have no detectable fields, with detection limits down to about an order of magnitude smaller.

2.2 Evolution of Ap magnetic fields during the main sequence phase

A very interesting question is how the magnetic fields of Ap stars might evolve during the main sequence phase of evolution. Since a star changes its structure rather little during this evolution stage, it might appear that not much change would be expected in the magnetic fields either, but recall that the main sequence covers about 90% of the time when a star is visibly luminous.

There are certainly theoretical reasons to expect field evolution during this evolution stage. First, if the field is not being actively regenerated but is simply decaying due to Ohmic loss, significant field decrease might be expected (see below for more discussion of this point). Secondly, although magnetic Ap stars rotate relatively slowly, they do rotate, and this leads to weak internal thermal imbalances that cause a slow large-scale flow inside the star known as meridional circulation (see for example Mestel 1999, chap. 9, or Tassoul 2007, chap. 4). These flows will almost certainly substantially distort any initial magnetic field, both in the stellar interior and at the surface. Finally, the star as a whole expands by a factor of about two in radius R during the main sequence. If the total magnetic flux through some surface of the star were conserved during this evolution, the field strength B would vary approximately as R^{-2}, so from this effect one might expect the field to decline by about a factor of four during the main sequence.

Clearly, 3D numerical modelling of large scale field evolution will be required to study field evolution theoretically. This has already begun. Braithwaite and Spruit (2004) and Braithwaite and Nordlund (2006) have studied numerically the evolution of initial "seed" magnetic fields in main sequence stars. They find that in general, such fields rather rapidly evolve to a configuration in which there is both a "poloidal" (dipole-like) component, which emerges from the surface, and a comparably strong toroidal component (a sort of large tube of magnetic flux wrapped around some of the dipolar field lines deep inside the star). Once the star has reached this state, the evolution of the field slows down to a relatively slow Ohmic decay, during which the toroidal field component migrates slowly towards the surface.

However, in parallel with such work, it is very desirable to have some hints from observation about field evolution, and to have results which may be used to test theoretical and modelling predictions. It is difficult to obtain much information about field evolution from the (often well-studied) magnetic Ap stars of the nearby field, as it is very difficult to determine their ages accurately, particularly if they are near the zero age main sequence (ZAMS). In contrast, magnetic Ap stars that are members of clusters or associations may have fairly precise ages, but until recently little was known about these relatively faint stars. Observations of such stars have now become practical thanks to the new spectropolarimeters FORS1 at ESO's VLT, and ESPaDOnS at the CFHT. Several colleagues and I have recently been carrying out a survey of cluster magnetic Ap stars which has provided some rather interesting results (see Bagnulo et al. 2006; Landstreet et al. 2007, 2008). We now have a large enough sample to study the evolution of Ap stars in the mass range between 2 and 5 $M_{\odot}$. In this whole mass range we find that fields are present from the ZAMS to the terminal age main sequence (TAMS). However, the fields decline strongly with stellar age, in general more rapidly than would be expected simply from the geometric expansion of the stars during the main sequence. A typical result is shown in Fig 2.2. It is found that the total emergent magnetic flux, as estimated by $B_{\rm rms}(R/R_{\odot})^2$, declines significantly in each mass bin from the ZAMS to the TAMS, although only by a factor of 2 or 3.

It is very exciting to be able to compare these observational data with numerical modelling such as that discussed above. It appears that the observations are in agreement with the conclusion from numerical modelling of field evolution that fields should be stable enough to persist throughout the main sequence without self-destructing through major instabilities, but the detailed time evolution discussed by Braithwaite & Nordlund (2006) is not yet in very close accord with the steady decline in magnetic flux with time that is seen in the observations.

2.3 Chemical abundances in atmospheres of magnetic Ap stars

The magnetic fields of magnetic Ap stars have a dramatic effect on the internal layers near the surface and on the atmospheres. In normal stars, the layers in and just below the atmosphere are convecting for stars with $T_{\rm eff} \leq 11\,000$ K ($M \leq 2.5 M_{\odot}$), and consequently the atmospheres are well mixed. In the magnetic stars, the field is strong enough ($B^2/8\pi \geq p_{\rm gas}$) to suppress convection within and slightly below the atmosphere. The atmospheres are not mixed, but instead can support variations in relative abundances of individual chemical elements from

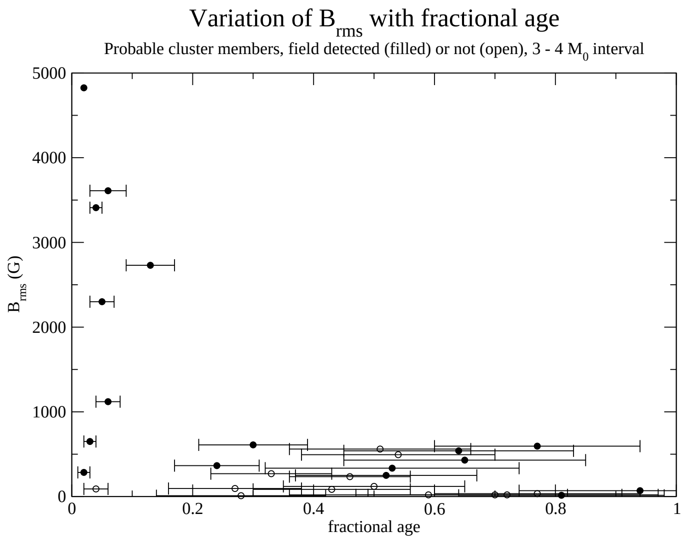

Fig. 1. The RMS field observed in a set of magnetic Ap stars in clusters of various ages, plotted as a function of the fraction of the main sequence lifetime elapsed, for stars in the range between 3 and 4 $M_\odot$.

place to place and at various heights. Such variations definitely occur in the magnetic Ap stars; they are the cause of the strong periodic variations in line strength with rotation that are seen in some of these stars. These variations clearly reveal that some elements are distributed horizontally in a very "patchy" way, a situation that can be sustained for a long time because of the stabilising effect of the magnetic field.

2.4 *The fields of Herbig AeBe (pre-main sequence) stars*

A particularly interesting category of intermediate mass stars is the immediate precursors to main sequence stars, the pre-main sequence stars. These are objects that are still contracting towards their zero-age main sequence (ZAMS) structure; in general they are not yet releasing enough energy from core nuclear reactions to balance losses from the surface, and so they are not yet in thermal equilibrium. For stars in the mass range of about 2 to 10 $M_\odot$, the stage between the end of rapid accretion and the zero-age main sequence lasts at most only a few tens of millions of years. The larger the mass, the shorter this period is.

Some intermediate mass pre-main sequence stars (and perhaps also some stars that have already reached the ZAMS) show striking "activity", with strong emission lines in the spectrum. This emission may be present only in the cores of

Balmer lines, particularly Hα, or may be pervasive in the spectrum, up to the point that most spectral lines are in emission rather than in absorption. Stars showing such emission, if they are found in association with other very young stars, and are in regions still full of interstellar material left from star formation, are known as "Herbig AeBe stars".

The cause of the Herbig AeBe phenomenon is still not clearly understood. In extreme cases the luminosity of the activity is very large; the emission lines may carry of the order of 10% of the total stellar radiation. It is not clear how dynamo magnetic activity (like that of the Sun), in a star with at most only a rather thin superficial convection zone, could release so much energy; it is also not clear how the activity could be produced in or by an accretion disk.

In any case, a group centred around C. Catala, G. Wade, and E. Alecian have been carrying out a large survey to try to detect magnetic fields in these stars. Alecian discusses the results in detail in her chapter. The essential result is that only a small minority of such stars have shown detectable fields. These fields appear to have a global structure that is roughly dipolar, as is found in magnetic Ap stars. The typical field strengths are of the order of a few hundred G. The fraction of Herbig AeBe stars found with fields is consistent with the hypothesis that such stars are the earliest known evolution stage of stars that later become magnetic ApBp stars. See Catala et al. (2007), Wade et al. (2007), and Alecian et al. (2008) for further details.

3 The Hanle Effect and field measurements in the solar chromosphere and corona

We now look at a rather different method of magnetic field detection and measurement, one which has so far found application essentially in studying the outer layers of the Sun, but which may prove more widely useful in the future. This is the Hanle effect.

The Hanle effect is usually discussed in the context of what is called the "second solar spectrum". This is the spectrum obtained by observing spectrum of linear polarisation from regions quite close to the limb of the Sun with very high spectral resolution. What is found was a great surprise to most people when it was first reported (see Stenflo & Keller 1997): sunlight from close to the limb is linearly polarised at roughly the 0.1% level, as one might expect from the general tendency of scattering through a right angle to produce linear polarisation, but in addition the spectrum of linear polarisation is as full of spectral "features" as the solar absorption spectrum! Furthermore, these features do *not* have a simple relationship to the spectral features in the I spectrum, but instead reveal a great variety of interesting quantum mechanical effects, as well as sensitivity to weak magnetic fields near the Sun's limb. It is of course this sensitivity to magnetic fields that interests us here.

The linear polarisation of the second solar spectrum is basically produced by *resonance scattering*. Consider an atom high in the Sun's outer atmosphere, near the limb of the Sun as seen by us. That atom is illuminated mainly from below. Suppose that a photon is absorbed by a particular transition, and then re-radiated by a transition back to the initial state (some absorptions will have this effect). If the re-radiated (or in fact, scattered) photon is sent towards us, it will be re-emitted in a direction at roughly 90° to its initial trajectory, and it will be linearly polarised perpendicular to the plane containing the initial and final directions. Since the atom is mostly illuminated from below, the resulting (tiny) linear polarisation is parallel to the solar limb. Some very nice illustrations of this effect may be seen in Stenflo & Keller (1997), and also at the web site http://www.obspm.fr/actual/nouvelle/sep01/bommier.en.shtml.

Now, if the scattering atom is immersed in a weak magnetic field, during the brief period when the atom is in the excited state, its angular momentum vector will *precess* about the magnetic field with a period of $4\pi mc/eB$. If this period is comparable to the lifetime of the upper atomic state, the precession will alter the plane of linear polarisation of the scattered photon, relative to the plane in which it would have been polarised in the absence of a field. The particular interest of the Hanle effect is that with typical atomic upper level lifetimes for scattering, rotation of the linear polarisation plane should be detectable for fields of a few tens of G. This makes the effect potentially very valuable for situations such as the solar chromosphere where the field expected is so small that it is extremely hard to detect by the normal Zeeman effect.

Although the Hanle effect has not found much application in stellar astronomy outside of the Sun, the effect may prove to be interesting for studying magnetic fields in scattering disks around stars

4 The huge fields of magnetic white dwarfs

Next we turn to methods for measuring magnetic fields in situations in which they are are really large (as large as 10^9 G = 1 GG = 100 kT). Very large fields, ranging from some 10s of kG up to 1 GG, are actually found in a small fraction of white dwarf stars.

White dwarfs are the collapsed remnants of stars. They must have masses below 1.4 $M_\odot$(the Chandrasekhar limit), and in fact most white dwarfs have masses near 0.6 $M_\odot$. They have radii of the order of 0.01 $R_\odot$, so their internal densities are of the order of 10^6 gm cm^{-3}. In such dense stars, the electrons are degenerate, and this effect provides permanent hydrostatic support (as opposed to the hydrostatic support available to earlier evolutionary stages, which inevitably fails when internal energy production cannot keep up with energy loss from the surface). The white dwarf stage is the final stage of evolution for a star that has a mass while on the main sequence of below about 8 $M_\odot$. It is clear that much mass loss must occur for most of these stars to become white dwarfs. It appears that most of this mass loss occurs during the red giant phases between the main sequence and the white dwarf stages, and that some final mass loss occurs when the collapse of the star on the asymptotic giant branch causes it to briefly produce a planetary nebula.

4.1 Detecting large magnetic fields

The huge magnetic fields found in some white dwarfs are observed and measured using several distinct detection methods which correspond to the behaviour of atoms in increasingly large fields.

- For fields below about 100 kG, the normal Zeeman effect (and the Paschen-Back effect in the Balmer lines of H) are used essentially as in non-degenerate stars.
- Between about 100 kG to 10 MG, the linear Zeeman effect is overtaken by the quadratic Zeeman effect, which provides a useful tool for studying the fields even in spectra that are not analysed for polarisation.
- Above about 10 MG, even the spectrum of H is seriously distorted, to the point that the spectral lines are no longer easily identified. At about this field strength, circular polarisation of the *continuum* radiation from the star becomes detectable, and a somewhat higher field the continuum radiation is usually also linearly polarised.

For the low-field end of the fields found in white dwarfs, we need to be aware of the quadratic Zeeman effect. Recall from my first chapter that the Hamiltonian of an atom in a magnetic field has two terms, one linear in field strength B and one quadratic in B. The linear term leads to Zeeman splitting of spectral lines, and in fact in fields of a few MG the splitting of Balmer lines is often rather obvious (a good example is shown by Moran et al. 1998). However, at these field strengths, the quadratic Zeeman effect also alters the spectrum, essentially by shifting spectral line Zeeman components to shorter wavelengths by amounts that depend on the specific components. The effect is approximately described by the expression

$$\Delta\lambda_{\mathrm{Q}} \approx \left(\frac{-e^2 a_0^2}{8mc^3 h}\right) \lambda^2 n^4 (1 + m_L^2) B^2 \tag{4.1}$$

where wavelengths are in Å, a_0 is the Bohr radius, and n and m_L are the principal and magnetic quantum numbers of the upper atomic level involved in the transition.

The quadratic Zeeman effect increases rapidly with n, so it has the effect of shifting different lines of the Balmer series of H by different amounts. The effect is generally small in Hα ($n = 3$), but for H10 (i.e. $n = 10$) at 3798 Å, the quadratic Zeeman effect is already larger than the linear effect for $B > 10$ kG. In a field of 1 MG, H8 would be shifted by 350 km s^{-1}relative to Hα, an amount that would be easily detectable even in spectra of such low resolution that Zeeman splitting would not be detectable. This effect was pointed out by Preston (1970) and used by him to show that very few white dwarfs have fields of more than about 1 MG.

The polarisation effects that occur in spectral lines are similar to those of the Zeeman effect, but at these large fields the Zeeman components are no longer split symmetrically about the position of the zero-field spectral line.

For fields larger than some tens of MG, perturbation theory is no longer an adequate description of the atom in the magnetic field. The magnetic terms in the Hamiltonian become *comparable* in importance to the Coulomb terms describing the central potential of the nucleus and the other electrons. The structure of the combined system can only be solved numerically; the big problem is that the Coulomb field has spherical symmetry while the comparably strong magnetic field has cylindrical symmetry, so separation of variables is not possible.

The energy structure of atoms in such large fields has been solved for H, and to a considerable extent for He I (for references consult Becken & Schmelcher 2002). The basic result is that in such large fields, each component of each spectral line decouples from the other components and moves about in wavelength in its own dramatic way.

Above roughly 50 MG the variation of wavelength with B is strong enough that the variation of the magnetic field over the stellar surface (by perhaps $\pm 20\%$ of the mean B value) tends to smear each line component out in the spectrum so much that the component becomes essentially undetectable. This is particularly true of sigma-like line components. However, it is found that some of the spectral line components (mostly pi-like ones) have a range of field strength over which the line wavelength does *not* vary strongly with B. These line components (often called "stationary components") are able to produce a visible feature in the overall stellar absorption spectrum in spite of the fact that the spectral line is produced in somewhat different field strengths at different points in the atmosphere. Examples of the wavelength variations of line components of Balmer lines of hydrogen are shown by Wunner et al. (1985).

Anther effect that is quite important for detection and measurement of fields in white dwarfs is *continuum polarisation.* It is easy to see physically why this effect occurs. Free electrons in the white dwarf atmosphere do not move in straight line trajectories between collisions; instead, they spiral around field lines. If you look along a field line with the magnetic field vector pointing away from you, all the electrons will spiral in a clockwise sense around the field line. The fact that the electrons spiral with a preferred sense of rotation means that absorption of light by these electrons is *dichroic*: right and left circularly polarised light, for which the electric vector is rotating in the same or opposite sense to the electron motion, will be absorbed slightly differently. Therefore, as radiation travels through the magnetised gas, more radiation of one sense of rotation will be absorbed than the opposite sense, and the radiation will emerge with a net circular polarisation. Similarly, for radiation propagating across the field lines, the fact that free electrons can move without hindrance along the field lines, but are (partially) trapped normal to the field lines, means that the absorption of linearly polarised light is different for the two directions of electric field oscillation, and so light will emerge with net linear polarisation.

This effect leads to easily detectable circular polarisation (of the order of 1% polarisation or more) of the continuum radiation from magnetic white dwarfs with fields in excess of about 10 MG. The imposition of linear polarisation turns out to be less efficient, and a field of order 10^2 MG is required to produce easily measurable broad-band linear polarisation.

However, although the underlying physical cause of this continuum polarisation is broadly understood, it is still not well modelled quantitatively. Efforts to compute theoretical polarisation spectra of magnetic white dwarfs have still not been very successful in predicting spectra in agreement with observed polarisation (cf. Koester & Chanmugam 1990).

The final result is that the spectrum of a high-field white dwarf typically has a number of (usually rather weak) spectral features at completely unfamiliar wavelengths, as well as circular and linear polarisation of a few percent, often with much structure in the polarisation spectra.

4.2 The fields of white dwarfs

Magnetic fields have now been found in more than 50 isolated white dwarfs and in over 40 "cataclysmic variable" binary systems (binary systems with a sub-giant star and a white dwarf that undergo occasional nova-like outbursts). The first magnetic white dwarf found, Grw+70° 8247 (Kemp et al. 1970) still has one of the largest fields known, estimated to be some hundreds of MG. The fields now known span a range from some kG to around 1000 MG. Field detections have been made by all the methods discussed above, from measurement of normal Zeeman polarisation in Balmer lines to detection of continuum circular and linear polarisation. Below some tens of MG the white dwarfs show familiar (if somewhat distorted) I spectra. Above 100 MG the spectra are increasingly bizarre. Good recent reviews of these stars include those of Putney (1999) and Schmidt (2002).

An example of a magnetic field with a field of order 500 MG and (probably) a He-rich atmosphere is shown in Fig. 4.2. In the I spectrum of this star, the strong absorption lines may be the result of several stationary components. Clearly a spectrum such as this one carries potentially a large amount of information about the stellar field, if only it can be modelled!

The fields of magnetic white dwarfs are either constant with time or vary periodically, typically with periods of hours or days. Since the changes in the variable white dwarfs are perfectly periodic, and resemble those of magnetic Ap stars, it is quite clear that the variations are due to rotation, and that the basic model of such a star is an oblique rotator, exactly as for magnetic Ap stars.

As with magnetic Ap stars, quantitative study of the magnetic fields present on the surfaces of magnetic white dwarfs requires modelling the observed spectra. Three regimes of modelling have been seriously explored so far.

For white dwarfs with (relatively!) weak fields of perhaps 100 MG or less, the line spectra have been modelled fairly successfully using simple field geometries (dipole, dipole plus quadrupole, etc) and the full magnetic Hamiltonian to describe the atomic splitting. An example of such a fit is shown by Putney & Jordan (1995).

The line spectra of white dwarfs with stronger fields can sometimes be qualitatively fit with the stationary components found in theoretical spectral line wavelength computations, at least if the atmosphere of the star is rich in H or He. In this case, it is not yet possible to produce a detailed synthetic spectrum which

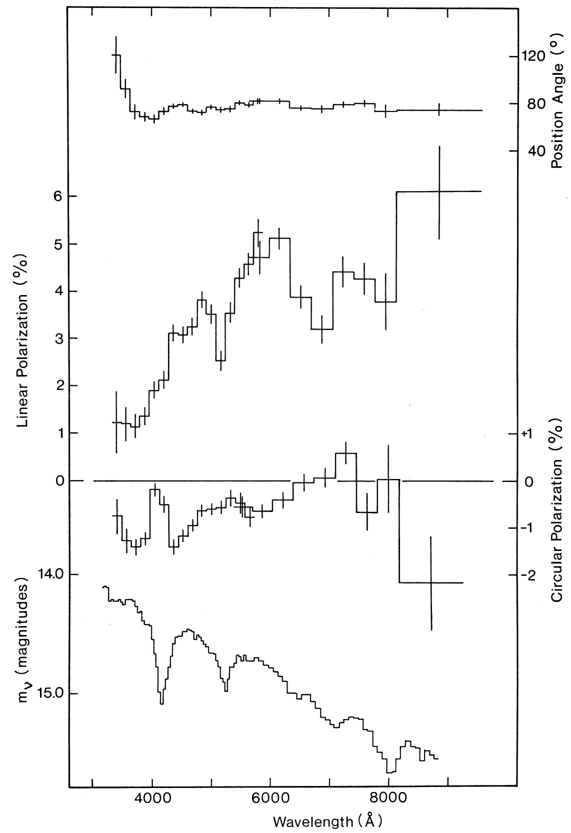

Fig. 2. The intensity (lowest), circular polarisation (second from bottom) and linear polarisation (percentage percentage: third from bottom; position angle: top) spectra of the strongly magnetic white dwarf GD 229.

corresponds closely to the observed one; instead, one simply searches for correspondences between stationary components and observed absorption features. Examples of how this is done are found in Wickramasinghe & Ferrario (1988) and Jordan et al. (1998).

Finally, a number of efforts to reproduce the continuum polarisation spectra of strongly magnetic white dwarfs have been made. In general, these efforts have been only partly successful (see Putney 1999). It seems clear that the atomic description of the dichroism of continuum absorption even of H is not yet very good.

Since the fields of white dwarfs appear to be stable on time scales of years, and the field structures in those (low field) stars that one can model seem to be relatively simple, we are encouraged to imagine that the field structures are qualitatively similar to those of the magnetic Ap stars.

This similarity has encouraged the idea that the magnetic white dwarfs are the evolutionary descendants of magnetic Ap stars. This is made more plausible by a comparison of the relative field sizes. Very roughly, if a magnetic Ap stars were compressed to the size of a white dwarf (which results in a decrease in radius of about a factor of 10^2), while approximately conserving its magnetic flux, the field should increase a lot. Since the field strength of a simple field is the ratio of magnetic flux to the area covered, the field strength should vary with flux conservation approximately as

$$B \sim (R_{\rm init}/R_{\rm final})^2. \tag{4.2}$$

According to this estimate, a main sequence star with a field of $B \sim 10^3$ G would become a white dwarf with a field of order 10^7 G. This is a typical field strength for magnetic white dwarfs.

In fact, the predicted fraction of white dwarfs that should have large fields according to this hypothesis (about 5%) is also about what is observed (Angel et al. 1981). However, while the distribution of magnetic fields in magnetic Ap stars is fairly peaked with a commonest value of around 1 kG for the local surface field strength, the distribution of white dwarf magnetic field strengths is rather uniform over four decades of field strength, from a few time 10^5 G to a few times 10^8 G. Clearly the picture of simple magnetic flux conservation is too simple (especially as the star passes, between the main sequence and white dwarf stages, through the largely convective giant phase during, during which much magnetic flux might be expelled, and also loses much mass, which also ought to carry off some magnetic flux).

Another remarkable aspect of the magnetic white dwarfs is the fact that the rotation periods are only a factor of a few times smaller than those of Ap stars. Conservation of angular momentum during later stages of evolution would predict that the contraction by two orders of magnitude from main sequence to white dwarf should lead to period reduction by a factor of order 10^{-4}, or to periods of the order of some seconds. Clearly almost all the main sequence angular momentum is somehow lost before the star reaches the white dwarf stage. The reason for this is still rather unclear.

5 The evolution of stellar magnetic fields

Two main mechanisms have been proposed to explain the presence of magnetic fields in stars. The *fossil field* hypothesis argues that since the interstellar medium is permeated by magnetic fields, contraction of clouds from this medium to form stars could sweep up magnetic flux lines, which would be attached to the collapsing cloud because it is a good electrical conductor. This effect would lead eventually to fields in main sequence stars. Such fields might be quite passive at present, as is the case for the fields of the magnetic Ap stars.

In contrast, the magnetic field of the Sun is extremely non-uniform spatially and extremely variable in time. These characteristics suggest that the solar field is not produced as the fossil remnant of the interstellar field, but is actively being generated at present as a *stellar dynamo field*. The basic idea is that hydrodynamical motions inside the Sun (specifically the rising and falling flows of the outer convection zone, coupled with the rotation of the star) entrain weak magnetic fields and twist and amplify them into stronger fields which emerge from the surface as flux tubes (ropes of twisted field lines supported by electrical current sheets circulating around the ropes). Such dynamo activity would be expected to increase rapidly with stellar rotation, and indeed the level of solar magnetic activity (revealed for example by the X-rays from the corona, and by flares) is much less than is found in rapidly-rotating solar-type stars. Stellar dynamos are discussed in more detail in other chapters in this course.

5.1 Fossil fields

Fossil fields, almost by definition, are inherited from some earlier stage of the star's evolution. The field does not have to originate in the interstellar medium; it could even have been produced by dynamo action during some earlier phase, even during the pre-main sequence era. However, it is usually assumed that fossil fields originate in the interstellar cloud from which the star forms.

Unlike a solar-type dynamo field, a magnetic field produced by the fossil mechanism would be expected to have field strength related to the details of formation, not to the present angular velocity. Because a long-lived field may help a star to lose angular momentum by providing a long moment arm for coupling the star's rotation to any outflowing material or even to nearby material encountered by the star, strong fossil fields might even be found preferentially in slowly rotating stars. In fact, it is often true of both magnetic Ap stars and magnetic white dwarfs that particularly large fields are found in very slow rotators.

Another very important diagnostic difference between a fossil field and a dynamo is that dynamo fields, like that of the Sun, are thought to change structure on a rather short time scale of weeks or months (or even, in the case of flares and other re-connection events, in seconds). In contrast, it is expected that fossil fields will evolve quite slowly, with a time-scale for significant changes of many millenia or more. The observed stability of the fields of magnetic Ap stars and magnetic white dwarfs, which vary periodically because of stellar rotation, but which always look the same at the same rotational phase year after year, is a strong argument for their fossil nature.

It may appear surprising that fossil fields do not die out rapidly due to Ohmic decay. However, this long lifetime is a direct result of Maxwell's equations and the very high electrical conductivity of the ionized gas inside a star. We may treat Maxwell's equations as order-of-magnitude estimates by introducing a characteristic length scale L and a characteristic decay (or variation) time $t_{\rm c}$. Then

$$\nabla \times E = \frac{1}{c}\frac{\partial B}{\partial t} \Rightarrow E/L \sim B/ct_{\rm c} \tag{5.1}$$

$$\nabla \times B = \frac{4\pi}{c} j \Rightarrow B/L \ \sim 4\pi\sigma E/c. \tag{5.2}$$

Here we are ignoring the displacement current (which only matters for very rapid variations), applying Ohm's Law $j = \sigma E$, and using the Maxwell equations to derive order-of-magnitude relations. Combining the two approximate relations, we get

$$t_{\rm c} \sim 4\pi\sigma L^2/c^2, \tag{5.3}$$

where everything is in cgs Gaussian units (of course). If we get an approximate value for the electrical conductivity σ from Spitzer (1962), we find that $t_{\rm c}$ is of the order of 10^{10} yr, so that the characteristic time for field variation in a main sequence star is considerably longer than the main sequence lifetime. The decay time is so remarkably long partly because the electrical conductivity inside a star is very high, but also because the size of a star is so large.

This long decay time leads us to the view that the large-scale fields of Herbig AeBe stars, of the main sequence magnetic Ap stars, and the magnetic white dwarfs may form an evolutionary sequence of stars that have fossil fields. These fields may even originate from the weak (μG) fields of the interstellar medium. Since the initial gas cloud undergoes contraction by a scale factor of the order of 10^7 to form a star, an initial 1 μG field could reach 100 MG in a main sequence stars if magnetic flux were conserved. The complete absence of fields even as large as 10^{-3} of this number shows that, if main sequence Ap fields originate in this way, almost all the initial magnetic flux must be lost or expelled. (This is actually not surprising; the contracting cloud goes through an extended period when the gas is virtually neutral and much flux slippage is to be expected.)

However, this hypothesis still leaves us with several important questions unanswered.

- Why do strong fossil fields occur only in main sequence stars above about 1.6 $M_\odot$?
- Why do only a small fraction of upper main sequence stars have strong magnetic fields?
- If the fields of white dwarf stars are the evolutionary descendants of the fields of magnetic Ap stars, how do those fields survive the giant stage when the star is almost fully convective and we would expect most of the magnetic flux to be expelled?

These questions represent some very substantial challenges for the upcoming generation of astrophysicists.

5.2 Evolution of angular momentum

Stellar angular momentum presents us with further important challenges.

Magnetic Ap and Bp stars typically have about 0.1 times as much angular momentum as normal A and B stars. This seems to be true even of very young magnetic stars. The excess loss of angular momentum (relative to normal stars of similar mass) probably occurred during the star formation process, possibly early in the pre-main sequence phase when the magnetic field would allow angular momentum to be transferred to a stellar wind (Stępień 2000). However, a small fraction of magnetic Ap stars have angular momentum that is another factor of 10 or 10^2 smaller still. What factor allowed these stars to lose virtually all their rotational motion?

Finally, the magnetic white dwarfs have still lower specific angular momentum. Their angular momentum is of the order of 10^4 times smaller than that of most magnetic Ap stars. And some magnetic white dwarfs appear not to rotate "at all". Why is this?

6 Conclusions

We may summarise the conclusions of these three chapters as follows.

- Strong, global magnetic fields are found in some (but not in most) middle and upper main sequence stars through the detection of various aspects of the Zeeman effect in stellar spectra. These data may be used more or less directly to obtain qualitative models of the field strength and structure of these stars.

- Much more information about the fields of these stars, and about stellar physical processes related to the presence of a field, can now be obtained by modelling the exciting new spectropolarimetric data obtained from the MuSiCoS spectropolarimeter, and from ESPaDOnS and Narval.

- Strong global magnetic fields are found in some (but not in most) white dwarfs. Modelling the polarised spectra of such stars still presents many unsolved problems.

- Plausibly, the fields found in some Herbig AeBe stars, those of magnetic Ap/Bp stars, and those of magnetic white dwarfs may form an evolutionary sequence of fossil fields (assuming rough magnetic flux conservation), but many questions remain.

- The evolution of angular momentum of this sequence of objects also presents several important puzzles.

References

Alecian, E., Catala, C., Wade, G. A., Donati, J.-F., Petit, P., Landstreet, J. D., Bhm, T., Bouret, J.-C., Bagnulo, S., Folsom, C., Grunhut, J., Silvester, J. 2008, MNRAS, in press

Angel, J. R. P., Borra, E. F., Landstreet, J. D. 1981, ApJS 45, 457

Aurire, M., Wade, G. A., Silvester, J., Lignires, F., Bagnulo, S., Bale, K., Dintrans, B., Donati, J. F., Folsom, C. P., Gruberbauer, M., and 15 coauthors 2007, A&A 475, 1053

Bagnulo, S., Landstreet, J. D., Mason, E., Andretta, V., Silaj, J., Wade, G. A. 2006, A&A 450, 777

Becken, W. & Schmelcher, P. 2002, PhysRevA 65, 033416

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

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

Catala, C., Alecian, E., Donati, J.-F., Wade, G. A., Landstreet, J. D., Bhm, T., Bouret, J.-C., Bagnulo, S., Folsom, C., Silvester, J. 2007, A&A 462, 293

Jordan, S., Schmelcher, P., Becken, W. & Schweizer, W. 1998, A&A 336, L33

Kemp, J. C., Swedlund, J. B., Landstreet, J. D. & Angel, J. R. P. 1970, ApJ 161, L77

Koester, D. & Chanmugam, G. 1990, Rep. Prog. Phys. 53, 837 (Sec. 8)

Landstreet, J. D., Bagnulo, S., Andretta, V., Fossati, L., Mason, E., Silaj, J., Wade, G. A. 2007, A&A 470, 685

Landstreet, J. D., Silaj, J., Andretta, V., Bagnulo, S., Berdyugina, S. V., Donati, J.-F., Fossati, L., Petit, P., Silvester, J., Wade, G. A. 2008, A&A, in press.

Mestel, L. 1999, *Stellar Magnetism* (Oxford: Clarendon Press)

Moran, C., Marsh, T. R., Dhillon, V. S. 1998, MNRAS 299, 218

Putney, A. & Jordan, S. 1995, ApJ 449, 863

Preston, G. W. 1970, ApJ 160, L143

Putney, A. 1999 in *11th European Workshop on White Dwarfs*, ASP Conference Series No. 169, Edited by S.-E. Solheim and E. G. Meistas. (San Francisco: Astronomical Society of the Pacific), 195

S. L. S. Shorlin, G. A. Wade, J.-F. Donati, J. D. Landstreet, P. Petit, T. A. A. Sigut, and S. Strasser 2002, A&A 392, 637

Schmidt, G. D. 2002, in *Magnetic Fields Across the Hertzsprung-Russell Diagram*, ASP Conference Proceedings Vol. 248. Edited by G. Mathys, S. K. Solanki, and D. T. Wickramasinghe. (San Francisco: Astronomical Society of the Pacific), 443

Spitzer, L. 1962, *The Physics of Fully Ionzed Gases* (New York: Interscience)

Stenflo, J.-O. & Keller, C. U. 1997, A&A 321, 927

Stępień, K. 2000, A&A 353, 227

Tassoul, J.-L. 2007, *Stellar Rotation* (Cambridge: Cambridge University Press)

Wade, G. A., Bagnulo, S., Drouin, D., Landstreet, J. D., Monin, D. 2007, MNRAS 376, 1145

Wickramasinghe, D. T. & Ferrario, L. 1988, ApJ 327, 222

Wunner, G., Rösner, W., Herold, H. & Ruder, H. 1985, A&A 149, 102