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Future challenges and opportunities for studies of stellar magnetism

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Abstract. This paper presents a very general overview of stellar magnetic fields from a somewhat observational point of view, emphasizing some of the most important unsolved problems and puzzling results in the field.

Key words: stars: magnetic fields – upper main sequence stars – lower main sequence stars – red giants – white dwarfs

1 Opening remarks

I would like to start this brief overview of challenges and opportunities in the study of stellar magnetism by thanking Yurii Balega, the Director of the Special Astrophysical Observatory; Yurii Glagolevskij, the founder of the SAO Branch of the Magnetic Mafia (one of the most important Mafia Gangs); and Iosif Romanyuk, the LOC, and the staff of the SAO for hosting this meeting. In its ongoing series of meetings about stellar magnetism, the SAO provides an important opportunity for astronomers interested in this field to get together for several days of really valuable discussions, and some Russian-style fun as well.

I have been very pleased to see a substantial increase in participation by astronomers from other parts of Central Europe, re-asserting the traditional strength and common interest of this region in stellar astrophysics. It is particularly nice that a number of young people from several countries were able to attend; they presented some of the most interesting talks (and videos) of the meeting.

As it turned out, the meeting had many very interesting reviews and new results. I found the event very stimulating, and I am sure most of the participants did too.

2 Star formation

Magnetic fields play a completely central role during star formation. The pervasive fields of dense clouds stabilize those clouds. Ambipolar diffusion across field lines makes it possible for clumps to form that are sufficiently dense (at a number density $\sim 10^5$ cm^{-3}) to collapse. During this phase, much angular momentum is transferred out of the shrinking clouds by the field. Once collapse is initiated, the protostar largely conserves its field and angular momentum as it shrinks to a density of $\sim 10^{10}$ cm^{-3}. At this point the main charge carriers are grains rather than ions or electrons, and ambipolar diffusion again becomes important as the cloud becomes more and more disk-like, eventually shrinking to become a protostar with an accretion disk from which a planetary system may form (see e. g. Mouschovias 2001).

During most of the stages of star formation from dense cloud to protostar, the magnetic fields, although thought to be highly important, have not been studied directly by observation. The fields can be observed in some of the clouds in which star formation is taking place; for example, fields between a few μG and a few mG are observed in such star forming regions as Orion, ρ Oph and W3 (e. g. Crutcher 1999). A little farther along in the star formation process, linear polarization maps of gas and dust surrounding a number of Bok globules suggest fields of this same general strength (see Wolf et al. 2001).

At about this point, the magnetic fields of shrinking pre-stellar clouds disappear off the radar screen of the observers. Fields are not actually observed again until they are found in Zeeman measurements of a few pre-main sequence stars, where they are about six orders of magnitude larger. Several T Tau stars have fields of order 2 kG (Johns-Krull et al. 1999; Johns-Krull et al. 2001), and a field has recently been found in the Herbig Ae star HD 104237 (Donati et al. 1997). Little is yet known about the structure or generation of these fields. This is clearly a field in which further observations are badly needed.

3 Upper main sequence stars

Once we reach the main sequence we know more. Between about 1.6 and 10 $M_\odot$, a few percent of stars are observed, via the Zeeman effect, to have global fields ranging in strength from $\sim 10^2$ to $\sim 3 \cdot 10^4$ G that vary periodically with the stellar rotation period. In general, the securely detected fields are all members of the Ap SrCrEu, Ap Si, He-wk (TiSr), or He-str classes of peculiar A stars, and indeed it now appears that all members of these classes have longitudinal fields of at least about 10^2 G (Aurière 2004). A currently maintained list of known magnetic stars is hosted by the SAO Magnetic Mafia at http://www.sao.ru/hq/lizm/catalogue/; an extensive recent bibliography is given by Bychkov et al. (2003).

Recently, however, the range of masses in which such fields are found was dramatically expanded, to include θ^1 Ori C, the brightest star in the Orion Nebula Cluster, which has a mass of about 50 $M_\odot$ (Donati & Wade 1999). Several fields have also been detected in B stars which are not obviously chemically peculiar (Donati et al. 2001).

On the other hand, the most recent polarimetric data cast serious doubt on earlier reports (e. g. Mathys & Hubrig 1995) of fields in Am and HgMn stars; not only are the measured longitudinal fields below the detection threshold of some tens of G, but there is no trace in the Stokes V/I line profiles of any field that is about as complex as those of strongly magnetic cool dwarfs (Shorlin et al. 2002). It appears at present as if these types of peculiar A and B stars do not host significant magnetic fields.

For many years the observations of various moments of the magnetic fields in Ap stars, such as $\langle B_z \rangle$ and $\langle B \rangle$, have been modelled with low order multipole fields, which usually describe the observations reasonably well. Models have been found using as a basis simple dipoles (Bohlender et al. 1993), collinear dipole, quadrupole, and octupole fields (Landstreet & Mathys, 2000; Strasser et al. 2001), dipole and quadrupole oriented independently (Bagnulo et al. 2002), and even magnetic charges (Glagolevsky & Gerth 2001). From remaining discrepancies between models and observations, however, it is clear that such models are at best rather rough approximations to the actual field distributions.

Recently, the MuSiCoS spectropolarimeter at Pic-du-Midi has made it possible to obtain routine spectropolarimetry in all four Stokes parameters (Wade et al. 2000). When these much more detailed data are compared to the predictions of models based on multipole expansions, the discrepancies are quite large (Bagnulo et al. 2001), and clearly show that such multipole models are *not* adequate descriptions of the detailed distribution of magnetic flux over the surfaces of Ap stars. An exciting recent advance has been the development by Piskunov and Kochukhov of a working Zeeman-Doppler imaging code for detailed inversion of the new four-Stokes data. This code has now been used for modelling of 53 Cam, and yields a model which is not closely similar to the multipole models, but which does account for all the new data quite satisfactorily (Kochukhov et al. 2004). The field distribution revealed here still has the overall dipolar topology of the old models (i. e. the star has most flux emerging in one hemisphere and returning in the opposite hemisphere), and hence still has a rough axis of symmetry. However, it appears that the higher multipole orders in the older expansions primarily describe statistical attributes of the field structure (such as mean field modulus on the visible hemisphere), without placing the flux correctly on the star. Zeeman-Doppler imaging is certain to yield many interesting results in the near future.

The overall dipolar topology of the Zeeman-Doppler images suggests that statistical results concerning the orientation of the dipolar axis, such as the conclusion that stars with rotation periods of less than a month or so typically have the dipole axis inclined to the rotation axis by a large angle, while longer-period stars generally have a small angle between rotation and field axis (Landstreet & Mathys 2000), are still probably valid.

The magnetic Ap and Bp stars have very unusual atmospheric abundances (e. g. Cowley 1993), even when compared to other “peculiar” stars. Almost everyone now agrees that these anomalous abundances are due to microscopic diffusion of trace elements relative to the dominant background H ions, under the combined influences of gravitation and radiative accelerations upwards (see e. g. Michaud et al. 1976). Diffusion must compete with various mixing mechanisms such as convective layers and possibly turbulent meridional circulation caused by rotation. In addition, there may be mass loss from the top of the atmosphere, which may either be well-mixed or separated (i. e. only some elements are lost; see Babel 1992). In the presence of so many competing physical effects, it is probably not surprising that detailed models of diffusion are still not entirely successful at reproducing abundance anomalies even in non-magnetic stars (Richer et al. 2000). However, it is discouraging that we still have no clear idea at all about why the abundances in magnetic Ap stars are so different from those in non-magnetic stars. That is, we do not yet know what the physical effect is that gives the magnetic field so much influence on the atmospheric abundances. The most obvious possible interaction is the trapping of ions on field lines, but this occurs only in the upper atmosphere, and it is not clear how this can strongly influence the observed abundances, unless through selecting elements which are or are not carried off by a wind.

Similarly, the very non-uniform distribution of elements over the stellar surface of many magnetic Ap stars is still not understood, even qualitatively. It is clear that the fact the magnetic energy density $B^2/8\pi$ is usually larger than the energy in the gas, nkT, means that the field can suppress weather (including horizontal winds) in the stellar atmosphere, and thus prevent mixing. However, this does not explain how the chemical patches, which sometimes involve abundance contrasts of two dex or more (e. g. Strasser et al. 2001), are established.

Another area where much work remains to be done is atmospheric structure. The atmospheres of magnetic Ap-Bp stars are certainly rather different from those of normal A and B stars. They have quite unusual chemical abundances, often including considerable overabundances of line-rich elements which should considerably increase line blocking and backwarming effects. The atmospheres may typically be stratified, with substantial abundance variations vertically. The presence of a magnetic field produces Zeeman splitting, and so directly increases the effects of line blocking, and the magnetic field may also have significant effects on the hydrostatic structure of the atmosphere (cf. Landstreet 1987). The peculiarity of the atmosphere structure is clearly visible in the unusual Balmer line profiles observed in some stars (Cowley et al. 2001; Bagnulo et al. 2003); the profiles of Balmer lines in some magnetic stars have been explained by the assumption of $T(\tau)$ structure rather different from that predicted by Kurucz models (Kochukhov et al. 2002). This is an area where further work is important.

The fields in upper main sequence stars are thought to be fossils, probably from (at least) the pre-main sequence phase. Direct evidence of the presence of fields in very young Ap-Bp stars is found in the very young magnetic stars in Orion OB Ic and the Rosette Nebula Cluster (Bagnulo et al. 2004), where Bp stars are found that have completed only a few percent of their main sequence lifetimes. A fossil origin for the fields is possible because the ohmic decay time is of order 10^{10} yr for a main sequence star (Cowling 1945).

The *small* size of Ap fields is surprising. If these fields result from (very approximate) flux freezing during star formation, from the giant molecular cloud phase up to the pre-main sequence, so that the magnetic flux $\Phi_{\rm mag} \approx \pi R^2 B \approx \pi (n_0/n)^{2/3} B$ is roughly constant, a field of 10^{-6} G at 10^3 particles cm^{-3} becomes 10^8 G at 10^{24} particles cm^{-3}. Presumably the *much* smaller observed fields in magnetic Ap-Bp stars are due to flux leakage at various stages during the contraction of the protostar. But we have no explanation for the observed fact that Ap-Bp main sequence stars have kilogauss fields, while normal main sequence stars have surface fields of less than a few tens of G.

Magnetic Ap stars have about one-tenth the angular momentum of normal tepid main sequence stars. In a significant fraction of the magnetic stars, the specific angular momentum is still smaller, of order 10^{-2} or even 10^{-3} of that found in normal A and B stars. Remarkably, it appears that the extremely slow rotators have a surface magnetic field structure that is substantially different from that of the more typical stars with periods of a few days. As mentioned above, Landstreet & Mathys (2000) have shown that the dipolar field structure tends to be aligned with the rotation axis in the extremely slow rotators, while it is usually inclined at a large angle to the rotation axis in stars with periods of a few days. The slow rotation of virtually all Ap-Bp stars is probably a consequence of magnetic transfer of angular momentum out of the star by a wind during the pre-main sequence phase. The theory of this braking is still not understood in detail, but Stępień (2000) has developed a very interesting phenomenological model of the slow-down process, which has been extended by Stępień & Landstreet (2002) to try to account for the extremely slow rotators. Again, this is an area in which more work would be valuable.

4 Lower main sequence stars

Cool stars have important fields too — our Sun is a prominent example. On the Sun, the field is *very* inhomogeneous. Magnetic flux emerges from sunspots, regions of kilogauss fields having a typical size of the order of 10^4 km. Sunspots are surrounded by larger active regions with similar flux to that in the sunspots. Flux also emerges in much smaller regions (bright points) on granular boundaries. Wherever flux emerges in concentrated spots or points from the surface, it often seems to have a typical strength of the order of one kG; different kinds of magnetic structure differ mostly in size. However, a weaker field of some G emerges diffusely from the granules.

The solar field is responsible for the whole gamut of solar activity — flares, prominences and filaments, and heating and partial confinement of the corona. Its influence on the photosphere is not remarkably great. A white-light image of the photosphere reveals mostly the extremely homogeneous granulation; the only obvious evidence of strong fields is furnished by sunspots and by the occasional flare. However, in the chromosphere and corona, the structure is completely dominated by the magnetic field. This is visible as excess heating of (magnetized) plage regions, in the shapes of filaments and prominences, and in the remarkable system of loops visible in X-ray images of the corona (e. g. Priest 2001).

In general, solar activity is a result of the solar magnetic fields (see e. g. Svestka 2003). These fields have important hydrostatic effects (depression of sunspots, forms of prominences and coronal loops), transfer mechanical energy from the convective zone to the chromosphere and corona, and suffer dramatic reorganization leading to rapid local energy release and often mass ejection (flares). However, in spite of decades of study, much of the physics of this activity is still poorly understood.

The field of the Sun is clearly *not* a fossil — it changes obviously and continuously. It is most likely generated by dynamo action. However, several physically different dynamo mechanisms have been proposed, and it is still not clear which is correct (see Charbonneau & Saar 2001).

We cannot yet detect in other stars a field covering as small a fraction of the stellar surface as the solar field does, but a few cool stars (young, rapidly rotating single stars and rapidly rotating active stars in close binaries) do have directly detectable fields. Fields have been detected via Zeeman polarization in a T Tauri star, in a Herbig Ae/Be star, in very young lower main sequence stars such as AB Dor, in a number of RS CVn binary systems, and in an FK Com star (Donati et al. 1997). Fields are also detected in a number of pre-main sequence and lower main sequence stars through Zeeman broadening of spectral lines which have unusually broad Zeeman patterns (Valenti & Johns-Krull 2001). These stars have in common that they have deep sub-photospheric convection zones and relatively rapid rotation rates, and thus probably generate their magnetic fields by the same dynamo mechanism that functions in the Sun. The fields that are detected seem to have strengths of the order of hundreds or thousands of G, similar to the solar field; they differ from the solar field particularly in that the fraction of the stellar surface covered with flux is much higher than the roughly 1% coverage on the Sun (this is what makes these fields detectable in unresolved stars). Nothing much is yet known about the structure of these fields. Study of the magnetic fields of solar-type stars is providing an extremely valuable complement to studies of the Sun, as it permits us to begin to see the solar field in an evolutionary context.

We cannot yet detect magnetic fields on most solar-type stars. However, several types of solar activity lend themselves to observation in other stars, and the study of such proxies has provided much valuable information about fields in cool stars. The most widely observable symptom of stellar activity is soft X-ray emission, similar to that emitted by the solar corona. Coronal X-radiation would be observable in the solar neighborhood with recent X-ray space missions in other stars in which the X-ray luminosity is similar to that of the Sun, and this provides the most powerful method presently available of searching for evidence of Sun-like fields in nearby stars. Remarkably, surveys of lower main sequence stars within about 25 pc of the Sun reveal that essentially 100% are detected as soft X-ray sources (Schmitt 2001) at a level of brightness similar to, or brighter than, the Sun. We conclude that essentially all lower main sequence stars have magnetic fields and magnetically heated coronae. Another analogue of solar activity that is observed in the X-ray band is occasional flaring.

Other magnetic field proxies are also valuable. The temperature reversal in the solar chromosphere (presumably mostly due to magnetic heating) leads to emission cores in the Ca II H and K lines. Such Ca emission cores have now been observed and studied in more than 100 solar-type stars (Donahue et al. 1996). These data reveal the growth and decay of active regions as well as activity cycles, and certainly provide fairly direct information about fields on a large number of low-mass stars.

A third field proxy is detection of starspots, either through observed photometric variations of stars, or through spectral line profile variations, or both. Such spots are at present only detectable if they cover much more of the stellar surface than the fraction of the Sun that is covered with sunspots, and the stars in which such starspots may be studied are far more active than the Sun. Observed starspots are now frequently mapped by Doppler imaging techniques (e. g. Rice & Strassmeier 2001). Such maps reveal sometimes huge spots, which (in contrast to the solar case) can appear at all latitudes, even close to the rotational poles. Furthermore, it appears that the spots can be used as tracers of stellar differential rotation. It seems likely that such spots are analogues of those on the Sun: huge regions of emerging magnetic flux (Schrijver 2002), so that studies of sunspots and starspots are mutually valuable.

It appears that, like the magnetic field in the relatively inactive Sun, fields in active (rapidly rotating) lower main sequence stars are geometrically complex, irregularly variable, and dynamo-generated. Like the solar field, these fields are very patchy, but typically occupy 20% or more of the surface (the condition for detectability) on the most active stars. However, as in the solar case, we don't know what relation these fields have to the fields present during star formation, or how the dynamos work.

5 Red giants

The large sizes of a giant stars suggests that fossil fields will not be detectable; if a main sequence Ap star were to become a giant while conserving flux, the kG field seen on the main sequence would diminish to a few G or less. Dynamo generated fields might be detectable, but the low energy density in the gas again suggests that such fields will be rather small. So far no fields have been detected directly.

However, activity is widely seen in giants earlier than about K2. Such stars emit X-rays: that is, they have coronae. It is plausible that these are heated through transfer of mechanical energy via a magnetic field. Thus the X-ray observations probably trace magnetic fields (Schmitt 2001). In contrast, cooler giants have slow, massive winds but little or no X-ray emission. It is hard to understand why cool giants should not have magnetic fields if slightly hotter giants do; perhaps the field structure changes dramatically as a star evolves to the giant or asymptotic giant branch?

Another clear tracer of significant magnetic fields is the presence of large starspots. These are found on giants as well as on cool main sequence stars, and Doppler imaging again provides the possibility of studying spot distributions and intensities as well as differential rotation (e. g. Strassmeier et al. 2003).

One very interesting giant star has been identified which may be the evolutionary descendant of a magnetic Ap star. The giant HR 1362 is a slowly rotating star which nevertheless shows convincing evidence of starspots. Stępień (1993) argues that it is an evolved 53 Cam, and Strassmeier et al. (1999) confirm the unexpectedly high level of magnetic activity in this 300-day rotator.

Considerable work has now been done observationally on magnetic field tracers in giants, using both X-rays and modelling of spots. However, because it is very difficult to get long time series of a single star with a spacecraft, most detailed study of single stars has been mapping of spots using visible light photometry and spectroscopy. Study of even a single star requires long series of observations and considerable analysis, so the sample of well-studied stars is not yet very large. Further observations and modelling of spotted giants is still very important. On the theoretical side, studying the relation of fields to spots and to X-ray emission, understanding the evolution of fields during the red giant phase, and connecting models of surface fields to observed surface activity such as X-ray flares, are some topics in which much work still remains to be done.

6 White dwarfs

White dwarfs are quite compact ($R \sim 10^7$ m) so from flux freezing arguments we expect — and find — fields of order 10^7 G in a small fraction of such stars (e. g. Schmidt et al. 2001; Schmidt 2001). The fields presently known range from a few tens of kG (detected by circular polarization measurements across Balmer lines), to some MG (detected by visible Zeeman splitting of spectral lines of H or He) and to fields of hundreds of MG (detected via continuum circular and sometimes linear polarization, or fits to strange and unique intensity spectra). The incidence of detectable fields in white dwarfs is of the order 1% per decade of field strength between 10^5 and 10^9 G (Schmidt 2001; Fabrika et al. 1997). More than 60 white dwarfs are now known to have detectable magnetic fields.

White dwarf fields are either constant, or vary periodically with periods of hours or days. These fields thus appear to be fossil fields, like those of magnetic Ap-Bp stars. From the fact that the longitudinal fields inferred from circular polarization in lines is typically of the order of 25% of the field strength deduced from

Zeeman splitting in the intensity spectrum, we deduce that the fields have a simple dipolar topology like that found on Ap stars. This result is confirmed by satisfactory fits to data with simple dipole-like models (Wickramasinghe 2001; Euchner et al. 2002).

For fields closer to 10^8 G, modelling required detailed knowledge of line splitting in fields whose effects on the atomic energy levels is comparable to the effect of the Coulomb field. Such calculations are notoriously difficult, and have only been carried through for H and He. The available atomic data now make it possible to obtain plausible fits to the intensity spectra of some of the very high-field white dwarfs (e. g. Wickramasinghe & Ferrario 1988), but the field geometry is not easily inferred from such modelling.

One very interesting connection between the presence of a magnetic field and basic stellar parameters is found. From the sample of roughly 20 magnetic white dwarfs for which accurate masses are available, it seems quite clear that the typical mass of a magnetic white dwarf is substantially larger than that of a non-magnetic white dwarf, about $0.9M_\odot$ compared to $0.6M_\odot$ (Liebert et al. 2003). This suggests either that magnetic white dwarfs descend from a different population than normal white dwarfs, or that such massive stars are produced by binary mergers which somehow also lead to magnetic fields.

Studies of the evolution of white dwarf fields are possible because white dwarf history is simply one of cooling, so that the age of a white dwarf since its formation may be estimated. Thus one can obtain information about field evolution by comparing samples of young and old magnetic white dwarfs. It appears that fields in white dwarfs are more common in older white dwarfs than in younger ones (Valyavin & Fabrika 1998; Liebert et al. 2003). This suggests that surface field strength may actually increase with time, perhaps as a result of flux leakage to the surface of the star.

An interesting class of magnetic white dwarfs is found in close binaries with mass transfer (AM Her systems), where the field completely controls accretion onto the white dwarf (e. g. Wickramasinghe 2001).

Much remains to be understood in this field, from obtaining unique models of field structure on individual stars to understanding the evolution of the stars that become magnetic white dwarfs, and the changes in their fields as these white dwarfs cool.

7 New possibilities for observations and theory

There is still much to do observationally. In addition to obvious possibilities, we have some less obvious ones:

- Interferometry — to resolve the nearest Ap's or active lower main sequence stars we need baselines of 1 km or more, which will — perhaps! — become available within years. But the nearest G dwarfs, and a number of cool giants, can be resolved with current instruments.
- Radio and X-ray observations are tools that are heavily exploited to study activity in lower main sequence and giant stars. For upper main sequence stars we have some very suggestive results, such as the clear detection of radio emission in cm bands from some of the hottest stars (Drake 1998) that need to be followed up!
- UV spectroscopy from space opens the possibility of studying low abundance ions not detectable in visible light, and maybe getting more clues about chemical peculiarity in UMS stars. Much archival data is available, both from IUE and from HST.

Finally let me add a few random thoughts:

- What makes observations interesting is interpretation and modelling. This is important for observers to keep in mind, and offers interesting opportunities for collaborations with astronomers elsewhere.
- Important information may be available from wavelengths other than optical — and there are very large public archives from space and other missions (e.g. Copernicus, IUE, HST, JCMT ...), mostly available over the Web.
- The huge power of PC's is a great equalizer — almost everyone can access “enough” computing power for important computations.

Stellar astronomy is one of the fundamental fields of astronomy, and understanding and results from our field are essential for other fields of astronomical endeavour such as studies of the evolution of galaxies and of the origin of planetary systems. There are still a lot of fascinating and important problems left for us to solve. It was good to see so many young people at this meeting, since the older generation is not going to be able to finish the job.

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