THE MAGNETIC FIELDS OF THE A AND B STARS

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Abstract. The strong magnetic fields found in the Ap and Bp stars are reviewed, with critical attention to the competing dynamo and fossil theories for their origin. A number of difficulties for the dynamo theory are identified. Whilst the fossil theory is not free of problems, they appear less severe. From the modulation of certain spectral lines, rather weaker fields are deduced to be present above the surface of Be stars. The question of whether observed spectral transients might arise from magnetic fluctuations is discussed.

1. Introduction

Comprehensive reviews of the magnetic fields observed in the early type chemically peculiar Ap and Bp stars can be found in Moss (1986) and Landstreet (1992), so only a brief summary will be given here. Large scale magnetic fields, of strength from about 10^2 to 10^4G, are observed at the surfaces of these CP stars. These figures refer to an integrated measure of the field over the surface: local fields strengths can be somewhat higher, typically by a factor of 3 or 4. The lower limit appears to be instrumental. Statistically these stars are slow rotators compared to non-magnetic stars of similar spectral type. Nevertheless, rotation periods vary from less than one day to perhaps tens of years, so rapid rotation certainly does not preclude a strong surface magnetic field. Early suggestions of a marked correlation between field strength and period have proved unfounded, and there is at best a weak statistical relation. Typical field strengths do seem to increase somewhat with stellar mass, but there is no apparent relation between field strength and spectral type, nor any other stellar property. Strong fields appear early in the main sequence lifetime of these stars: the age of the OB1 association in Orion is estimated as about 5×10^6 years, and it possesses stars with kilogauss fields. The CP star magnetic fields vary strictly periodically, with magnetic and rotation periods equal.

Observations have nothing to say about the interior stellar magnetic fields and cannot, for example, rule out the possibility that strong internal fields are present in the interiors of even observably non-magnetic stars. There are only null field measurements for the Be stars, giving an upper limit to the poloidal field strength of about 100G. However, in these stars regular modulation at the rotation period of spectral lines formed in the wind regions is interpreted as indirect evidence for the presence of large scale fields, perhaps no more than of order 10G, corotating with the star (e.g. Barker 1982). Significant toroidal fields could also be present, but evade detection.

The CP star magnetic fields are ordered on a global scale, without substantial small scale components. In almost all cases the field geometry can be

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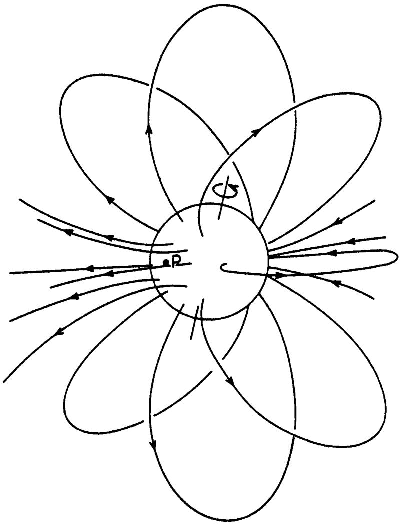

Fig. 1. The geometry of the oblique rotator/displaced dipole model. P marks the nearer magnetic pole.

well approximated by a dipole, often with its centre displaced from the centre of the star along the axis of field symmetry. Field variations are well represented phenomenologically by the 'oblique rotator' (OR) model, in which this 'displaced dipole' (DD) field is inclined at angle $\chi > 0$ to the rotation axis, and rotates rigidly with the star. Thus the observed field variations are caused by the advection of a field that is invariant in the corotating frame, see Fig.1.

In this review, evidence for the competing fossil and contemporary dynamo theories of field origin is critically examined. We also discuss some ideas related to the inferred rapid changes in the fields believed to be present in the Be stars.

2. Field Origin

The fossil and contemporary dynamo theories are the two serious contenders to explain the origin of the CP star magnetic fields.

2.1. THE DYNAMO THEORY

Stars of a few solar masses on or near the main sequence have a convective core extending over 20% or less of the stellar radius, surrounded by a static envelope in radiative equilibrium. The dynamo theory of field origin proposes that a magnetic field is generated by a turbulent dynamo operating in the core. This field rises through the envelope to penetrate the surface, where it is observed. Certain statements about the nature of such a dynamo can be made immediately, independently of any particular dynamo theory.

1. The field must be steady in the rotating frame, otherwise skin effects would confine the field to the core (Moss 1980).
2. Stable nonaxisymmetric modes must be excited, as $\chi > 0$ is always observed.
3. The envelope differential rotation must be small, otherwise the nonaxisymmetric part of the field would be wound up and reconnection would occur, leaving only an axisymmetric field (Rädler 1986; Moss 1992).

Further, the differential rotation in the dynamo active core cannot be too large. This conclusion may depend slightly on the dynamo model, but follows basically from point 3 above. Adopting a mean field dynamo viewpoint, the dynamo then must be approximately an α^2 dynamo, and the relevant parameter is

$$C_\alpha = \frac{\alpha R_{\text{core}}}{\eta_{\text{turb}}} \sim \frac{\Omega_0 R}{u_t}. \tag{1}$$

Here it is assumed conventionally that $\alpha \sim \Omega_0 l$, $\eta_{\text{turb}} \sim \frac{1}{3} u_t l$, where Ω_0 is the angular velocity, $l \sim R_{\text{core}}$, R is the stellar radius and u_t a typical speed of the convective elements. With representative stellar parameters, $C_\alpha \gg 1$, and so it can be expected that a dynamo will operate.

If the turbulence is anisotropic and/or large-scale circulations are important in the core, then it is plausible that stable nonaxisymmetric dynamo modes are excited (Rüdiger & Elstner 1993; Barker & Moss 1993). The relevant questions are then

1. Can the field reach the stellar surface in the time available ($\lesssim 5 \times 10^6$ years for the youngest objects)?
2. If it can, will it be strong enough and of an appropriate geometry?

In a radiative envelope the classical magnetic diffusion time is $O(10^{10})$ years—clearly much too long. Magnetic buoyancy will cause flux tubes to rise on a relatively slow timescale, governed by the rate of diffusion of heat into the rising tubes. From Parker (1979) the rise time can be estimated to be

$$\tau_{\text{rise}} \sim \frac{Rp}{F_{\text{RAD}}} \frac{8\pi p}{B^2} \left(\frac{R_T}{\lambda}\right)^2 \text{secs}, \tag{2}$$

where F_{RAD} is the radiative flux, R_T is the flux tube radius and λ is the temperature scale height. With values appropriate to the lower part of the radiative envelope, $\tau_{\text{rise}} \lesssim 5 \times 10^6$ years $B \gtrsim 10^7$ G if $R_T \sim 10^{-2} R$, that is flux tubes must be thin and strong.

Now we will try and estimate the possible strength of a dynamo field in the core. In an α^2 dynamo, the poloidal and toroidal field components are of comparable strength and nonlinear limitation will occur for $B^2/8\pi \lesssim \frac{1}{2}\rho u_t^2$, where **B** is the large scale part of the field. This may possibly be a considerable overestimate of the equipartition value of B^2. With typical values, $|B| \lesssim 10^5$G. (An estimate for an $\alpha\omega$ dynamo is not very different.) Thus in order to reach the surface in the time available, flux tubes must have $R_T/R \ll 10^{-2}$: the field must rise as thin 'spaghetti', but reform into a 'clean', coherent, large scale quasi - dipolar field at the surface.

There is always the possibility that unknown instabilities might cause a rapid transport of field from the core to the surface: against that the development of a molecular weight gradient at the base of the radiative envelope as the star evolves will tend to stabilize the envelope against vertical motions.

A further restriction on surface field strengths can be obtained as follows. $R_{\rm core}/R \lesssim 0.2$. If magnetic field lines connect the core and the surface, then flux conservation gives $R^2_{\rm core}B_{\rm core} \geq R^2 B_{\rm surf}$ (with equality only if no field lines close within the star). Given that $B_{\rm core} \lesssim 10^5$G, then $B_{\rm surf} \lesssim 4 \times 10^3$G, and the observed effective or longitudinal field is no more than about 10^3G.

Finally, dynamo theory appears to have some difficulty in explaining the lack of correlation between field strength and period: without an extra parameter some relation of the form $B = B(\Omega)$, and even perhaps $\chi = \chi(B)$, might be expected, but stars with periods differing by an order of magnitude can have similar surface fields. One suggestion is that the differential rotation profile in the envelope with which the star arrives on the main sequence might provide this extra degree of freedom: a stronger differential rotation would then give smaller nonaxisymmetric components at the stellar surface (Krause 1983). This would imply that the non magnetic A and B stars have strong internal differential rotation.

2.2. FOSSIL THEORY

Now the CP star flux is posited to be the remnant of that present in the interstellar medium from which the star contracted. Certainly there is enough flux present in the ISM and, indeed, a substantial proportion must be lost for star formation to occur (eg Mestel 1965). One possible hurdle to be overcome is the Hayashi turbulence during contraction to the main sequence, when the field might be tangled and destroyed or expelled from the star. It now seems that stars of several solar masses may avoid a significant Hayashi phase (eg Stahler et al. 1986; Shu et al. 1987), but in any case it is plausible that some field might survive in thin ropes, diffusing to a more uniform configuration as the turbulence dies away. (A hybrid version of the fossil theory would have a turbulent dynamo operating at this time, with the field being frozen into the stellar material as the convection ceased.) On the main sequence the global decay time is $O(10^{10})$ years – much greater

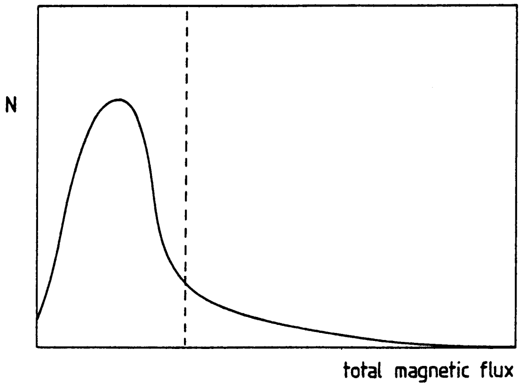

Fig. 2. A schematic distribution function for the magnetic flux on the zero age main sequence. Only stars in the tail of the distribution, to the right of the broken line, will be the observably magnetic stars.

than the main sequence lifetime. The initial magnetic flux, its orientation with respect to the rotation axis, and the local state of the ISM now provide the extra parameters needed to avoid relations of the form $B = B(\Omega)$. The relatively low incidence of observable magnetism among the A and B stars can be explained if the magnetic flux on the zero age main sequence has a distribution peaked at small values with a high flux tail, and if it only is the stars from this tail that become observably magnetic (see Fig. 2).

Detailed model calculations have elucidated some of the processes that influence the observable magnetic fields. The rotationally driven Eddington-Sweet circulation (symmetric about the rotation axis) influences the field geometry in at least two ways, provided that its mean magnetic Reynolds number is greater than order unity and that some measure of the mean magnetic field strength in the star is not large enough that the field can choke the flow. With conventional values for the resistivity and plausible field strengths, advection by the circulation is important during a main sequence lifetime for rotational periods of a few days or less. It is clear intuitively that, if there is a significant freezing in of the field into the stellar material, then the circulation will cause an increase in χ, see Fig 3a. A further effect depends on the value of χ. Suppose $\chi = 0$; in this case a sufficiently rapid circulation will drag field lines beneath the surface, whilst leaving the interior field little changed (Fig 3b and c). When $\chi = \pi/2$, consideration of Fig 3d shows that the circulation will tend to compress the field at the surface near to the equator, but *not* to bury it. The two regimes are separated by an angle $\chi_c \approx 55^o$. Clearly, the evolution of the field is quite a complex process, but these gross effects are confirmed by detailed model computations (eg Moss 1990).

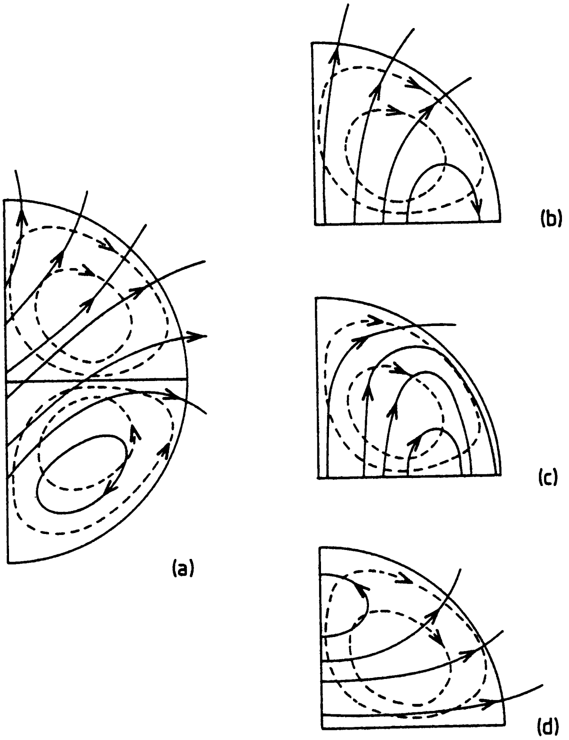

Fig. 3. In each figure magnetic field lines are solid, circulation streamlines are broken and the rotation axis is vertical. Two quadrants of a cross-section of a sphere are shown in a), one in b), c) and d). a) Schematic relationship between modified Eddington-Sweet circulation and oblique magnetic field, $0 \leq \chi \leq \pi/2$. b) Schematic Eddington-Sweet circulation and magnetic field lines when $\chi = 0$, initial configuration. c) As b), but at a later time, showing reduction of surface flux. d) As b), but $\chi = \pi/2$.

Thus we can in principle find relations of the form $\chi = \chi(\text{conductivity}, \chi_0, \Omega_0, \mathbf{B}_0, t)$, $\mathbf{B}_{\text{surf}} = \mathbf{B}_{\text{surf}}(\text{conductivity}, \chi_0, \Omega_0, \mathbf{B}_0, t)$, where $\chi_0 = \chi(t = 0)$ and $\mathbf{B}_0 = \mathbf{B}(t = 0)$. With conventional values of the resistivity, significant changes in χ can occur in a main sequence lifetime. (If non-classical sources of resisitivity markedly increase the effective value, changes in χ may be much reduced.) The situation is complicated by the existence of other mechanisms affecting $\chi(t)$, such as internal motions driven dynamically by the non-symmetry of the magnetic distortion about the rotation axis (Mestel et al. 1981), and stellar wind torques (Mestel & Selley 1970), but in principle such relations could provide a test of the theory if the distribution of angles χ_0 were known or, alternatively, could give information about χ_0. Unfortunately the number of well determined values of χ is too small for this to be useful. The analysis of Mestel *et al.* (1981) and the models of Moss (1990 and references therein) are, however, consistent with interior field strengths not being greatly in excess of those seen at the stellar surfaces.

The stability of such large scale fields has attracted considerable attention, but no completely definitive answers. It is clear that a necessary condition for dynamical stability is that the topology be that of linked poloidal and toroidal fields. Even so, fields that are symmetric about the rotation axis may still be subject to instabilities (e.g. Tayler 1982). Comparatively few results are available for rotating nonaxisymmetric configurations—it may be significant that only $\chi > 0$ is observed.

In summary, according to the fossil theory, the fields that we observe in the CP stars are the primeval fields, after some expulsion, decay and advection. The picture is generally consistent with the OR/DD model. From a perhaps rather personal viewpoint, and with a *caveat* about stability, the evidence does at the moment appear to favour the fossil theory.

3. Be Stars

If the regular modulation seen in certain spectral lines is caused by a stellar wind in the presence of a corotating magnetic field, it is natural to try to explain irregular fluctuations in these lines as being associated with magnetic fluctuations. There seem to be two basic ideas.

By analogy to the OR model for the magnetic CP stars, the large scale field, $\mathbf{B}_b$ say, might be expected to be stable and unchanging. But what if Be stars have even a very thin sub-surface region that is unimportant for energy transport, but is the site of rapid turbulent motions. Could such motions influence the field, producing fluctuations $\mathbf{B}_1$? Given the existence of such a turbulent layer, there appear to be two possibilities. (This discussion does not depend on the nature of the origin of the large scale field $\mathbf{B}_b$.)

1. A dynamo operates in the turbulent region.

   a. Consider a conventional mean field dynamo. Put $u_t = f_1 c_s$, $\Omega_0^2 R = f_2 g$, $\eta_{\rm turb} = f_3 u_t d$, $\alpha = f_4 \Omega_0 d$, where c_s is the sound velocity, g the acceleration of gravity, d the depth of the turbulent layer and $f_i \lesssim 1$. Then

$$C_\alpha = \frac{\alpha d}{\eta_{\rm turb}} = \frac{f_2^{1/2} f_4}{f_1 f_3} \left(\frac{d}{R} \frac{d}{H_p} \right)^{1/2} \ll 1, \qquad (3)$$

   where H_p is the pressure scale height and d/H_p is not large. Similarly $C_\omega = \Omega_0 d^2/\eta_{\rm turb} \ll 1$. Thus there is no conventional α^2 or $\alpha\omega$ mean field dynamo action.

   b. Does a small scale 'fluctuation' dynamo operate? Simulations (e.g. Meneguzzi & Pouquet 1989) suggest that such a dynamo will be excited if $R_m = u_t l/\eta_{\rm true} \gg 1$, where $\eta_{\rm true}$ is the normal, non-turbulent resistivity and l is a turbulent length scale. This condition is adequately satisfied in this case. However these numerical experiments do not have the extreme aspect ratios of very thin sub-surface turbulent zones of the type considered here, nor do they take account of the presence of the large scale background field which may alter the nature of the turbulence, so the situation is not altogether clear. Scaling from numerical simulations and the solar convection zone suggests that timescales could be of order one day.

2. There is no dynamo action, but high *Rm* turbulent motions in a relatively thin layer distort $\mathbf{B}_b$. To order of magnitude $(\mathbf{B}_b + \mathrm{B}_1)^2/4\pi\rho u_t^2$ will be less than unity. There are enough uncertainties that it is difficult to make good numerical estimates but, with $|\mathbf{B}_b|$ of order 100G, significant fluctuations with $|\mathbf{B}_1| \sim |\mathbf{B}_b|$ seem *a priori* plausible. However we can note that observations of the integrated longitudinal field in even the weaker field classical CP stars do not show corresponding variations, which may imply that this estimate for $|\mathbf{B}_1|$ is rather generous, and that really $|\mathbf{B}_1| < |\mathbf{B}_b|$. Even so, fluctuations could still be large enough to influence the wind.

Thus a combination of sub-surface turbulence and a stable background field might, in principle at least, provide a mechanism to generate fluctuations in the wind and hence in the spectral lines formed in the wind regions of Be stars. However, the presence of such a turbulent layer is not unambiguously established. B stars may be sufficiently massive that they do not have the sub-surface convection zone found in slightly less massive main sequence stars. With the recently available OPAL opacities, a thin sub-surface convectively unstable layer reappears in stars on the ZAMS with masses greater than about 15 solar masses (Alberts, these Proceedings). It is unclear how firmly this limiting mass is established. Very speculatively, it is possible that a shear instability near the stellar surface could result in such a turbulent layer, although the situation is not theoretically clearcut (see, e.g. Vauclair 1976 and the discussion in section 2.4 of Moss & Smith 1981). Note that rapid rotation favours such instabilities, but that a large scale magnetic field, if strong enough, might well inhibit them.

Another, quite different, suggestion is that Be stars are unstable to a number of g modes of nonradial oscillation. These modes are perturbed by the rapid rotation and may possess sufficient net helicity to provide an α-effect that could drive a dynamo (e.g. Dziembowski, these Proceedings). This idea is as yet unquantified: presumably any such dynamo would have to operate in a chaotic regime in order to explain the irregular spectral fluctuations.

Further, Smith (1989) has proposed that spectral transients arise from flare-like events, associated with regions of tangled magnetic field above the stellar surface.

At the moment none of these ideas are well developed. We should keep well in mind the indirect nature of the evidence for the magnetic fields in these objects: direct, rather than inferential, field detection would be very welcome!

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Discussion

Henrichs: Stellar structure calculations of massive stars with the new OPAL opacities show that there is a convection zone at a fractional radius of about 0.98, the depth of which somewhat increases with mass. This convection zone did not appear in earlier calculations. See Alberts (these Proceedings). I wonder how this affects your considerations, in particular in the light of the observationally suggested correlation between mass and field strength.

Moss: This convection zone appears for main sequence masses somewhat in excess of those of the B stars, and any fields associated with such a convection zone seem unlikely to be related to the observed large scale fields in CP stars.

Mathys: Although detailed modelling is still lacking, there is growing evidence that the magnetic fields of most classical Ap and Bp stars do not have cylindrical symmetry about an axis passing through the centre of the star. Could you comment on the implications for the origin of the field?

Moss: The magnetic fields in my published A and B star models (Moss 1990 and references therein) naturally depart from cylindrical symmetry after time zero, even if they are initially cylindrically symmetric, provided that the initial inclination angle χ (β) is non zero. This results from the interaction of the meridional circulation with even an initially cylindrically symmetric field. Additionally, with the fossil field theory, there is no reason for fields on the age zero main sequence to be strictly cylindrically symmetric.

Megessier: Following the question from G. Mathys: is it possible to distinguish between the two magnetic field geometries—decentred dipole or a mixture of dipole and quadrupole? In the case of a decentred dipole, it is necessary to have the distance between the magnetic field and stellar centres as large as one third of the stellar radius. Is that conceivable?

Moss: I regard the displaced dipole and dipole plus quadrupole (multipole) descriptions as convenient parameterizations of the real field: there is no reason to expect that the actual stellar field corresponds exactly to either of these structures (except, of course, that any cylindrically symmetric field must have a multipolar expansion, and that an arbitrary field must be expandable in spherical harmonics).

Smith: With regard to spectral line profile transients in Be stars, you were careful to point out that any fluctuation in **B** may be smaller than the strength of a background global field. But if the energy of this fluctuating field structure is dissipated on a short timescale, it may not matter that $|\mathbf{B}_{\rm fluctuation}| < |\mathbf{B}_{\rm background}|$.

Moss: I agree, if it is the energy dissipated by the fluctuation field that is important. It might be, however, that the relevant mechanism is an additional modulation of the wind by the fluctuation field.

Cassinelli: In your discussion of the core dynamo, you considered the effects of buoyancy and diffusion. Couldn't the circulation currents affect the rate at which the field is brought to the surface?

Moss: Their timescale is a diluted global thermal timescale, and they are thus much too slow to be important.

Vakili: If we were able to resolve angularly the photosphere of Be stars, we could then 'see' dipolar or quadrupolar magnetic structures. This would need two orders of magnitude improvement on currently operational stellar interferometers. If so, how would the 'magnetic image' of these stars appear?

Moss: I would like very much to know! Detailed field geometries of evolving CP star models depend to some degree on the initial flux distribution in the star. If we assume that the large scale surface fields of the Be stars are analogous to those of the Bp stars, ie approximately displaced dipoles, but that there is a strong wind, then the answer might depend somewhat on the height above the surface to which the observations referred.

Dudurov: What can you say from a theoretical viewpoint about the difference between the magnetic and normal hot stars?

Moss: From the fossil viewpoint one can imagine that stars reach the ZAMS with a range of magnetic fluxes, depending on local conditions in the interstellar medium where they formed, and their detailed history. Plausibly this initial flux distribution is peaked at relatively small fluxes, with a high flux tail (see Fig. 2). Then it is the members of this tail that are subsequently the observably magnetic stars.

Owocki: When thinking about magnetic structures on stars, I think it is important to keep in mind some properties of the solar magnetic field. Near solar minimum, the global coronal and interplanetary magnetic field is quite well described by a tilted dipole (much as you and the previous speaker described for magnetic stars), which has a magnitude of only about 1 gauss. Nonetheless, this can have a dominant influence on the solar wind, e.g. inducing high and low speed streams. In addition, there are small scale fields of much greater magnitude ($\sim 10^4$ G) that play an important role in solar activity. Although I understand that much of the physics of hot stars is different, it does not seem impossible that similar ranges of field scales could exist in them also.

Sareyan: Given that there is no direct detection of magnetic fields in Be stars, can you make a comment about correlations between magnetic field variations, photometry variability and Doppler imaging in some stars?

Moss: No!