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The origin of magnetism on the upper main sequence

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ABSTRACT

We consider the incidence of magnetism in main-sequence stars with mainly radiative envelopes. We propose that the small fraction, which increases with mass, of stars which are magnetic can be explained if towards the end of the formation process, after the stars have developed a substantial radiative envelope, a correspondingly small fraction of stars merge. Such late mergers would produce a brief period of strong differential rotation and give rise to large-scale fields in the radiative envelopes. Such late mergers can also account for the lack of close binaries among these stars.

Key words: stars: evolution – stars: formation – stars: magnetic fields – stars: pre-main-sequence.

1 INTRODUCTION

Magnetic surveys have revealed that magnetism on the mid-main sequence is restricted almost exclusively to the chemically peculiar Fp, Ap, Bp stars (see Donati & Landstreet 2009, for a recent review). The fields tend to be stable, large scale and ordered with the incidence of magnetism increasing sharply from 0.5 per cent for F0-type stars to about 8.2 per cent at spectral type A5 and then rising more gradually to 15.5 per cent in the spectral range B7, B8 and B9 (Johnson 2004). The field strengths B range from a few tens of kG, corresponding to a maximum magnetic flux $\Phi \approx 10^{27}$ G cm^2, to $B \approx 300$ G with $\Phi \approx 10^{25}$ G cm^2. The observed lower limit to the fields of A and late B stars is well above the current limit of detectability of the most sensitive surveys ($B \approx 30$ G; Aurière et al. 2008). It thus appears that a magnetic dichotomy exists. A and late B stars either are highly magnetic ($B \gtrsim 300$ G) or are not magnetic up to the current detectability level of $B \approx 30$ G (Aurière et al. 2008). In addition, observations have shown a total absence of magnetic stars in the mass range 1.5– 1.6 $M_\odot$ which is bounded above by the Ap–Bp stars and below by stars with convective envelopes where there is a 100 per cent incidence of magnetism (Donati & Landstreet 2009).

Until recently, magnetism in upper-main-sequence stars has been inferred through the observed variability of stellar winds and the detection of non-thermal radio and X-ray emission. The discovery of an ordered magnetic field in θ Orion C (spectral type O4, $B = 1100 \pm 100$ G; Donati et al. 2002) through Zeeman techniques provided the first direct confirmation of a magnetic field in an O-type star. The magnetic flux of this star, $\Phi \approx (7 \pm 3) \times 10^{27}$ G cm^2, is similar to the magnetic fluxes of the strongly magnetic Ap and Bp stars. Strong fields have since been discovered in other massive stars such as HD 191612 ($B \approx 1500$ G, spectral-type O6; Donati et al. 2002). Petit et al. (2008) have argued that 25 per cent of the massive stars ($M > 20\,M_\odot$) in the Orion Nebula have extremely high magnetic fields ($B \gtrsim 1000$ G), but it has also been noted that this cluster exhibits a highly abnormal massive star mass function (Pflamm-Altenburg & Kroupa 2006). Hubrig et al. (2008) conducted spectropolarimetric measurements of magnetic fields in early B- and O-type stars and found longitudinal fields with strengths in the range $100 < B/\mathrm{G} < 300$ in about 30 per cent of their sample. They also conclude that large-scale dipolar fields of strengths $B \gtrsim 1000$ G, like those found in the Orion observations, are not very common among the general class of massive stars, so there is a cluster-to-cluster variation. Thus, all these studies support an incidence of magnetism among O-type stars of 25 per cent at a level $B \gtrsim 100$ G, although it should be noted that the samples are small. For the same reason, it is still not clear whether magnetic upper-main-sequence stars also have a lower limit to their field strengths, and therefore it is still not known whether a magnetic dichotomy persists in the upper-main-sequence stars. However, Hubrig et al. (2008) point out that fields as low as a few tens of gauss are all that are required to explain the wind variability observed in the ultraviolet in these stars.

There have been several recent studies of different groups of early B stars with spectral types that span the range between the early-type O stars and the Ap and Bp stars. These suggest that magnetism is prevalent in these groups too. These include the β Cephei stars, the slowly pulsating B-type stars (SPBs), the fast-rotating emission-line Be stars and ordinary early B stars. Hubrig et al. (2009a,b) reported the detection of fields of 300–400 G in about 30 per cent of β Cephei stars, and about 50 per cent of the SPB stars were reported to be weakly magnetic at a level of $B \lesssim 200$ G. They also detected weak longitudinal magnetic fields in two of the seven normal B-type stars they observed. The smallest fields observed are a few tenths of a gauss (Bouret et al. 2008).

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In summary, current observations are consistent with the hypothesis that radiative main-sequence stars are either strongly magnetic or barely magnetic at all, and that the incidence of magnetism increases with mass along the main sequence (once $M \geq 1.6\,\mathrm{M_\odot}$) to earlier spectral types. Furthermore, the observations appear to indicate that there is an upper limit $\Phi_{\rm max} = (7 \pm 3) \times 10^{27}\,\mathrm{G\,cm^2}$ to the magnetic flux on the main sequence over the mass range 1.6–45 $\mathrm{M_\odot}$. There is also some indication that the maximum magnetic flux increases with mass. Reisenegger (2009) suggests that the most highly magnetized objects obey an approximate relationship

$$\beta_{\rm max} = \frac{8\pi P}{B^2_{\rm max}} \approx \frac{8\pi^3 G M^2}{\Phi^2_{\rm max}} \approx 3 \times 10^6 \left(\frac{M}{\mathrm{M_\odot}}\right)^2, \tag{1}$$

where

$$P \approx \frac{GM^2}{R^4} \tag{2}$$

is a global measure of the stellar pressure and R is the radius of the star. This suggestion is in line with the findings of Braithwaite (2004, 2009) and Braithwaite & Spruit (2004) concerning the stability of magnetic field strengths and configurations in radiative stars together with the idea that the maximum field strength is somehow mediated by magnetic buoyancy effects.

2 ORIGIN OF THE FIELD

The stars we are considering all have substantial radiative envelopes. This implies that, provided that the field configurations are stable, the decay time-scales of the magnetic fields found in these stars (about 10 Gyr) are comparable to, or longer than, the lifetimes of the stars themselves. Thus, in line with many other authors (see Mestel 1999, for a review), we argue that the origin of the fields in these stars is to be found at the time of their birth. In this sense, the fields are fossil fields.

Consistent with the low-mass stars, we argue that a convective envelope drives a powerful dynamo (Tout & Pringle 1992) which generates a strong but small-scale field and that such a field wipes out any long-lived large-scale component. So the generation of a persistent large-scale field must take place after the star has developed a radiative envelope in which it can be maintained. This occurs on the Henyey part of the pre-main-sequence track towards the end of the star's contraction to the main sequence.

2.1 The star formation picture

Over the last 20 years or so, our picture of the environment in which stars form, and the manner in which they do so, has changed considerably. The early simple picture (Shu, Adams & Lizano 1987) in which stars form one at a time from isolated magnetized cloud cores by some slow process mediated by ambipolar diffusion has given way to a more dynamic picture (Bate, Bonnell & Bromm 2002a,b, 2003; Bate & Bonnell 2005; Bate 2005, 2009a,b) which involves turbulent and chaotic motions of both gas and stars with disc fragmentation, competitive accretion and close dynamical interactions all playing a role. Current ideas have been developed to take account of the observations that stars form in highly turbulent, high-density regions, that they form in relatively dense clusters and that most of them are in binary, if not multiple, systems. Thus, as we now understand it, a star itself starts out as a small self-gravitating core, maybe a few Jupiter masses in size, which grows from the surrounding medium, mostly through a protostellar accretion disc.

Given this picture, it is not easy to understand how the central radiative star could end up with a large-scale magnetic field. There are two basic problems. First, although accretion discs are thought to be mediated by magnetic fields (Balbus & Hawley 1998), without some special coincidence (see e.g. Spruit & Uzdensky 2005; Rothstein & Lovelace 2008) and unless the effective magnetic diffusivity is anomalously low (which appears not to be the case; Guan & Gammie 2009; Lesur & Longaretti 2009), the disc itself is not able to drag inwards an external poloidal component (Lubow, Papaloizou & Pringle 1994). The disc itself contains magnetic field, which is advected on to the central star, but this field is mostly small scale, of the order of the disc scaleheight. This could provide a seed field for a dynamo process, that would be expected to occur in convective envelopes, but it would be difficult to construct a large-scale stellar field from it. The presence of jets from protostars does indicate that the disc can also produce a larger scale, but lower strength, field perhaps by some form of inverse cascade (Tout & Pringle 1996). However, such a field is likely to have a random direction (King et al. 2004) and so does not lead to accretion of a strong net stellar field. Secondly, if all stars form in this same manner, we would have to argue that all radiative stars should have similar fields. But then there seems to be no obvious physical reason why some small fraction of stars end up strongly magnetic while the rest do not.

2.2 Dynamo fed by differential rotation

Following this line of argument, we are led to the idea that perhaps the small fraction of stars form in a different manner and one which leads to the production of a strong large-scale field. Here, we are encouraged by the findings of Braithwaite (2004). In chapter 5 of his dissertation, he shows that, in a radiative envelope which has driven differential rotation, it is possible to construct a dynamo which feeds only off the differential rotation. This, coupled with an initial seed field, gives rise to a strong toroidal component. The toroidal component becomes unstable, presumably at least in part through buoyancy effects, and produces a new poloidal component completing a feedback loop. The final field configuration is likely to be that found by Braithwaite & Spruit (2004) and Braithwaite (2009) who show that an initial random field decays through instabilities to a stable configuration which has comparable toroidal and poloidal components. The time-scales on which such instabilities operate are typically the crossing time-scale for Alfvén waves

$$t_{\rm mag} \approx \beta^{1/2} \left(\frac{R^3}{GM}\right)^{1/2}. \tag{3}$$

Using equation (1) we find that

$$t_{\rm mag} \lesssim 0.1 \left(\frac{M}{\mathrm{M_\odot}}\right)^{1/2} \left(\frac{R}{\mathrm{R_\odot}}\right)^{3/2} \mathrm{yr}. \tag{4}$$

It seems therefore that a possible means by which a small number of stars end up with large-scale fields is if a small fraction of stars are subject to differential rotation driven on a time-scale of approximately $t_{\rm mag}$ towards the end of their formation process. Disc accretion on to a young star does indeed drive differential rotation because the disc material arrives with high specific angular momentum $h \approx \sqrt{GMR}$. But the time-scale for such driving by disc accretion is roughly the same as the accretion time-scale itself, $t_{\rm acc} \approx M/\dot{M}$. Typical protostellar accretion rates are thought to be of the order of $\dot{M} \approx 10^4\,\mathrm{M_\odot\,yr^{-1}}$ so that $t_{\rm acc} \gtrsim 10^4$ yr. Thus, disc accretion is not likely to be rapid enough to drive a sufficiently powerful dynamo by differential rotation.

2.3 Merger-driven field generation

The simplest mechanism by which strong differential rotation can be driven in a star as it is formed is if a substantial part of the final stellar mass is added not through standard disc accretion but as part of a merger with another young protostar. The idea that mergers might play an important role in the formation of massive stars has been propounded by Bonnell, Bate & Zinnecker (1998) and Bonnell & Bate (2002). Further, the idea that magnetic field generation by mergers might be implicated in the formation of a strongly magnetic class of white dwarfs has been put forward by Tout et al. (2008). Indeed, the analogy with the ideas of Tout et al. (2008) goes further. As for the magnetic white dwarfs, there is evidence that magnetic upper-main-sequence stars are deficient in close binary companions. A curious fact, first noted by Abt & Snowden (1973) in mid- and upper-main-sequence magnetic stars, is that they tend not to be members of close binary systems even though they do occur with the normal frequency in wide binary systems. A more extensive study of cool Ap stars by Carrier et al. (2002) has confirmed this general result. With one exception, Ap stars have orbital periods $P \geq 3$ d and tend not to exhibit circular or low-eccentricity orbits. Typically, in numerical simulations of turbulent and chaotic star formation close binary systems occur predominantly because stars, once formed, are brought together through dissipative dynamical interactions with protostellar material, usually discs (cf. Clarke & Pringle 1991). If a small fraction of such interactions drive what would otherwise end up as a close binary system all the way to a late merger of the young protostars then this could explain why a small fraction of stars end up very magnetic and why those stars are not typically found in close binary systems.

3 DISCUSSION

We have argued that an explanation for the finding that a small fraction of stars on the upper-main sequence (where stellar envelopes are radiative) are strongly magnetic, while the rest of them are not, could be found in the possibility that, for a fraction of stars, the final addition of mass during their formation process comes from a merger of two protostars. Such a merger would drive strong differential rotation and hence a large-scale dynamo field. If such an explanation is correct then it requires that the fraction of late mergers, that is those that take place after the star has developed a radiative core in which a large-scale field can be maintained, match the fraction of magnetic stars as a function of mass. We therefore envisage a situation where the merger occurs when one of the stars is on the Henyey part of the pre-main-sequence track towards the end of the star's contraction to the main sequence. If the merger takes place earlier, while the star is on the convective Hayashi track, we argue that a convectively driven dynamo would wipe out any large-scale field. The absence of strong magnetism in stars of 1.5–1.6 $\mathrm{M}_{\odot}$ stars is then due to the fact that they develop radiative envelopes very late on when mergers have become less likely. It might also be that the range of fields in the magnetic stars comes about through the range of mass ratios involved in the merger process.

We expect that the time-scale for the merging process should be between the typical dynamical

$$t_{\mathrm{dyn}} = \sqrt{\frac{R^3}{2GM}} \approx 0.5\,\mathrm{h} \tag{5}$$

and thermal

$$t_{\mathrm{KH}} \approx \frac{GM^2}{RL} \approx 10^7\,\mathrm{yr} \tag{6}$$

time-scales of a protostar. Thus, for a 1 $\mathrm{M}_{\odot}$ star of 1 $\mathrm{R}_{\odot}$, we expect the merging time to be around 10^2–10^3 yr, in between the Alfvén magnetic crossing time (see equation 4) and the accreting time-scales. However, we expect differential rotation to be raised to its highest levels in the early stages of the merger. If a strong enough persistent field can be set up at this time, it could quench any rotationally driven dynamo (Tout & Pringle 1995) that might subsequently operate as the merged object accretes the last of its disrupted companion and as it spins down.

In general, simulations of the star formation process have tended to concentrate on the low-mass end of the stellar mass spectrum. This is so even in the most recent computations (Bate 2009b) where some account is taken of radiative feedback, which will be of much greater importance in the process of the formation of more massive stars (Krumholtz 2006). Computations of the formation of more massive stars are complicated by the general result that more massive stars tend to form in more massive molecular clouds and more massive clusters and by the additional complication that radiative feedback on the accreting material from the stars as they form must be fully accounted for. Both these effects make the numerical simulations more difficult to perform. A further complication, as far as our predictions of mergers are concerned, is that because of the large range of scales involved, numerical simulations cannot, in general, follow the smallest scales down to a size of the stellar radius (around 0.01 au). To circumvent this, it is usual to replace the highest density regions in the simulation by sink particles which have typical sizes of a few au. These sink particles represent stars formed in the simulation. They are able to accrete and to interact dynamically with the surrounding gas and with each other, but they are not permitted to merge. Thus, the predictions we make here with regard to the frequency and nature of late mergers in the star formation process have not yet been tested with current theoretical models.

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