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Dynamo Action in The Presence of an Imposed Magnetic Field

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The persistent magnetic fields of Ap stars are generally thought to be of primordial origin, but dynamo generation of magnetic fields may offer alternative possibilities. Deep within the interiors of such stars, vigorous core convection likely couples with rotation to yield magnetic dynamo action, generating strong magnetic fields. Recent numerical models suggest that a primordial field remaining from the star's formation may possess a highly twisted toroidal shape in the radiative envelope. We have used detailed 3-D simulations to study the interaction of such a magnetic field with a dynamo generated within the core of a 2 solar mass A-type star. Dynamo action realized under these circumstances is much more vigorous than in the absence of a fossil field in the radiative envelope, yielding magnetic field strengths (of order 100 kG) much higher than their equipartition values relative to the convective velocities. We examine the generation of these fields, as well as their effect on the complex dynamics of the convective core.

1 Introduction

Much attention has been given to the magnetic fields of the peculiar A-type (Ap) stars since their disovery by Maury (1897). The peculiarity of these stars stems from the vast regions of rare earth metals (typically Si,Sr, Hg for instance) on the their surfaces that rotate into and out of view as the star rotates. Most of the Ap stars exhibit surface magnetism as well, with typical field strengths of a few hundred Gauss, but fields ranging from 20,000 G down to the detectability limit (100-200 G) having been observed (e.g. Borra et al. 1982, Mestel 1999).

The central cores of these stars are convectively unstable. This convective core is surrounded by a large radiative envelope comprising the bulk of the star (by volume). Dynamo action within the convective cores of Ap stars has long been suspected (e.g., Krause & Oetken 1976) and has been shown by Brun, Browning & Toomre (2005) to be quite vigorous, yielding magnetic fields in approximate equipartition with the convective motions.

While the cores of these stars are thought to harbor dynamo action, the lack of temporal variation of these magnetic fields has led many to suspect a primoridal origin for the surface magnetic fields in these stars (see Mestel 1999 and references therein). Braithewaite & Spruit (2004) have studied the likely geometry and evolution of a primordial field remaining in the stellar radiative zone of these stars. They have found that the magnetic field in such a radiative zone tends to seek a twisted toroidal shape as it evolves towards a stable configuration. Using a helical field reminiscent of that found in the simulations of Braithewaite & Spruit (2004), as well as a purely toroidal field, we examine the dynamo action achieved when such fields are imposed onto a dynamo within the core of an A-type star.

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2 Numerical Model

Our simulations have been carried out with the anelastic spherical harmonic (ASH) code. This code solves the three-dimensional MHD equations in a rotating, spherical frame under the anelastic approximation (see Clune et al. 1999, Brun, Miesch, & Toomre 2004). In systems such as the deep interior of A-type stars, the fluid motions are distinctly subsonic, and thermodynamic variables are small compared to their mean, horizontally averaged values at a given depth. The anelastic approximation is thus both appropriate here and computationally expedient as it filters out sound waves and fast magneto-acoustic modes.

We model a main-sequence A-type star of $2M_\odot$ rotating at four times the solar rate. The computational domain extends from the inner 2% to 30% of the star by radius. The inner 2% of the star has been neglected to avoid the coordinate singularity at r=0, as well as the increasingly smaller timesteps that accompany the smaller horizontal mesh size at the small radii. The inner 15% of this star is convectively unstable, with an overlying stable, radiative zone comprising the outer portion of the computational domain. Further details of this model may be found in Browning, Brun, and Toomre (2004).

For boundary conditions, we have adopted impenetrable, stress free boundaries for both simulations. Each boundary is also treated as a perfect conductor (i.e. E_ϕ and E_θ vanish at the boundaries). These conditions prevent the leakage of both angular momentum and magnetic energy through the boundaries. Energy flux through the top and bottom boundaries is determined by a 1–D stellar model and held constant throughout the simulation.

We have used the dynamo model of Brun, Browning, and Toomre 2005, with a superimposed magnetic field as our initial condition for this simulation. The dynamo of Brun et al. (2005) was initialized using a well equilibrated hydrodynamic simulation from Browning et al. (2004) and adding a small dipole seed field to this system. Steady dynamo action realized in this simulation yielded nearly equipartion magnetic energies. The magnetic energy in this system was largely comprised of fluctuating (non-axisymmetric) fields, with the axisymmetric poloidal and toroidal fields constituting only a small fraction ($\sim 5\%$) of the magnetic energy. Magnetic fields built by this dynamo where highly intermittent in space and time, and generally possessed higher energies than the flow at the smaller scales.

We have investigated two geometries for the imposed magnetic field, with the same functional form for the longitudinal magnetic field B_ϕ employed in each case. B_ϕ was taken to be symmetric in longitude with a Gaussian-cross section of amplitude 30 kG, centered along the equator at $r_0 = 0.17R_{start}$ with a halfwidth of $0.2r_0$. In one case we added no poloidal field. For the other a poloidal component consistent with a current threading through the center of our magnetic torus was added. The strength of this field was adjusted so that the ratio of energy in the poloidal field to that in the toroidal field was 1:9. This ratio has been suggested by Braithewaite & Spruit (2004) as being the probable ratio for a stable twisted torus residing in the radiative zone of an A−type star. These two external fields were then superimposed on the existing magnetic field of our progenitor case at a time corresponding to day 2000 of case C4m from BBT05. In each case, the magnetic energy of the imposed field constituted a $\sim 10\%$ increase in the magnetic energy of the system.

3 Ordered Flows and Fields

Dynamo action realized in the presence of these fields varies quite significantly between the two cases. The dynamo operating in the purely toroidal field case shows little variation from that achieved in the progenitor case. Namely, this case sustains magnetic fields throughout the core in rough equipartition with the kinetic energy there. For the twisted case, however, magnetic energies undergo a slow, steady phase of growth, and exhibit continued growth even at late times in the simulation. Ultimately, magnetic energies in the twisted field case rise to about 10 times the kinetic energy density (or 100−fold growth). We now turn our focus to the subsequent development of organized field and flows in

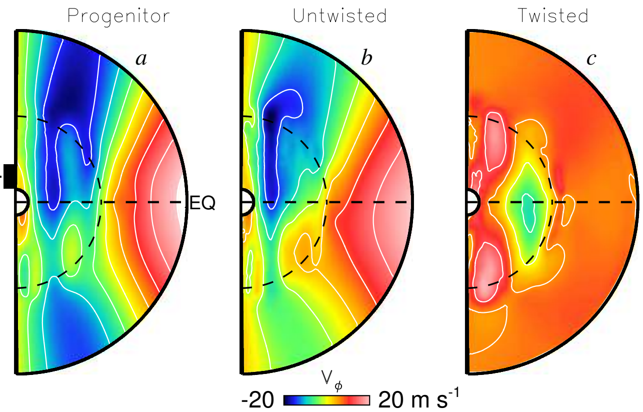

Fig. 1 Longitudinal averages of V_ϕ shown in a meridional plane (as a function of radius and latitude). V_ϕ has been taken with respect to the rotating frame, and has been averaged over longitude and a time period of 200 days in each instance. The curved, dashed line denotes the boundary of the convective core. The slow column of differential rotation characterizing the progenitor case is present in the untwisted case. A state of near solid body rotation exists in our twisted case, however, with a region of weakly retrograde rotation in the outer core.

these solutions following the imposition of a twisted fossil field.

3.1 Alteration of the Mean Flows

The twisted field case exhibits significant modifications to the mean flows and fields not present in the purely toroidal and progenitor cases. We have plotted the longitudinal velocity (with respect to the rotating frame) V_ϕ of each of these three systems in Figure 1. These profiles of V_ϕ have been averaged in azimuth and over several hundred days in each case. Differential rotation of the progenitor system, as well as the untwisted case is marked by a slow column of flow near midcore, extending parallel to the rotation axis. The fast equator and slow core characterizing these solutions are absent in the twisted field case. Poloidal field lines cutting across differentially rotating columns in the radiative exterior have served to induce a state of near solid-body rotation throughout the radiative zone.

As this simulation has evolved, magnetic torques have developed in the radiative zone, ultimately slowing the fast outer equator, and helping to eliminate the slow columnar differential rotation achieved in the progenitor. A weak retrograde jet, spanning both the northern and southern hemisphere, is all that remains of this slowly rotating region.

3.2 Development of Magnetic Structure

In Figures 2*a* and 2*b*, we have plotted averages of B_ϕ for the twisted and untwisted cases. Late-time evolution in the twisted field case has seen the growth of two large toroidal magnetic structures near the core-radiative zone interface. These large, oppositely signed torii, encompass the bulk of

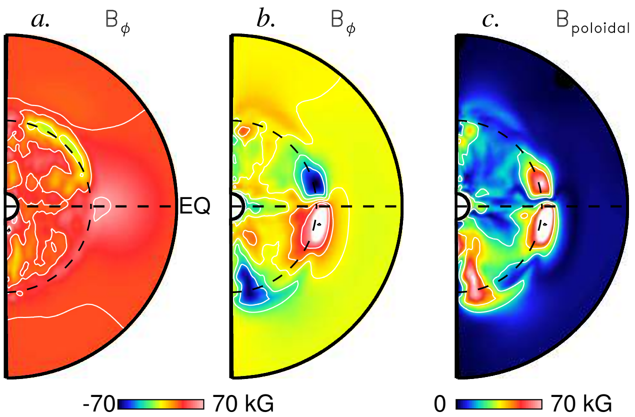

Fig. 2 (a) B_ϕ averaged over longitude and time for the case of the purely toroidal imposed field. (b) B_ϕ for the twisted field case. Large toroidal structures not present in (a) are visible here. (c) Poloidal field modulus for the twisted field case. The large flux ropes encircling the core both have a substantial poloidal component.

the star's equatorial region and possess peak field strengths of ~ 100 kG. Regions of previously strong shear, now absent (see Fig. 1), coincide spatially with these structures. Strong radial shear near the outer core has acted on the poloidal component of our external field, apparently generating these regions of strong B_ϕ via an $\Omega-$effect. These structures are maintained against diffusion by the relatively weak shear present near the edges of the retrograde jet near the outer core (see Fig. 1c). The toroidal structures present in the twisted field case have also developed a comparably sized poloidal component. Figure 2c depicts the time and longitudinally-averaged poloidal field modulus. Poloidal field lines for both structures possess the same sense as those present initially in the external field, tending to run counterclockwise. These field lines wrap around the individual torii, and also provide an common, outer, poloidal envelope. Strongest near the core of the torii, the mean components of these fields reach ~ 100 kG as well.

While Figure 2 has been produced via averaging in space and time, these strong toroidal structures are apparent in instanteous snapshots of the system as well. A volume rendering of B_ϕ is shown in Figure 3a. Toroidal structures of opposite sign are clearly visible just above and below the equator. The corresponding field lines, colored according to the field modulus, have been traced in Figure 3b. Twist in the field is most noticeable near the leftmost portions of this snapshot, where weak poloidal field couples these two torii. The prominent toroidal belts discussed here constitute only about 20% locally to the magnetic energy makeup. This is slightly higher than the toroidal structures deeper within the core which constitute about 10% of the magnetic energy. Magnetic energies in the twisted field case have risen to nearly 10 times the level of the kinetic energies. The entirety of this system has seen an increase in energy, with the convective core seeing the bulk of the rise. But how does this energy distribute itself on average as a function of scale?

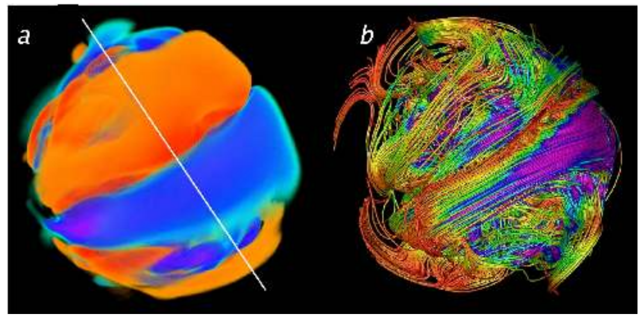

Fig. 3 (a) Volume rendering of B_ϕ from a single, late$-$time instant in the twisted field simulation. Red tones indicate negative field values, and blue tones positive field values. The white line indicates the orientation of the rotation axis. (b) Field line tracings from the same instant in time and with the same orientation as $(a.)$ Red tones indicate low values of the field modulus, and blue tones high values. Large toroidal structures are visible just above and below the equator, with a poloidal component joining the two flux tubes.

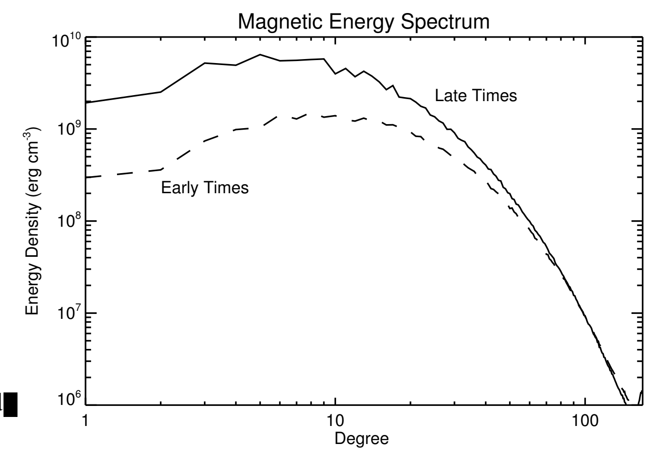

Fig. 4 Time averaged magnetic energy spectra taken on a spherical slice at mid-core ($r = 0.075 R_{star}$). Late-time spectra (solid line) show higher energy, particularly at lower l than spectra from early on in the simulation (dashed line).

In Figure 4, we show the magnetic energy spectrum of our system, taken on a spherical slice at mid core, as a function of spherical harmonic degree l. Magnetic energy has increased on scales as small as $l = 60$, but the larger scales ($l \leq 10$) exhibit the most growth. The imposition of an external field has thus led to the growth of the large-scale components of the field, while leaving the smaller structures relatively unchanged strengthwise, or even diminished slightly.

4 Conclusions

Imposing an organized magnetic field onto a fully developed dynamo seems to have consequences largely dependent on the geometry of the imposed field. In this case, our dynamo has been particularly sensitive to the imposed field possessing a poloidal component, or possibly some net helicity. Preliminary results from simulations where we have imposed a purely poloidal field exibit properties similar to those of our twisted case. Poloidal fields, rather than helicity, thus seem to be the likely cause of the dynamics observed in our twisted field case. Ultimately it is the interplay between these imposed mean fields and the differential rotation of the system that leads to the development of the large-scale toroidal structures observed here.

More generally, our results suggest that the dynamics of stellar interiors, specifically those of A−type stars can be significantly influenced by the presence and geometry of primordial magnetic fields. The interplay between this field and the stellar dynamo can lead to the development of much more organized and large−scale magnetic structures than those that exist in the absence of such a field. Such fossil fields can dramatically alter the differential rotation realized in these systems, both within the convective core, and well into the radiative zone. Fossil fields may also affect the dynamos achieved within the cores of these stars, leading to substantially higher (super−equipartition) magnetic fields should the fossil field exhibit a poloidal component.

The lack of variation of magnetic activity (in a frame of reference corotating with the star) has generally been taken to indicate a primordial origin for the magnetic fields in most of these stars. Nevertheless, we have demonstrated that by accounting for the presence of a fossil field, our simplified dynamo model shows a tendency to build strong toroidal ropes near the equator. Should these ropes become sufficiently strong, the possibility exists that they may become buoyant and rise to the stellar surface.

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References

Borra, E.F., Landstreet, J.D., Mestel, L.: 1982, Ann. Rev. Astron. Astrophys. 20, 191
Browning, M.K., Brun, A.S., Toomre, J.: 2004, ApJ 601, 512
Brun, A.S., Miesch, M.S., Toomre, J.: 2004, ApJ 614, 1073
Brun, A.S., Browning, M.K., Toomre, J. : 2005, ApJ 629, 461
Braithwaite, J., Spruit, H.C.: 2004, *Nature* 431, 819
Krause, F., Oetken, L.:1976, *Physics of Ap Stars*, edited by W. W. Weiss, H. Jenkner, and H. J. Wood Universitatssternwarte Wien, Vienna, 29
Maury, A.C.: 1897, Harvard Ann. 28, 96
Mestel, L.: 1999, *Stellar Magnetism*, Oxford University Press, Oxford

