Spontaneous Formation of Cool Polar Spots in Global Dynamo Simulations

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Abstract. We report the spontaneous formation of cool spots in a global numerical simulation of dynamo in a rapidly rotating spherical shell. The simulation generates a magnetic field which quenches convection in localized regions. Such quenching hampers convective heat transport and produces dark spots which form primarily at high latitudes. Our models provide a novel mechanism for generating polar dark spots in rapidly rotating cool stars.

1. Introduction

Observational techniques have revealed that, like the Sun, other cool stars also possess dark spot-like features on their surface. But, unlike the sunspots, dark spots on other stars appear at a wide range of latitudes. Some cool stars, especially the rapidly rotating ones, exhibit dark spots very close to the rotational poles (Berdyugina 2005; Strassmeier 2009). Extending the solar paradigm, for rapidly rotating cool stars it has been suggested that rising flux-tubes appear at high latitudes either due to the influence of strong Coriolis forces (Schüssler & Solanki 1992) or that they appear at low latitudes and are then advected polewards by near-surface flows (Schrijver 2001). However, dynamos in stars where rotation plays a dominant role might be fundamentally different from the Solar case (Christensen et al. 2009; Donati & Landstreet 2009). Similar to the dynamos thought to be working in planetary interiors, a distributed dynamo in stars that pervades the entire convection zone can potentially avoid many of the shortcomings of the flux-tube models (Berdyugina 2005).

Studies based on using direct numerical simulations to model distributed dynamos and cool spots have been rather disconnected: global dynamo models simulate the generation of large scale magnetic fields (e.g. Käpylä et al. (2012); Gastine et al. (2012); Brun et al. (2013)), while local simulations study the formation of cool spots in the presence of a prescribed magnetic field (e.g. Cheung et al. (2010); Brandenburg et al. (2011)). In this study we combine these two disparate approaches and produce magnetic field as well as dark spots in a single global simulation. (Also see Mitra et al. (2014) for a somewhat similar approach in a cartesian box simulation.)

2. Methods

We simulate thermal convection in a rapidly rotating spherical shell. The convection zone spans 5 density scale heights (density contrast ≈150). The bottom boundary of the simulation is at radius of $0.35R_{star}$, while the top boundary lies at a radial level few percent below the photosphere of a star. We use the MHD equations under the anelastic approximation (Lantz & Fan 1999) to model the sub-sonic flows in the interior of a star. The equations are solved using the MagIC code (Gastine & Wicht 2012) which uses spherical harmonics in horizontal and Chebyshev polynomials in the radial direction to decompose various quantities. The bottom and the top boundaries are stress free and insulating. The entropy is fixed on both boundaries.

3. Results

The control parameters of the simulation are such that convection is highly influenced by rotation almost throughout the convection zone. Top panel in Fig. 1 shows the radial velocity near the outer boundary of the simulation. The upwellings are broader while the downwellings are narrower. This asymmetry is a generic trait of convection in density stratified fluids. The convection cells are also aligned north-south near the equator due to the influence of rotation on convection.

A distributed dynamo operates in the bulk of the convection zone which generates an axial dipole dominant magnetic field configuration shown in the middle panel of Fig. 1. Due to the sweeping motion of the upwellings most of the magnetic flux lies in the narrow downwellings. The simulation frequently generates sizable patches of magnetic flux where the field strength is high enough to locally quench convection. Such regions have suppressed flow and hence reduced heat transfer efficiency. Occasionally the simulation also produces rather large patches (large as compared to the length scale of convection cells) of strong magnetic field. These large patches appear at high latitudes and are formed by the merger of sizable patches.

As show in the bottom panel of Fig. 1 the convective heat flux is reduced in the patches with strong magnetic flux, forming dark spots which are reminiscent of the sunspots and starspots. The convective heat flux is decreased by about 60% as compared to the mean surface heat flux in the big polar spot shown in Fig. 1. The dark spots formed in the simulation are also rather shallow and no heat flux quenching is observed at radial level 10% below the outer boundary of the simulation. The big dark spots formed in the simulation evolve slowly and maintain their identity for many 10s of rotations.

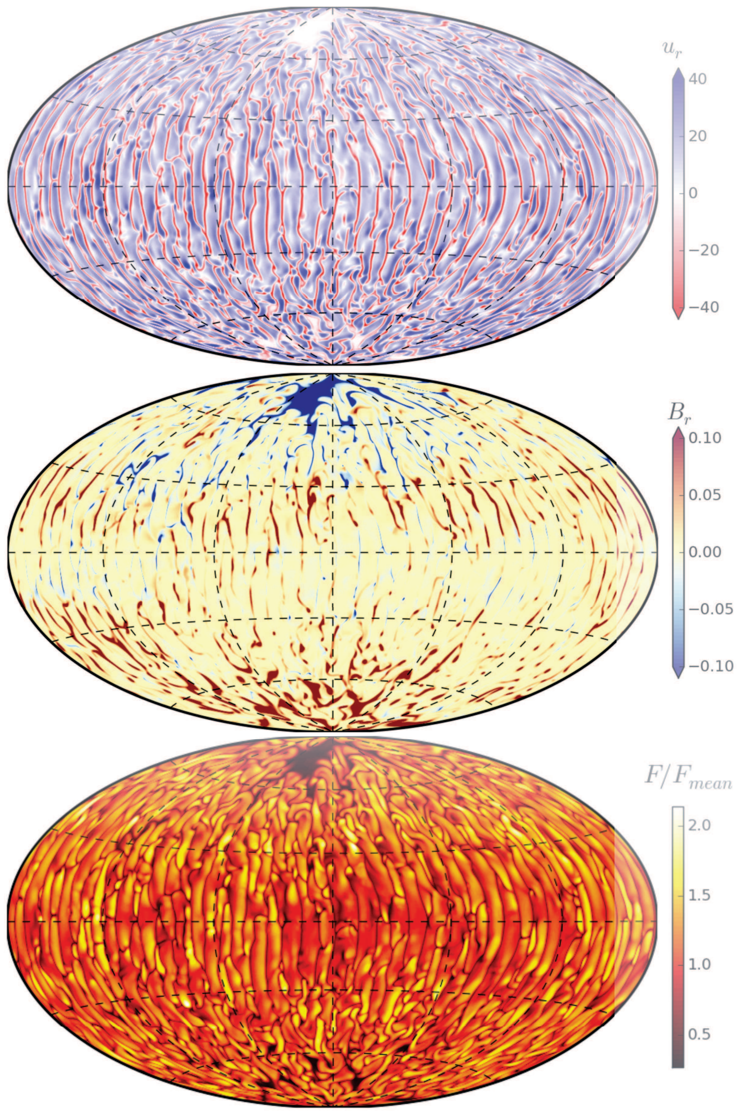

Figure .1: Radial velocity u_r (top panel) and radial magnetic field B_r (middle panel) close to the outer boundary of the simulation. The former is expressed in terms of the Reynolds number while the latter is normalized by equipartition field strength calculated using the volume averaged kinetic energy. Bottom panel shows the heat flux normalized by mean surface heat flux on the outer boundary of the simulation. Image from Yadav et al. (2014).

4. Discussion

What are the main ingredients which drive the formation of dark spots in the simulation described above? Computational constraints do not allow us to carry out an extensive parameter study to pin-point the main cause, but, based on some preliminary investigations, the following ingredients appear to be crucial. Rapid rotation is needed to drive a distributed dynamo in the convection zone which can generate strong magnetic fields. High density stratification in convection zone is also important because, in a *single* simulation, it allows the possibility of having rotation-dominated convection which drives the dynamo and near surface convection which is less influenced by rotation (due to faster flow speeds) and does not participate in magnetic field generation. In such setups near surface convection can be quenched by the magnetic field coming from deeper layers without affecting the dynamo mechanism. Dynamos with axial dipole dominant magnetic field configuration might be especially efficient at generating big dark spots: the magnetic field in such dynamo solutions is in general stronger than dynamos with multipolar magnetic fields (Gastine et al. 2012; Yadav et al. 2013a,b); the field at high latitudes is dominated by one polarity which allows the sizable dark spots to coalesce and form big dark spots, as seen in the simulation above. Interested reader is referred to Yadav et al. (2014) for more details about the simulation and results.

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