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Recurrent flux emergence from dynamo-generated fields

Jörn Warnecke[1,2] and Axel Brandenburg[1,2]

[1]Nordita, AlbaNova University Center,
Roslagstullsbacken 23, SE-10691 Stockholm, Sweden
email: joern@nordita.org

[2]Department of Astronomy, AlbaNova University Center,
Stockholm University, SE 10691 Stockholm, Sweden

Abstract. we investigate the emergence of a large-scale magnetic field. This field is dynamo-generated by turbulence driven with a helical forcing function. Twisted arcade-like field structures are found to emerge in the exterior above the turbulence zone. Time series of the magnetic field structure show recurrent plasmoid ejections.

Keywords. Sun: magnetic fields, Sun: coronal mass ejections (CMEs)

1. Introduction

The magnetic field at the visible surface of the Sun is known to take the form of bipolar regions and the field continues in an arch-like fashion. These formations appear usually as twisted loop-like structures. These loops can be thought of as a continuation of more concentrated flux ropes in the bulk of the solar convection zone. Twisted magnetic fields are produced by a large-scale dynamo mechanism that is generally believed to be the motor of solar activity (Parker 1979). One such dynamo mechanism is the α effect that produces a large-scale poloidal magnetic field from a toroidal one. In order to study the emergence of helical magnetic fields from a dynamo, we consider a model that combines a direct simulation of a turbulent large-scale dynamo with a simple treatment of the evolution of nearly force-free magnetic fields above the surface of the dynamo. In the context of force-free magnetic field extrapolations this method is also known as the stress-and-relax method (Valori *et al.* 2005). Above the solar surface, we expect the magnetic fields to drive flares and coronal mass ejections through the Lorentz force. In the present paper we highlight some of the main results of our earlier work (Warnecke & Brandenburg 2010).

2. The Model

The equation for the velocity correction in the Force-Free Model is similar to the usual momentum equation, except that there is no pressure, gravity, or other driving forces on the right-hand side, so we just have

$$\frac{\mathrm{D}\boldsymbol{U}}{\mathrm{D}t} = \boldsymbol{J} \times \boldsymbol{B}/\rho + \boldsymbol{F}_{\mathrm{visc}}, \tag{2.1}$$

where $\boldsymbol{J} \times \boldsymbol{B}$ is the Lorentz force, $\boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{B}/\mu_0$ is the current density, μ_0 is the vacuum permeability, $\boldsymbol{F}_{\mathrm{visc}}$ is the viscous force, and ρ is here treated as a constant the determines the strength of the velocity correction. Equation (2.1) is solved together with the induction equation. In the lower layer the velocity is excited by a forcing function

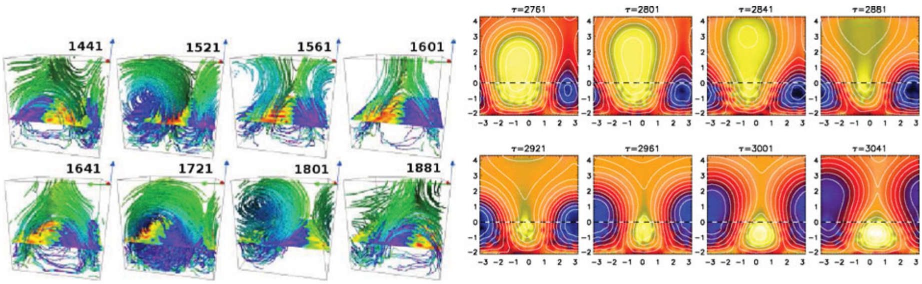

Figure 1. *Left panel*: Time series of arcade formation and decay. Field lines are colored by their local field strength which increases from pink to green. The plane shows B_z increasing from red (positive) to pink (negative). The normalized time τ is giving in each panel. *Right panel*: Time series of the formation of a plasmoid ejection. Contours of $\langle A_x \rangle_x$ are shown together with a color-scale representation of $\langle B_x \rangle_x$; dark blue stands for negative and red for positive values. The contours of $\langle A_x \rangle_x$ correspond to field lines of $\langle \boldsymbol{B} \rangle_x$ in the yz plane.The dotted horizontal lines show the location of the surface at $z = 0$. Adapted from Warnecke & Brandenburg (2010).

and the density is evolving using the continuity equation. The forcing function consists of random plane helical transversal waves with an average forcing wavenumber k_f.

3. Results

The magnetic field grows first exponentially and then shows subsequent saturation that is typical for forced turbulent dynamo action. In the turbulent layer the magnetic field reaches around 78% of the equipartition field strength, B_eq. The dynamo generates a large-scale field whose vertical component has a sinusoidal variation in y. After some time the magnetic field extends well into the exterior where it tends to produce an arcade-like structure, as seen in the left panel of Figure 1. The arcade opens up in the middle above the line where the vertical field component vanishes at the surface. This leads to the formation of anti-aligned field lines with a current sheet in the middle. The dynamical evolution is seen clearly in a sequence of field line images in the left hand panel of Figure 1, where anti-aligned vertical field lines reconnect above the neutral line and form a closed arch with plasmoid ejection above. This arch then changes its connectivity at the foot points in the sideways direction (here the y direction), making the field lines bulge upward to produce a new reconnection site with anti-aligned field lines some distance above the surface. Field line reconnection is best seen for two-dimensional magnetic fields, because it is then possible to compute a flux function whose contours correspond to field lines in the corresponding plane. In the present case the large-scale component of the magnetic field varies only little in the x direction, so it makes sense to visualize the field averaged in the x direction. The right panel of Figure 1 shows clearly the recurrent reconnection events with subsequent plasmoid ejection. The dynamics of the magnetic field in the exterior is indeed found to mimic open boundary conditions at the interface between the turbulence zone and the exterior at $z = 0$. In particular, it turns out that a twisted magnetic field generated by a helical dynamo beneath the surface is able to produce flux emergence in ways that are reminiscent of that found in the Sun.

References

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