Solar Cycle Variation of Magnetic Flux Ropes in a Quasi-Static Coronal Evolution Model

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Received: 12 November 2009 / Accepted: 24 March 2010 / Published online: 20 April 2010
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Abstract The structure of electric current and magnetic helicity in the solar corona is closely linked to solar activity over the 11-year cycle, yet is poorly understood. As an alternative to traditional current-free “potential-field” extrapolations, we investigate a model for the global coronal magnetic field which is non-potential and time-dependent, following the build-up and transport of magnetic helicity due to flux emergence and large-scale photospheric motions. This helicity concentrates into twisted magnetic flux ropes, which may lose equilibrium and be ejected. Here, we consider how the magnetic structure predicted by this model – in particular the flux ropes – varies over the solar activity cycle, based on photospheric input data from six periods of cycle 23. The number of flux ropes doubles from minimum to maximum, following the total length of photospheric polarity inversion lines. However, the number of flux rope ejections increases by a factor of eight, following the emergence rate of active regions. This is broadly consistent with the observed cycle modulation of coronal mass ejections, although the actual rate of ejections in the simulation is about a fifth of the rate of observed events. The model predicts that, even at minimum, differential rotation will produce sheared, non-potential, magnetic structure at all latitudes.

Keywords Coronal mass ejections, theory · Magnetic fields, corona · Magnetic fields, models · Solar cycle, models

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1. Introduction

The number of sunspots has long been known to vary with a period of about 11 years. Since the early 20th century it has been recognised that sunspots carry magnetic flux originating from the Sun’s interior. Once this magnetic flux emerges into the corona, it dominates both the structure and evolution of the plasma there. This is evidenced by 11-year variations in many phenomena, including solar flares (Aschwanden, 2005), prominences (d’Azambuja, 1955; Hansen and Hansen, 1975), X-ray flux (Pevtsov and Acton, 2001), coronal mass ejections (CMEs; Webb and Howard, 1994; Cremades and St. Cyr, 2007), and the solar wind (Richardson, Wang, and Paularena, 2001).

Despite the connection to observed phenomena, the coronal magnetic field cannot usually be measured directly due to the tenuous nature of the plasma, so only isolated measurements exist (e.g., Lin, Penn, and Tomczyk, 2000; Casini et al., 2003; Tomczyk et al., 2007). Usually, it must be extrapolated from the routinely observed magnetic field in the solar photosphere, perhaps using images of high-temperature loops to constrain the field topology. This topology is often found to contain non-zero electric currents (e.g. in X-ray sigmoids; Canfield, Hudson, and McKenzie, 1999), and extrapolation of such magnetic fields is not yet robust, even when limited to a single active region (De Rosa et al., 2009). On the global scale, which concerns us in this paper, it is usual to assume a current-free magnetic field (a potential field). This is uniquely determined in the corona given an observed radial component on the photosphere and vanishing horizontal components at an upper “source surface” (usually placed at $r = 2.5R_\odot$; Altschuler and Newkirk, 1969). Even the more realistic models that solve for MHD equilibria in the corona usually assume a potential magnetic field which is then perturbed to be consistent with a given thermodynamic structure and solar wind (Riley et al., 2006; Cohen et al., 2007). Whilst the potential-field model has been successful in describing certain large-scale aspects of coronal magnetic structure – such as the locations of coronal holes (Wang, Hawley, and Sheeley, 1996) – it does not include the development of currents and free magnetic energy that are needed to model solar eruptions. In fact, the highly sheared magnetic fields observed in long-lived filament channels all over the Sun (Martin, Bilimoria, and Tracadas, 1994) show that, even outside active regions, the assumption of a potential field can be inadequate.

As a first step toward understanding the structure of currents and magnetic helicity in the global corona, we have investigated an alternative model for the coronal magnetic field, based also on observational input of the photospheric magnetic field. In this model, the large-scale mean magnetic field in the corona evolves in time through a quasi-static relaxation, in response to flux emergence and to surface motions (van Ballegooijen, Priest, and Mackay, 2000; Yeates, Mackay, and van Ballegooijen, 2008; Yeates and Mackay, 2009b). The consequence is that, unlike in a sequence of potential-field extrapolations, current and magnetic helicity are generated in and transported through the corona. Flux cancellation above photospheric polarity inversion lines (PILs) then leads to the concentration of helicity in either sheared arcades or twisted magnetic flux ropes (through the mechanism described by van Ballegooijen and Martens, 1989). Comparison of the simulated magnetic field direction at these locations with observations of filament chirality has demonstrated that, despite its simplicity, the model is able to reproduce the general structure of the magnetic field at most of these locations (Yeates, Mackay, and van Ballegooijen, 2008).

In this paper, we use the quasi-static model to simulate the coronal magnetic field during six distinct periods over cycle 23. Our aim is to consider how the magnetic field structure predicted by this model varies over the 11-year solar activity cycle. We focus on a particular