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Large-scale transport of solar and stellar magnetic flux

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Abstract. Surface flux transport (SFT) models have been successful in reproducing how magnetic flux at the solar photosphere evolves on large scales. SFT modelling proved to be useful in reconstructing secular irradiance variations of the Sun, and it can be potentially used in forward modelling of brightness variations of Sun-like stars. We outline our current understanding of solar and stellar SFT processes, and suggest that nesting of activity can play an important role in shaping large-scale patterns of magnetic fields and brightness variability.

Keywords. Sun: activity, Sun: magnetic fields, stars: magnetic fields

1. Introduction

The transport of magnetic flux on the Sun is one of the few astrophysical phenomena that occurs in front of our eyes, thanks to synoptic observations of the line-of-sight magnetic field. At a given solar cycle, bipolar magnetic regions (BMRs) emerge with their dipole-moments showing a mean tilt angle with respect to the east-west direction, such that the leading polarities are closer to the equator than the trailing ones. The tilt angle exhibits a large scatter around its mean value of a few degrees. Following their emergence, BMRs are subject to differential rotation, meridional flow, and turbulent convective motions that disperse magnetic flux elements in a random-walk fashion, which is generally modelled as a two-dimensional diffusion problem (Leighton 1964, but see also Schrijver 2001). The diffusion occurs at the convective length scales of supergranulation, at a rate of about 250 $km^2\ s^{-1}$. For extensive reviews of SFT we refer the reader to Mackay & Yeates (2012) and Jiang *et al.* (2014a).

2. Flux transport on the Sun

The main motivation for SFT modelling has been to understand the surface physics relevant to the magnetic butterfly diagram of azimuthally averaged radial magnetic field. SFT has also been useful in constraining the boundary conditions of flux-transport dynamo models (Muñoz-Jaramillo *et al.* 2010, Cameron *et al.* 2012), as well as generating synthetic irradiance variations for the past solar activity (Dasi-Espuig *et al.* 2016), coronal field extrapolations (e.g. Nandy *et al.* 2018), and the evolution of the open magnetic flux shaping the heliosphere (Jiang *et al.* 2011).

When data-driven SFT models are compared with observations, several observed features are reproduced, such as the poleward plumes of signed magnetic flux, which eventually reverse the polar fields. Some missing pieces of the model have been incorporated recently, such as the observed tilt angle scattter (Jiang *et al.* 2014b) and inflows around active regions (Jiang *et al.* 2010, Cameron & Schüssler 2012). In rare occasions, BMRs can emerge across the equator, or with a negative or abnormally large tilt angle

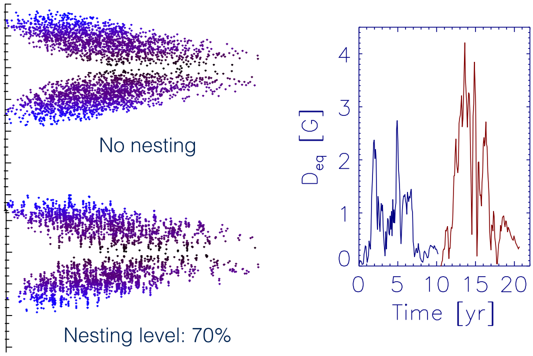

Figure 1. Cycle variation of the equatorial dipole moment for random BMR longitudes (first decade, blue; right panel), and for two-dimensional nesting (second decade, red) with a probability of 70%, each corresponding to the relevant butterfly diagram on the left panel.

nearby the equator. As Cameron *et al.* (2013) demonstrated, one such event can change the hemispheric magnetic flux by 60% (see also Jiang *et al.* 2015).

In an SFT model based on random-walk flux dispersal, Schrijver (2001) considered nesting of emerging BMRs for individual flux emergence events, with a probability of 40%. To demonstrate the importance of nesting in shaping the large-scale field geometry, we show in Fig. 1 a comparison of the global equatorial dipole moment, D_{eq} for two SFT simulations, over an activity cycle. As opposed to random BMR longitudes, a strong degree of nesting (70%) in both longitude and latitude amplifies the fluctuations of D_{eq}, reaching levels comparable to observations (Wang 2014). This is because the probability for a nonzero equatorial dipole-moment contribution from ensembles of nested BMRs from both hemispheres becomes higher when BMRs tend to emerge into active nests.

3. Flux transport on late-type stars

Application of the SFT model to other cool stars is useful to better assess possible drivers of stellar brightness and spectral variability. As an example, a long-standing question concerning the morphology of starspots is whether the observed starspots are monolithic or conglomerates. As demonstrated by Işık *et al.* (2007), the corresponding spot lifetimes can be very different in these two cases, which should be considered when interpreting observational relationships between spot sizes and lifetimes. Another example is the effect of meridional flow speeds that are much faster than solar values, leading to strong polar fields with intermingled polarities on rapidly rotating active stars (Holzwarth *et al.* 2006).

Later, Işık *et al.* (2011) developed a model combining a deep-seated $\alpha\Omega$ dynamo, flux-tube rise and SFT to demonstrate how surface fields evolve over cycle timescales. For stars of type G2V, K0V, and K1IV, they showed that the observed surface variations can be very different from the internal dynamo, owing to a combination of rotational effects on rising flux, convection-zone geometry and SFT. Scaling an SFT model with coronal feedback to higher levels of activity, Lehmann *et al.* (2018) found a good match between their simulations and the observed 3D geometry of large-scale magnetic fields on fast-rotating Sun-like stars.

The effect of nesting considered in Sect. 2 can be very important for stellar variability in rotational timescales. A comprehensive simulation framework including this effect has been developed by Işık *et al.* (2018), who presented SFT models driven by a Sun-like butterfly diagram at the base of the convection zone, and the emergence latitudes and tilt angles calculated using flux-tube simulations. Figure 2 shows pole-on snapshots of radial

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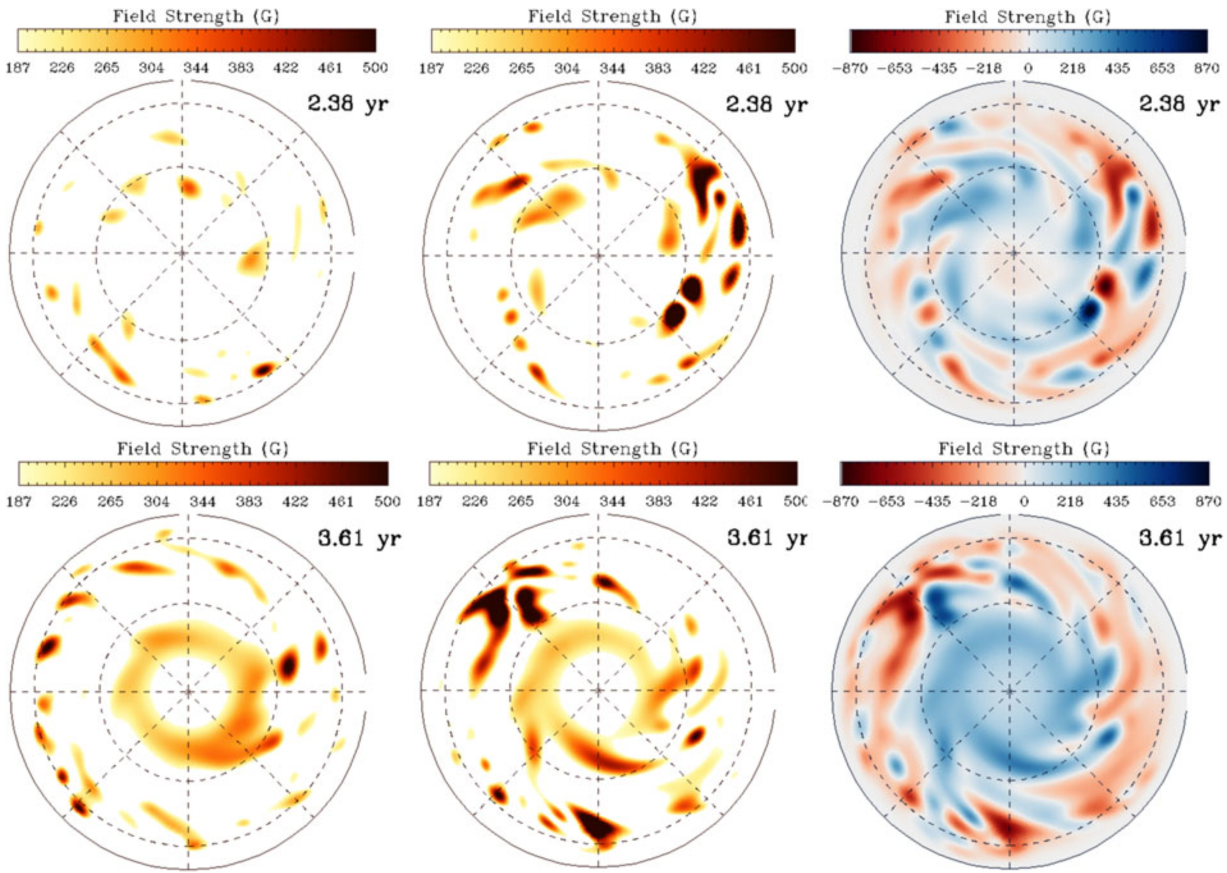

Figure 2. Pole-on views of a Sun-like model with a rotation rate and BMR emergence rate eight times higher than for the Sun, at two different phases of the activity cycle. First and second columns show unsigned field above a threshold to represent starspots, without and with nesting as in Fig. 1, respectively. The last column shows the signed-field snapshots corresponding to those on the second column.

magnetic field for a Sun-like star rotating eight times faster and more active than the Sun. With nesting, the spot distributions become highly non-axisymmetric as compared to random longitudes. This can affect the rotational modulation of activity indicators.

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