Astronomy & Astrophysics manuscript no. 3459 May 30, 2005
(DOI: will be inserted by hand later)

Research note
Is there a phase constraint for solar dynamo models?

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Received; accepted

Abstract. The spatio-temporal relationship between the sign of the observed radial component of the magnetic field at the solar surface and the sign of the toroidal field as inferred from Hale's polarity rules for sunspots is usually interpreted as signifying the phase relation between the poloidal and the toroidal magnetic field components involved in the solar dynamo process. This has been taken as a constraint for models of the solar dynamo. This note draws attention to the fact that the observed phase relation is naturally and inevitably produced by the emergence of tilted bipolar regions and flux transport through surface flows, without any necessity of recourse to the dynamo process. Consequently, there is no constraint on dynamo models resulting from the observed phase relation.

Key words. Sun: magnetic fields— Sun: activity — MHD

The relationship between the sign of the observed longitude-averaged radial magnetic field component in the photosphere, B_r, and the sign of the azimuthal field, B_ϕ, as inferred from the polarities of the following and preceding parts of sunspot groups (according to Hale's rules), is taken by many authors as an important constraint for models of the solar dynamo (e.g., Stix 1976; Yoshimura 1976; Parker 1987; Schmitt 1993; Schlichenmaier & Stix 1995; Rüdiger & Brandenburg 1995; Bonanno et al. 2002; Ossendrijver 2003; Brandenburg 2005).

Stix (1976) considered Mount Wilson magnetograph data for the period 1959–1973. Taking B_r positive in the outward radial direction and B_ϕ positive in the direction of solar rotation, he found the relation $B_r B_\phi < 0$ to hold in the sunspot zones below 35 degrees heliolatitude. In a time-latitude diagram, the average radial field shows 'butterfly wings' that closely match the corresponding sunspot pattern. The 'phase relation', $B_r B_\phi < 0$, then means that the average radial field has the same polarity as the preceding parts of the active regions emerging during the same half cycle (Stenflo 1972; Howard & Labonte 1981; Schlichenmaier & Stix 1995, see also the upper panel of Fig. 1).

When taking the phase relation as a constraint for solar dynamo models, the tacit assumption is made that the observed radial field at the surface actually represents the poloidal field component resulting from the (deep-seated) dynamo process. However, there is evidence that this assumption is not necessarily valid. The observed evolution of sunspots and active regions indicate that the corresponding magnetic flux is dynamically disconnected from its subsurface roots within a few days after emergence (Fan et al. 1994; Schrijver & Title 1999; Schüssler 2005; Schüssler & Rempel 2005). In fact, the large-scale evolution of the observable magnetic flux at the solar surface is reproduced quite well by the so-called flux-transport models, which simulate the passive advection of the radial magnetic field by the near-surface flows of supergranulation (described as a turbulent diffusion process), differential rotation, and meridional circulation (e.g., Wang et al. 1989; Schrijver 2001; Mackay et al. 2002; Baumann et al. 2004). The flux input in such models is provided by the emergence of bipolar magnetic regions, taken either directly from the observational data or assumed at random locations, but keeping the basic statistical properties of active regions (tilt angle according to Joy's law, latitude drift of the activity belt, Hale's polarity rules). As an illustration, Fig. 1 shows a comparison of the result from the flux-transport model of Baumann et al. (2004) with the actual time-latitude diagram of the (longitudinally averaged) observed surface field. The input for the flux-transport simulation has been derived from the RGO and NOOA/USAF SOON sunspot data (Baumann et al. 2005, in preparation).

It turns out that all such flux-transport models reproduce the observed phase relation, $B_r B_\phi < 0$, in low latitudes, i.e., they all show that the longitude-averaged radial field predominantly has the same polarity as the leading parts of the active regions emerging throughout the same half cycle (see also Fig. 3 of Baumann et al.

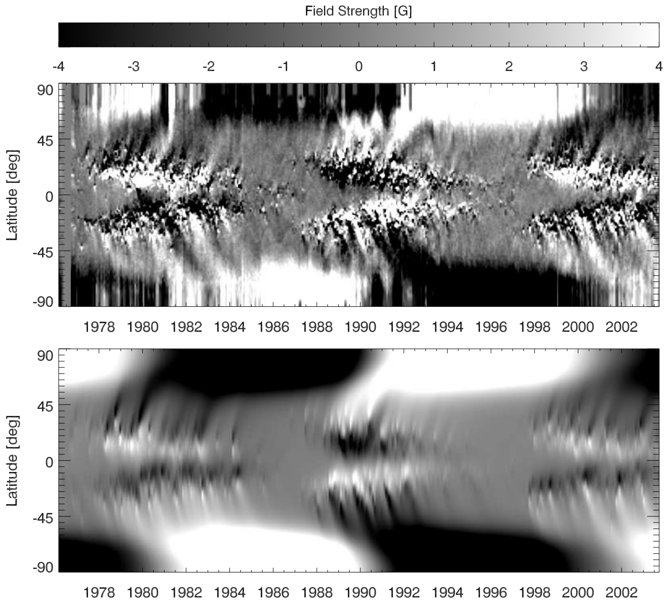

Fig. 1. Comparison between observed and simulated time-latitude plots (butterfly diagram) of the longitudinally averaged radial magnetic field at the solar surface. *Upper panel:* Evolution of the observed field, based upon NSO Kitt Peak synoptic maps (courtesy D. Hathaway). *Lower panel:* Simulation for the same period of time with the flux transport code of Baumann et al. (2004). The emerging active regions have been determined from the RGO and NOOA/USAF SOON sunspot data. In both cases, the grey scale is saturated at 4 G to better bring out the low-latitude fields. The dominance of the leading-polarity flux in low latitudes (corresponding to the phase relation $B_r B_\phi < 0$) due to the tilt angle of the emerging active regions is reproduced by the flux-transport simulation, which does not involve any assumption about the working of the dynamo. The phase relation therefore cannot be taken as a constraint on dynamo models.

2004). No assumption about the dynamo and, in particular, about the phase relation between the poloidal and toroidal field components in the dynamo process is required to obtain this result. In fact, the basic assumption underlying these models is that the large-scale radial surface flux results exclusively from the local emergence of active regions. The dominance of the leading-polarity flux in low latitudes arises from the tilt of the bipolar regions: the leading parts are nearer to the equator, so that they dominate, on average, the low latitudes. This effect is amplified by the latitude gradient of the poleward meridional flow speed, which leads to a preferential poleward transport of the (opposite-polarity) following parts of the bipolar regions. The same result is found in the complimentary model of Choudhuri & Dikpati (1999), who consider longitude-averaged quantities in the meridional (r, θ) plane: the poloidal field resulting from tilted bipolar regions reproduces the observed phase relationship with the toroidal field component, in the absence of any assumptions concerning the dynamo process.

As a side remark, we note that in the class of Babcock-Leighton-type advection-dominated dynamos (e.g., Dikpati & Charbonneau 1999) the tilt of the bipolar magnetic regions provides the source of the poloidal field for the *next* (half) cycle. In that sense, this kind of dynamos automatically reproduces the observed phase relation, but that does not exclude other dynamo models that do not rely on the tilt of active regions as the source for the poloidal field. Note also that Joy's law for the tilt angle of bipolar magnetic regions is explained completely independent from any dynamo model by the action of the Coriolis force on rising flux loops (e.g., D'Silva & Choudhuri 1993; Fan et al. 1994; Caligari et al. 1995).

Several authors have pointed out that the tilt angle of active regions leads to a dominance of leading polarity flux in the sunspot latitudes (e.g., Stenflo 1972; Howard & Labonte 1981; Wang et al. 1991; Choudhuri & Dikpati 1999). The message that this provides a natural explanation for the phase relation independent of the dynamo process apparently has not reached the majority of the dynamo community. It is the purpose of this note to draw attention to this result and thus prevent the exclusion of dynamo models because of an inappropriate constraint.

Acknowledgements. Ingo Baumann kindly provided Fig. 1.

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