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Origin of solar magnetic variability

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Abstract. Solar variability on all observationally accessible temporal and spatial scales is intimately connected with the variation of the solar magnetic field and its interaction with the non-stationary flow patterns in the convection zone. Theoretical models for the various manifestations of solar magnetic variability are addressed. Especially, the long-term variability of the global solar cycle and the underlying dynamo mechanism are discussed in detail.

Key words. Magnetohydrodynamics (MHD) – Sun: interior – Sun: activity – Sun: magnetic field – Sun: sunspots

1. Introduction

Coronal mass ejections and flares as well as the variable wave and particle radiation lead to space weather and space climate (Scherer et al. 2005). Changes of the total and the spectral irradiances as well as the modulation of galactic cosmic rays by the interplanetary magnetic field may effect climate on Earth (Friis-Christensen et al. 2000; Wilson 2000; Pap & Fox 2004).

All these effects and more are due to the solar magnetic field. It is generated by a dynamo process driven by convection and rotation and varies on many time scales.

Variations on minutes to days are caused by the interplay of the magnetic field with convection. Active regions evolve on a time scale of days to months, while global flux transport in the surface layers acts on months to years. The most important time scale of solar magnetic variability is the 11-year activity cycle, which is modulated on decades to centuries, sometimes interrupted by grand minima (e.g. Schüssler & Schmitt 2004; Schüssler 2005). I concentrate on the cycle and its modulation in what follows.

2. The solar cycle

The solar cycle is most prominently displayed by the number of sunspots in time, which exhibits the variable amplitudes, lengths and shapes of the cycles (Fig. 1). At the beginning of a cycle, sunspots appear at middle latitudes, in the course of a cycle they occur closer and closer to the equator, leading to the famous butterfly diagram (Fig. 2). Sunspots usually appear in pairs, bipolar active regions, with leading and following spots inclined to east-west direction (Joy's law). Hale's polarity rules manifest that the Sun's magnetic field is mainly antisymmetric with respect to the equator and has a period of about 22 (2×11) years. A recent overview of sunspot cycle properties has been given by Usoskin & Mursula (2003), while the cycle properties deduced from Zürich sunspot number (Waldmeier 1961) and group sunspot

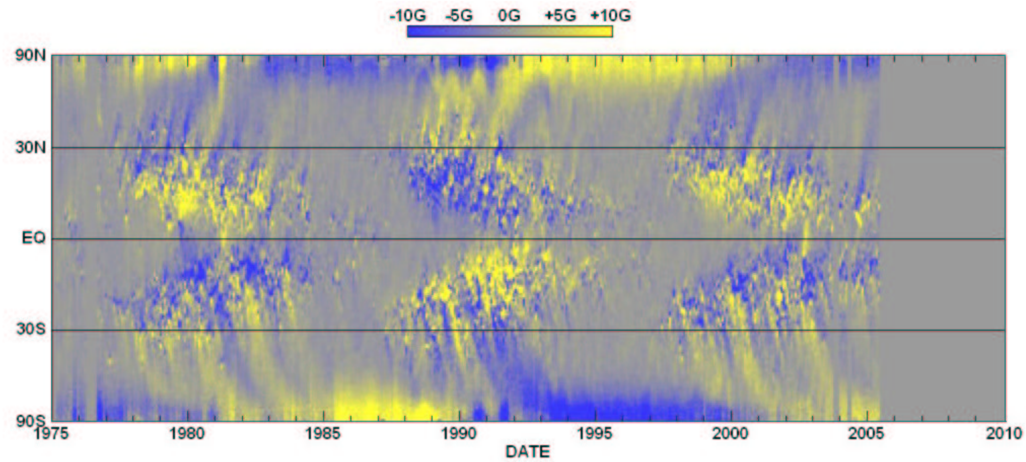

Fig. 2. Time-latitude diagram of the longitudinally averaged magnetic field in the solar photosphere for the last three activity cycles (courtesy D. Hathaway, NASA). The emergence of magnetic flux in active regions generates the familiar butterfly wings in lower latitudes. The combined effect of diffusion, differential rotation and meridional circulation lead to the magnetic flux transport to high latitudes and thus cause the reversals of the polar magnetic fields in phase with the activity cycle (Baumann et al. 2005).

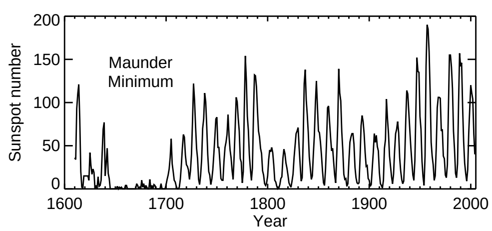

Fig. 1. Relative sunspot number since 1610. Besides the 11-year solar cycle, the sunspot record shows century-scale modulation and periods of low activity. The most prominent of these is the Maunder minimum in the 17th century, when only few sunspots appeared for a period of about 60 yr.

number (Hoyt & Schatten 1998) records have been compared by Hathaway et al. (2002). Solanki et al. (2005) studied moments of the latitudinal distribution of the sunspot cycles and found remarkable correlations between them.

It is generally believed that the cyclic evolution of the large-scale magnetic field of the Sun is the consequence of dynamo action, i.e. the conversion of kinetic into magnetic energy by inductive effects of fluid motions in an electrically conducting fluid. Recent reviews are by Ossendrijver (2003), Rüdiger & Arlt (2003) and Charbonneau (2005)

Three processes are thought to play a major role in the solar dynamo process. The first is differential rotation which generates toroidal magnetic field by shearing poloidal magnetic field. The internal rotation of the Sun is determined by helioseismology and reveals a layer of strong radial rotational shear straddling the transition between the radiative zone and the convection zone, the so-called solar tachocline (Schou et al. 1998).

Secondly, helical motions, be it either by convection or by hydromagnetic instabilities in the rotating Sun, are most crucial for a dynamo. By helical motions magnetic field lines are bent into twisted loops, which reconnect by turbulent diffusion and regenerate the poloidal field. In mean-field theory this process is often called the α-effect (Krause & Rädler 1980).

Both, differential rotation and helical motions form the basis of the solar dynamo. The first generates a toroidal field by winding up a poloidal field which in turn is regenerated in opposite direction by helical motions. In mean-field theory the solar dynamo is of $\alpha\Omega$-type (Fig. 3).

A third process, global meridional circulation, is not inducing magnetic field, but transports magnetic flux, at the surface towards the poles and deeper down equatorwards, thereby crucially influencing the interplay of toroidal and poloidal flux generation by the main two dynamo processes.

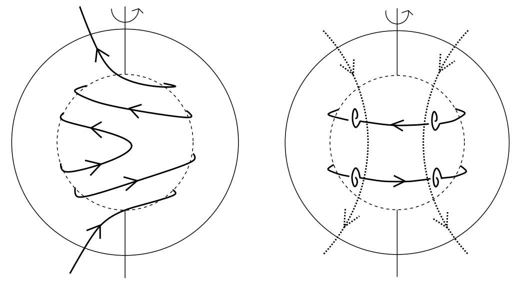

Fig. 3. Sketch of an $\alpha\Omega$-type solar dynamo. Left: Differential rotation (Ω-effect) in the tachocline winds up the toroidal field from a poloidal field. Right: Helical motions (α-effect) bend magnetic field lines into twisted loops which reconnect by enhanced diffusion and regenerate the poloidal field in opposite direction.

3. Dynamo models

The classical solar dynamo was thought to operate in the convection zone (Steenbeck & Krause 1969; Stix 1976). This picture faced many difficulties and in the 1980's the importance of the overshoot region below the convection zone in amplifying and storing magnetic field was realized (Spiegel & Weiss 1980) and led to the development of overshoot layer dynamos. Later, combinations of both, the interface dynamo and the flux transport dynamo, were introduced.

The main difficulties of convection zone dynamos are that the magnetic field is highly intermittent (Proctor & Weiss 1982). In order to obey the polarity rules these flux concentrations must have strong field strengths, of the order of 10^5 G in the lower part of the convection zone, in order to avoid strong twisting by the convective motions (Caligari et al. 1995). Such strong fields are however magnetically buoyant and can not be stored in the convection zone for sufficient long times for the dynamo to generate the field (Moreno Insertis et al. 1992). Furthermore, the internal rotation law, deduced from helioseismology, does not show significant radial gradients of the angular velocity in the convection zone proper, which are needed for the equatorward migration of $\alpha\Omega$-dynamo waves.

The buoyancy and storage problem is released by placing the bulk of the solar magnetic field in the overshoot layer below the solar convection zone (Ferriz Mas & Schüssler 1993, 1995). Furthermore the reduced magnetic diffusivity in the overshoot layer leads to dynamo periods of the order of the solar cycle. Additionally, helioseismology reveals strong radial gradients of angular velocity. The strong field strength requires a dynamic α-effect which is provided by hydromagnetic instabilities (Schmitt 1984, 2003; Brandenburg & Schmitt 1998; Dikpati & Gilman 2001a).

Disadvantages of thin layer dynamos are many overlapping wings and no clear separation of dipolar and quadrupolar parity selection. Furthermore, the radial gradient of angular velocity in the overshoot region is largest near the poles while sunspots emerge at low latitudes. This is circumvented either by an α-effect concentrated near the equator, which is the case for magnetic buoyancy instabilities (Ferriz Mas et al. 1994; Schmitt 2003), or by an equatorward flux transport, e.g. by meridional circulation (see Dikpati & Gilman 2001b).

Overshoot layer dynamos were presented by Schmitt (1993), Prautzsch (1993), Rüdiger & Brandenburg (1995) and Dikpati & Gilman (2001b).

Parker (1993) proposed a combination of both models, with differential rotation and most of the flux in the less turbulent overshoot layer and the classical α-effect in the turbulent convection zone. Detailed models of this kind were developed by Charbonneau & MacGregor (1997) and Zhang et al. (2004).

Another class of dynamo models was first proposed by Durney (1995) and evaluated by Choudhuri et al. (1995) and Dikpati &

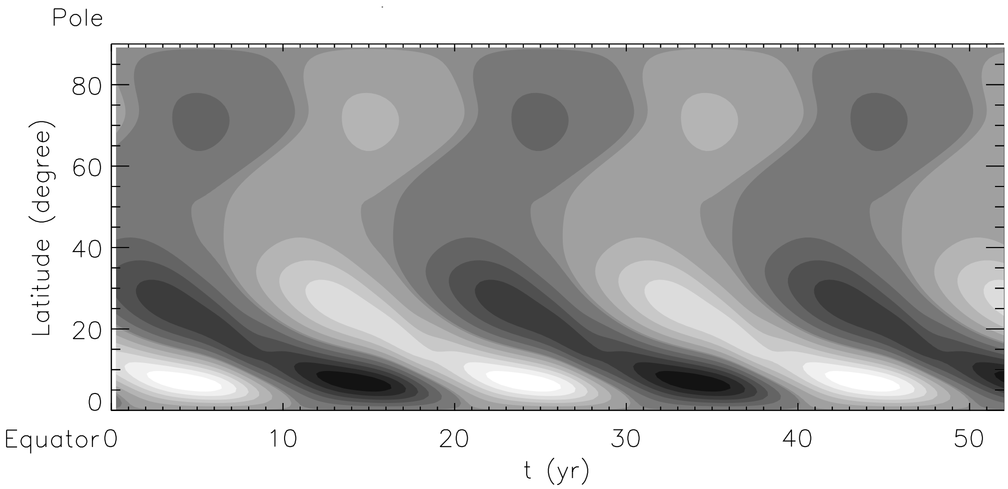

Fig. 4. A flux-transport overshoot layer dynamo after Dikpati & Gilman (2001b). Shown is the toroidal magnetic field in a time-latitude diagram, which due to an equatorward mean flow exhibits strong butterfly wings near the equator.

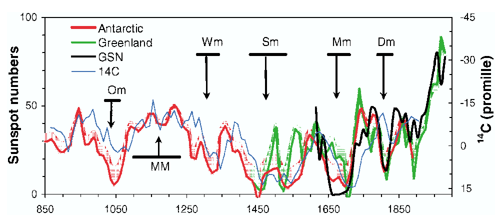

Fig. 5. Time series of the 11-yr smoothed sunspot number as reconstructed from ^{10}Be concentration in ice cores from Antarctica and Greenland. The thick black curve shows the accordingly time-averaged observed group sunspot number since 1610 and the thin curve gives the ^{14}C concentration in tree rings, corrected for the variation of the geomagnetic field. The horizontal bars with attached arrows indicate the times of great minima and maxima. The temporal lag of ^{14}C with respect to the sunspot number is due to the long attenuation time for ^{14}C. After Usoskin et al. (2003).

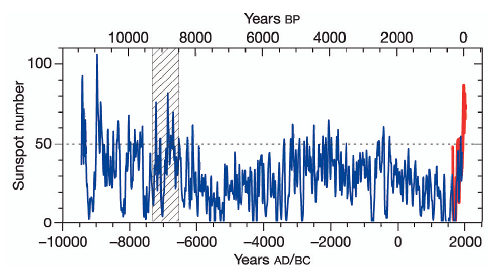

Fig. 6. Reconstructed 10-yr averaged sunspot number from ^{14}C data of tree rings since 9500 BC and group sunspot number since 1610. The level of solar activity during the past 70 yr is exceptional and the previous period of equally high activity occurred more than 8000 yr ago. After Solanki et al. (2004).

Charbonneau (1999), among others. Here the regeneration of the poloidal field is through the tilt of decaying bipolar active regions in near-surface layers, an idea going back to Babcock (1961) and Leighton (1969). The rotational shear for the generation of the toroidal field is in the tachocline and the interaction of both separated dynamo layers is through the transport of magnetic flux by meridional circulation.

An attractive model is that of Dikpati & Gilman (2001b), an overshoot layer dynamo combined with meridional circulation. This results in solar-like butterfly diagrams and the deep-seated α-effect prefers dipolar parity in contrast to the near-surface located Babcock-Leighton picture (Fig. 4).

4. Long-term variations and grand minima

Long-term variations and grand minima are mainly caused by variations of the dynamo process. The modulation of differential rotation, stochastic fluctuations of the α-effect, the variation of meridional circulation and on-off intermittency have been studied. I first summarize the observations.

The various cycles are individually strong and there is a weak anticorrelation between cycle amplitude and cycle duration. Even-numbered cycles are usually, but not always, followed by stronger odd-numbered cycles (Gnevyshev & Ohl 1948). In the 17th century activity was particulary low, the so-called Maunder Minimum (Eddy 1976), with only a few sunspots mainly in the southern hemisphere (Ribes & Nesme-Ribes 1993). There are some indications by ^{10}Be data that the cycle may have continued at a low level (Beer et al. 1998).

By tracing back solar activity through the modulation of cosmogenic isotopes (Stuiver & Braziunas 1989; Beer et al. 1990; Beer 2000) we know of many more grand minima irregularly occurred in the past (Fig. 5).

By calibrating ^{14}C data into sunspot numbers, Solanki et al. (2004) recently showed, that one has to go back more than 8000 yr into the past to find a Sun similar active as it has been in the last 70 yr (Fig. 6).

I now come to the interpretation of the long-term variability. Weiss & Tobias (2000) review the backreaction of the induced magnetic field onto differential rotation. They found regularly occurring periods of reduced magnetic activity reminiscent of grand minima. They further found that sometimes the parity may change after a grand minimum from dipolar to quadrupolar and vice verse and in between one observes asymmetric cycles.

In a different approach Hoyng (1993, 1996) realized that the α-effect may considerably fluctuate as a result of turbulent convection. By varying the strength of the fluctuations Hoyng et al. (1994) found periods of strong and weak activity as well as asymmetries with respect to the equator. In their model the amplitude correlates with the phase shift similar to the solar case as does the asymmetry between northern and southern hemisphere which is naturally largest during cycle minima (Ossendrijver et al. 1996) (Fig. 7).

Charbonneau & Dikpati (2000) considered a variable meridional circulation. In this model stronger cycles last longer, contrary to the solar case. With the same code they also varied the α-effect and the cycle amplitude and length are then in anticorrelation, as in the case of the Sun.

Another scenario was proposed by Schmitt et al. (1996). They studied an overshoot layer dynamo with an α-effect driven by a flux tube instability (Ferriz Mas et al. 1994). This magnetic buoyancy instability and thus dynamo action sets in only when the field strength exceeds a lower threshold (Ferriz Mas & Schüssler 1993, 1995). When the field strength falls below this threshold, which in the case of the Sun is several 10^4 G, dynamo action stops, resulting in grand minima. Through the interplay with magnetic fields in the convection zone, the dynamo can be switched on again, leading to the continuation of regular cycles. Fig. 8 shows a typical result of such on-off intermittent dynamo solutions (Schüssler et al. 1997; Schmitt et al. 1998).

The interplay between the dynamo in the overshoot region and magnetic fields in the convection zone, by magnetic buoyancy in the upward direction and by downdrafts in the downward direction, was extended in a 2D model by Ossendrijver (2000) with similar results.

5. Summary and conclusions

The solar magnetic field varies on a large range of time and spatial scales. This has consequences for space weather and terrestrial climate. The long-term variation of the magnetic field is due to variations of dynamo processes. As long as there is no accepted solar dynamo

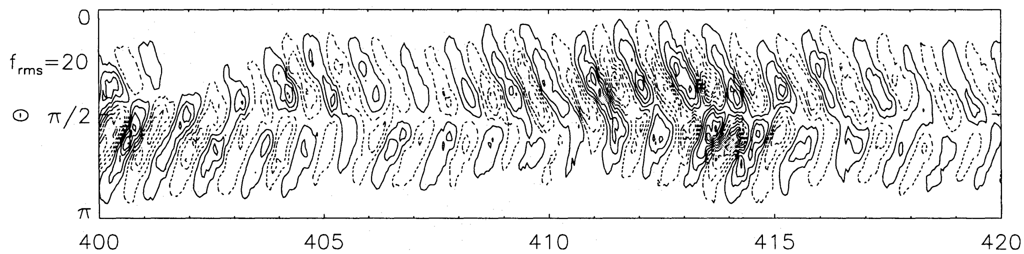

Fig. 7. Contour plot of the toroidal magnetic field versus time in dynamo periods. Random fluctuations of the α-effect lead to a modulation of the cycle amplitudes and an asymmetry between the hemispheres. After Ossendrijver et al. (1996).

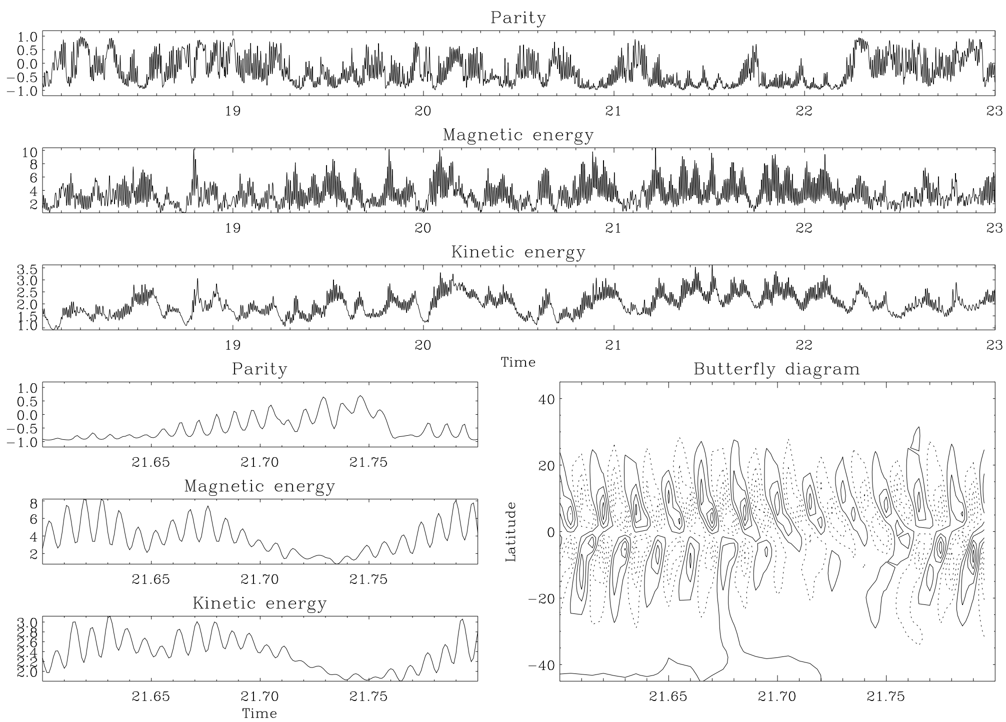

Fig. 8. Time evolution of an on-off intermittent dynamo with a lower threshold in field strength for dynamo action, a fluctuating source term and, as limiting nonlinearity, a back-reaction of the magnetic field on the differential rotation. The dominant dipolar parity during the oscillatory phases give way to a mixed parity in grand minima. Typically, a strong north-south asymmetry develops during such phases.

model it is difficult to pin down the responsible process.

For making progress in this direction new helioseismic observations and inversions of the internal velocity field as well as comprehensive numerical modeling of the dynamo are required. These are difficult and challenging tasks.

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