SUNSPOT CYCLE 24: IS SUN ENTERING A GRAND MINIMUM?

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ЦИКЛ 24: СОЛНЦЕ ВХОДИТ В ГРАНДИОЗНЫЙ МИНИМУМ?

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Во время периодов „нормальной” активности солнечное динамо работает в умеренно адвективно-доминированном режиме в верхней части конвективной области и в диффузионно-доминированном режиме в основании конвективной области. Это можно установить из корреляций между скоростями поверхностной и глубокой меридиональной циркуляции и амплитудой максимума следующего цикла солнечных пятен. Во время больших максимумов солнечной активности динамо переключает в другом режиме. В последнем цикле солнечных пятен корреляции между скоростями циркуляции и максимумом солнечных пятен изменились, но это еще не является началом большого минимума, так как не наблюдается дополнительная особенность – резкое уменьшение скорости поверхностной циркуляции и отношения скоростей поверхностной и глубокой циркуляции.

According to the classical flux-transport solar dynamo mechanism, the sunspot cycle is produced by an oscillation between toroidal and poloidal components, similar to the oscillation between kinetic and potential energies in a simple harmonic oscillator [Parker, 1955]. The upper part of the Sun, the convection zone, stretching down to 0.7 solar radii, rotates differentially, with the rotation rate highest at the equator and decreasing with increasing latitude, while the radiation zone beneath rotates rigidly. Due to the interaction with convection, the magnetic field in the convection zone concentrates in bundles of field lines – magnetic field tubes. At the tachocline, the thin boundary between the convection and radiation zones, the differential rotation stretches the magnetic field tubes in east-west direction, thus transforming the poloidal field into toroidal. When the toroidal magnetic field is strong enough, the field tube becomes buoyant and emerges, piercing the solar surface in two spots with opposite magnetic polarities – sunspots.

The mechanism for poloidal field regeneration was proposed by Babkock [1961] and mathematically developed by Leighton [1969]: Due to the Coriolis force acting on the emerging field tube, the bipolar pair of spots is tilted with the leading (in the direction of solar rotation) spot at lower heliolatitude than the trailing spot (“Joy’s law”). Late in the sunspot cycle the sunspot pairs appear at low latitudes and the leading spots can diffuse across the equator where their flux is canceled by the opposite polarity flux of the leading spots in the other hemisphere. The flux of the trailing spots and of the remaining sunspot pairs is carried toward the poles. Opposite leading and trailing polarity flux cancels on the way, but as there is excess trailing polarity flux, the net flux reaching the poles has the polarity of the trailing sunspots. It first cancels the polar field of the previous solar cycle and then accumulates to form the poloidal field of the next cycle with polarity opposite to the one in the preceding cycle.

In the original Babkock-Leighton mechanism, the flux is carried to the poles by diffusion-like process caused by supergranular convection [Leighton, 1964]. Wang et al. [1991] suggested that an additional factor transporting the flux is a large-scale meridional circulation with a surface flow toward the poles where the poloidal flux accumulates and sinks to the base of the solar convection zone, and a counterflow there which carries it back to low latitudes to be transformed into toroidal flux and to emerge as the sunspots of the nest solar cycle.

Theory predicts that the amplitude and period of the sunspot cycle are determined by the speed of the deep meridional circulation (Wang et al., 2002; Hathaway et al., 2003; 2011; Karak and Choudhuri, 2011), while the regime of operation of the solar dynamo is ruled by the relative importance of the advection by meridional circulation and turbulent diffusion, determining which of the two processes is more efficient in carrying the flux to the poles at the surface and to the equator at the tachocline [Yeates et al. 2000; Hotta and Yokoyama, 2010; Choudhuri, 2011] – in other words, which time scale is shorter: the advection time-scale $\tau_{adv\_}$= L/V or the diffusion time-scale $\tau_{dif} = L^2/\eta$.

At the surface $\tau_{adv\_surf} = L_{surf}/V_{surf}$, and $\tau_{dif\_surf} = L_{surf}^2/\eta_{surf}$ where L_{surf} is the distance from sunspot latitudes to the poles, η_{surf} is the diffusivity in the upper part of the solar convection zone, and V_{surf} is the speed of the surface poleward circulation. If $\boldsymbol{\tau_{adv\_surf} < \tau_{dif\_surf}}$ (**advection dominated regime**), the meridional circulation carries the flux to the poles before it can reach there by means of random supergranular diffusive walk, and in this regime a faster poleward flow means less time for the leading polarity flux to diffuse across the equator and to cancel with the leading polarity flux in the opposite hemisphere, so more leading polarity flux will be carried to the poles, canceling on the way part of the trailing-polarity flux. Less uncanceled trailing-polarity flux will reach poles to form the polar field of the next cycle, and a weaker toroidal field will be generated at the base of the convection zone from this weaker polar field [Wang et al., 2002]. Jiang et al. [2007] have calculated that the regime in the upper part of the convection zone is advection dominated if $\eta_{surf} \sim 10^{11}$ cm^2/s.

If $\boldsymbol{\tau_{dif\_surf} < \tau_{adv\_surf}}$ (**diffusion dominated regime**), a significant part of the poloidal field radially diffuses down before it can be carried to the poles by the meridional circulation [Hotta and Yokoyama, 2010], and all of the toroidal field is generated from the flux which has shortcircuited the merifional circulation. Only a small part of the trailing polarity flux reaches high latitudes before being diffused, and reverses the polar field there. In this regime a shorter time for transport of the flux to the poles means a shorter time for diffusion of the flux and therefore a stronger poloidal field. According to Hotta and Yokoyama [2010], the regime in the upper part of the convection zone is diffusion dominated if $\eta_{surf} \sim 2–9.10^{12}$ cm^2/s and $\eta_{surf}/V_{surf} > 2.10^9$ cm.

An **intermediate regime** is also possible, when the speed of the surface meridional circulation is not high enough for an advection dominated regime, and the diffusivity is not high enough for a diffusion dominated regime. In this regime, a part of the flux diffuses to the tachocline before reaching the poles, short-circuiting the meridional circulation, and another part makes the full circle to the poles, down to the base of the convection zone and equatorward to sunspot latitudes. Jiang et al. [2007] estimated that this regime occurs when η_{surf} $\sim 1–2.10^{12}$ cm^2/s, and suggested that in this case the polar field at sunspot minimum and the strength of the next sunspot maximum may be correlated not because the polar field is the source of the next sunspot maximum, but because both of them independently arise from the poloidal field produced by the Babcock–Leighton process in the mid-latitudes. In this case, the sunspot maximum will be a superposition of the toroidal field generated by the flux diffused to the tachocline at midlatitudes, and the one which reached the poles and sunk there to the base of the convection zone, so the solar cycle will be double peaked [Georgieva, 2011].

Similarly, there are two possible regimes of operation of the solar dynamo at the base of the solar convection zone: “diffusion dominated” and “advection dominated” [Yeates et al., 2008]. If the diffusion is high, higher speed of the deep circulation leads to a higher sunspot maximum because it means less time for diffusive decay of the poloidal field during its equatorward transport before it can be transformed into toroidal field and hence a higher cycle amplitude. If the diffusive decay is not so important, a higher circulation speed leads to lower cycle amplitude because there is less time to generate toroidal field in the tachocline through which the magnetic fields are swept at a faster speed.

In order to determine in which regime the Sun operates, it is necessary to know the cycle-to-cycle variations of the speed of the surface and deep meridional circulation and the diffusivity in the upper and lower parts of the solar convection zone, and to find their correlation with the magnitude of the polar field and the amplitude of the sunspot maximum. There are no long-term observations of these quantities, but we have evaluated them from geomagnetic data [Georgieva and Kirov, 2011]. A negative correlation is found between V_{surf} and both the magnitude of the polar field (Fig.1a) and the amplitude of the next sunspot maximum (Fig.1b, note the reversed scale of V_{surf}) meaning that in the upper part of the convection zone the Sun operates in advection-dominated regime.

Fig. 1c presents the values of the diffusivity in the upper part of the solar convection zone η_{surf} and the ratio η_{surf}/V_{surf}, and demonstrates that advection does not dominate strongly, therefore in the upper part of the convection zone the dynamo operates in intermediate regime. In the lower part of the convection zone, the correlation between the speed of the deep meridional circulation and the following sunspot maximum is positive (Fig. 1d), therefore the regime there is diffusion dominated.

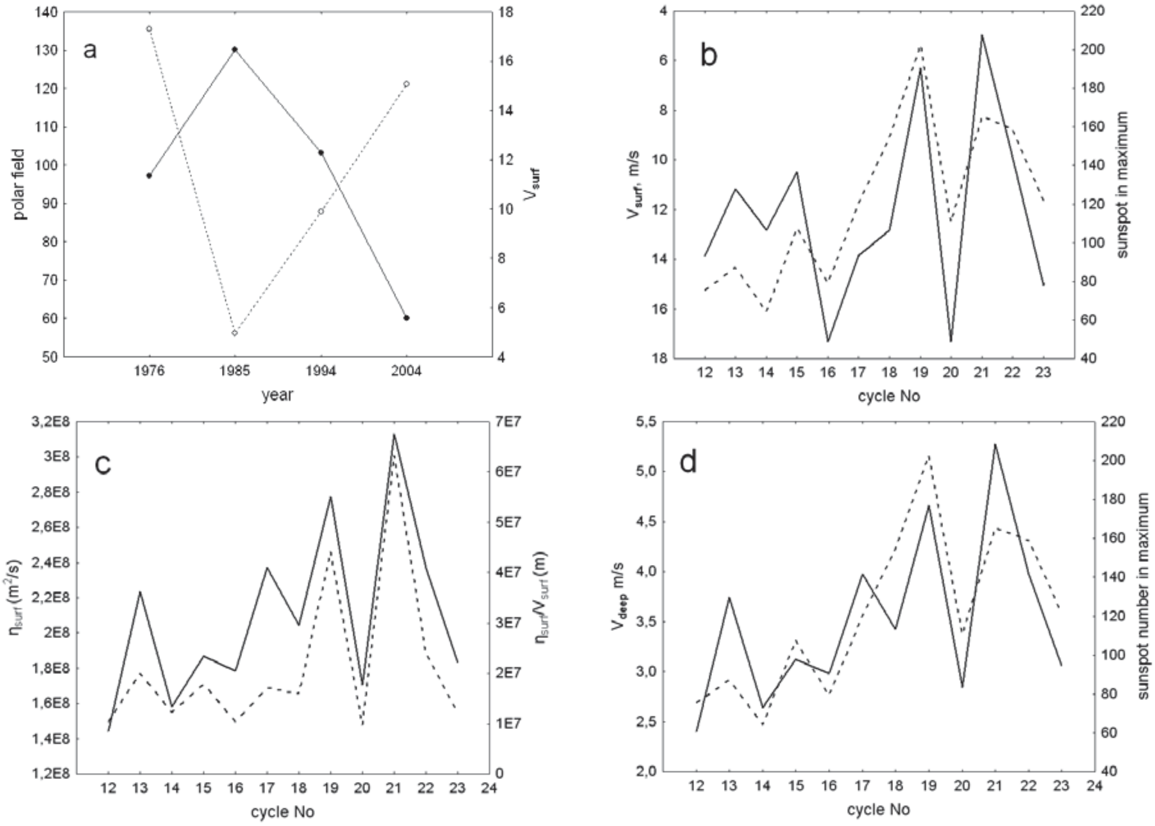

Fig. 1. (**a**) polar field in the last four sunspot minima (solid line) and V_{surf} preceding it (dotted line); (**b**) V_{surf} (solid line) and the amplitude of the next sunspot maximum (dashed line); (**c**) diffusivity η_{surf} (solid line) and the ratio η_{surf}/V_{surf} (dashed line); (**d**) V_{deep} (solid line) and the amplitude of the next sunspot maximum (dashed line).

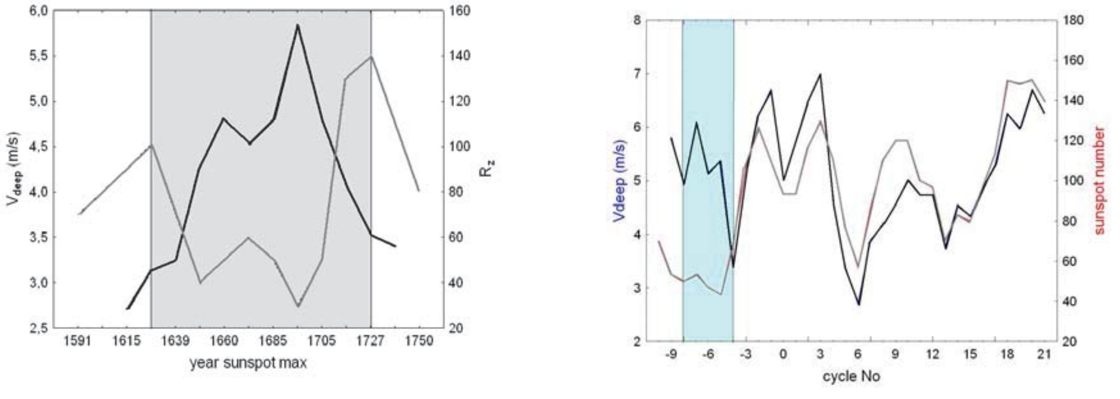

Fig. 2. V_{deep} (black) and the amplitude of the following sunspot max (grey) based on ^{10}Be (*left*) and ESAI (*right*) reconstructions. The period of the Maunder minimum is shaded.

Based on ^{10}Be data for the period of the Maunder minimum [Beer et al., 1998] and Sporer minimum [McCracken et al., 2004; Caballero-Lopez et al., 2004], group sunspot number Rz [Hoyt and Schatten, 1998], sunspot reconstructions of Schove [1979, 1983], and ESAI database [Nagovitsyn et al., 2004], we calculated the meridional circulation during periods of grand minima (Fig. 2).

In contrast to "normal" periods, the correlation between V_{deep} and the amplitude of the next sunspot maximum is negative in grand minima, both based on data from ^{10}Be (Fig. 2a) and ESAI (Fig. 2b). Therefore, periods of grand minima are marked by a change in the regime of operation of the solar dynamo.

A change in the correlations between the speed of the meridional circulation, the polar field and the amplitude of the next sunspot maximum, is recorded in sunspot cycle 24 (Fig. 3). Does this mean that the Sun is entering a period of a grand minimum?

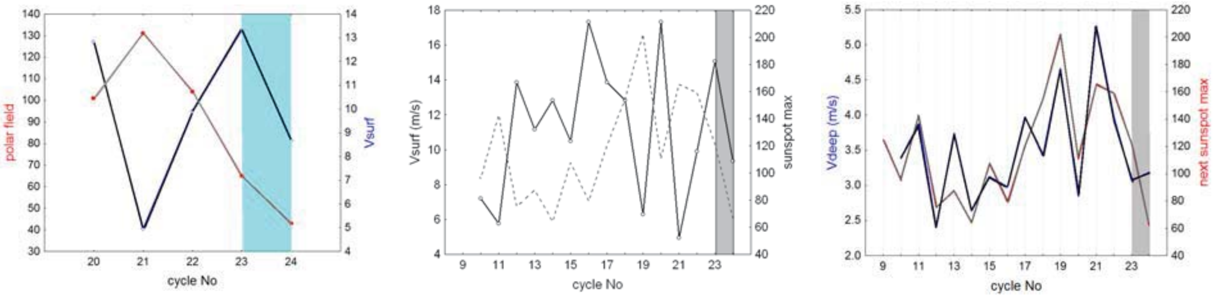

Fig. 3. Relation between Vsurf and the polar field (*left*), Vsurf and the amplitude of the next sunspot max (*middle*) and Vdeep and the amplitude of the next sunspot max (*right*).

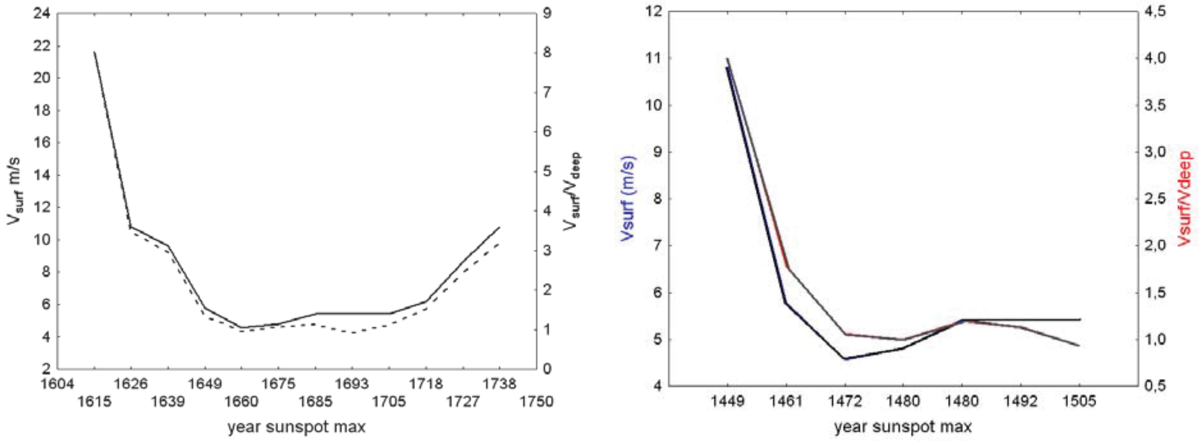

Fig. 4. Speed of the surface meridional circulation and the ratio between the speeds of the surface and deep circulation during the Maunder minimum (*left*) and Sporer minimum (*right*).

In both the Maunder and Sporer minima, a characteristic feature was not only the reversed correlations between the speed of the circulation and the amplitude of the next cycle, but also the sharp drop in the speed of the surface meridional circulation, and of the ratio of the speeds of the surface and deep circulations which falls to 1 (Fig. 4). In cycle 24 this ratio is about 3. Therefore, there are some indications that the Sun is heading toward a grand minimum, but such a grand minimum has not yet started.

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