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NORTH-SOUTH ASYMMETRY OF SUNSPOT ACTIVITY DURING THE MAUNDER MINIMUM

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ABSTRACT. An important key to studying the impact of solar activity variations on the Earth's climate is the Maunder Minimum (late 17th century), during which extremely little sunspots were observed. Applying the rare event analysis method to these observations led the researchers to conclude that the appearance of sunspots during the Maunder minimum had a weak amplitude 22-year cycle. The concept of continuity of magnetic cycles at this time is also confirmed by measurements of cosmogenic radionuclides in natural terrestrial archives. Therefore, today it is believed that during the Maunder Minimum, the cyclic magnetic activity of the Sun did not stop, although the amplitude of the cycles was quite low. In the αΩ dynamo model, this may be due to the fact that the magnitude of the magnetic induction of the toroidal field, excited by radial differential rotation in the solar convection zone (SCZ), at this time did not reach the threshold value required for lifting magnetic power tubes to the solar surface (nonlinear dynamo mode). Possible physical mechanisms describing the suppression of the dynamo process at time intervals, when no sunspots were observed, are analysed. A scenario for explaining the north-south asymmetry of magnetic activity during the Maunder Minimum is proposed. A key role in the proposed scenario is played by the special nature of the internal rotation of the Sun, revealed in the helioseismological experiments. According to helioseismology data, the SCZ is naturally divided into polar and equatorial domains with opposite signs of the radial angular velocity gradient. In addition, the radial angular velocity gradient penetrates into the deep layers of the stable radiant zone below the SCZ. It is shown that, taking into account these helioseismology data, the αΩ dynamo excites two harmonics (dipole and quadrupole) of the toroidal magnetic field in the SCZ, which cyclically change their direction. The αΩ dynamo excites two harmonics (dipole and quadrupole) of the toroidal field in the RMS, which cyclically change their direction. At the same time, the deep Ω effect in the radiant zone creates the toroidal field of stationary orientation. The summary toroidal magnetic field (the dynamo-field of the SCZ + the field of the radiant zone) rising to the Sun's surface due to magnetic buoyancy may contribute to the north-south asymmetry in sunspot activity.

Key words: sunspots, the Sun's magnetic cycle, the convection zone, differential rotation, dynamo, the radiant zone, helioseismological data.

АНОТАЦІЯ. Важливим ключем до вивчення впливу варіацій сонячної активності на клімат Землі є мінімум Маундера (кінець XVII століття), під час якого спостерігалося надзвичайно мало сонячних плям. Застосування методу аналізу рідкісних подій до цих спостережень призвело дослідників до висновку, що появі сонячних плям у мінімумі Маундера був притаманний слабкий за амплітудою 22-річний цикл. Концепція безперервності магнітних циклів у цей час також підтверджується вимірюваннями космогенних радіонуклідів у природних наземних архівах. Тому сьогодні вважається, що впродовж мінімуму Маундера циклічна магнітна активність Сонця не припинялася, хоча амплітуда циклів була досить низькою. У моделі αΩ-динамо це може бути пов'язано з тим, що величина магнітної індукції тороїдального поля, збудженого радіальним диференціальним обертанням у сонячній конвективній зоні (СКЗ), у цей час не досягла порогового значення, необхідного для підйому магнітних силових трубок на поверхню Сонця (нелінійний режим динамо). Проаналізовано можливі фізичні механізми, що описують пригнічення процесу динамо в інтервали часу, коли сонячних плям не спостерігалося. Запропоновано сценарій для пояснення північно-південної асиметрії магнітної активності впродовж мінімуму Маундера. Ключову роль у запропонованому сценарії відіграє особливий характер внутрішнього обертання Сонця, виявлений в геліосейсмологічних експериментах. Згідно з даними геліосейсмології СКЗ природно поділена на полярні і екваторіальні домени з протилежними знаками радіального градієнта кутової швидкості. Крім того, радіальний градієнт кутової швидкості проникає у глибинні шари стабільної променистої зони нижче СКЗ. Врахувавши ці дані показано, що αΩ-динамо збуджує дві гармоніки (дипольну та квадрупольну) тороїдального поля в СКЗ, які циклічно змінюють свій напрямок. Водночас глибинний Ω-ефект у променистій зоні створює тороїдальне поле стаціонарної орієнтації. Сумарне магнітне тороїдальне поле (динамо-поле СКЗ + поле променистої зони), що піднімається до поверхні Сонця завдяки магнітній плавучості, може сприяти північно-південній асиметрії активності сонячних плям.

Ключові слова: сонячні плями, магнітний цикл Сонця, конвективна зона, диференційне обертання, динамо, промениста зона, геліосейсмологічні дані.

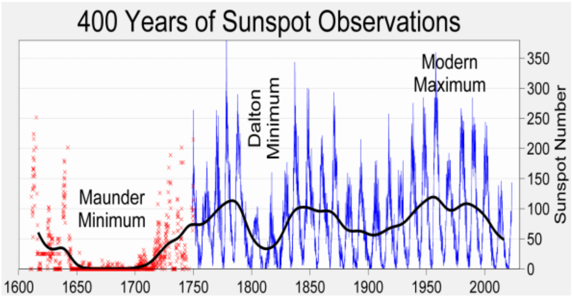

Figure 1: Long-term variations in solar activity.

The Maunder Minimum was a period of long-term decrease in the number of sunspots from approximately 1645 to 1715 (Fig. 1). This was first noted by F. Spörer (1887) while processing the observational data of R. Wolf (1868). Spörer's work was soon summarized by E. Maunder (1894) and Clerke A. M. (1894).

For a long time, the anomaly of solar activity did not arouse the keen interest of researchers. And only almost a century later, interest in the problem was revived by John Eddy (1976), who published a number of additional evidence regarding the sharp weakening of the solar activity in the period 1645–1715, calling it the Maunder Minimum.

(In honor of the couple Annie (1868–1947) and Edward (1851–1928) Maunder, who studied archives of solar observations on changes in the location of sunspots on the solar surface over time). According to Maunder calculations, only about 50 sunspots were observed during this period instead of the usual 40-50 thousand. The decrease in solar activity during the Maunder period was later confirmed by analysis of the radionuclides ^{10}Be (in trees) and ^{14}C (in glaciers) whose origin is associated with the penetration of cosmic rays into the Earth's atmosphere. Using the rare event analysis method during these observations, Sokoloff (2004) concluded that the appearance of sunspots during the Maunder Minimum had a weak amplitude 22-year cycle. The concept of the continuity of magnetic cycles is also confirmed by measurements of cosmogenic radioisotope proxies ^{10}Be and ^{14}C in natural terrestrial archives. Therefore, it is generally accepted that during the Maunder Minimum, the cyclic magnetic activity of the Sun did not stop, although the amplitude of the cycles was quite low (Wang & Sheeley, 2003). The most widespread belief among researchers is that the solar magnetic cycle is triggered by the $\alpha\Omega$ dynamo process (Vainshtein, Zeldovich & Ruzmaikin, 1980). For the $\alpha\Omega$ dynamo model, the Maunder Minimum explanation may be the fact that the magnitude of the magnetic induction of the toroidal field, excited by the radial differential rotation in the SCZ, did not reach the threshold value necessary for the lifting of the magnetic force tubes to the solar surface (nonlinear dynamo mode) at this time. Research over the past decade has shown that modern dynamo models can reproduce the Maunder Minimum under specific initial conditions. It can be assumed, for example, that the absence of sunspots at this time is mainly due to changes in the field configuration and its latitudinal and radial redistribution, rather than a decrease in the

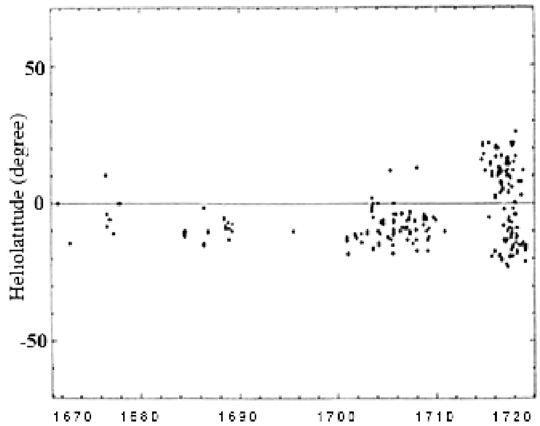

Figure 2: Butterfly diagram of sunspot, Paris archives: 1670-1719 (Sokoloff & Nesme-Ribes, 1994).

magnetic field amplitude itself (Pipin, Sokoloff & Usoskin, 2012). Eddy, Gilman &Trotter (1976) processed observational data on sunspot displacements across the solar disk. It was found that 20 years before the onset of the Maunder Minimum, the latitudinal differential rotation was the same as in the modern era. However, it is important that later (in the initial phase of the Minimum), the equatorial velocity became 3-5% higher, and the latitudinal gradient of angular velocity increased three times. If we assume that these changes were accompanied by a decrease in the radial gradient of angular velocity due to the redistribution of angular momentum, then the magnitude of the magnetic induction of the toroidal field excited by this radial differential rotation could not reach the threshold value required in dynamo models for the lifting of magnetic force tubes to the solar surface. The presence of long-term suppression of the dynamo process is often explained in terms of the α effect, which may contain a fluctuation part associated with chaotic turbulent motions (Ossendrijver, 2000), leading to irregular large minima (Brandenburg &Spiegel, 2008).

A very important feature of the solar activity during the Maunder Minimum was its strong north-south asymmetry (Fig. 2), when sunspots were observed mainly only in the southern hemisphere of the Sun.

Sokoloff & Nesme-Ribes (1994) suggest that this asymmetry can be interpreted within the framework of the nonlinear $\alpha\Omega$-dynamo theory. It has been shown that sunspot activity results from the action off a nonlinear rotation on a general magnetic field exhibition two mixed-parity solutions: a dipole and a quadrupole component. One mixed-parity solution is relevant to modern Schwabe cycles while the other could account for peculiar sunspot activity during the Maunder Minimum.

We suggest that the observed north-south asymmetry of sunspot surface magnetism may be related to the north-south asymmetry of the structure of the deep magnetic field of the Sun. Therefore, it is necessary to look for ways to detect this asymmetry. To explain the phenomenon, we in the paper (Krivodubskij, 2021) proposed a dynamo scenario in which the superposition of the cyclic dynamo-component of the toroidal field of the SCZ and the stationary toroidal field of the radiant zone may lead to

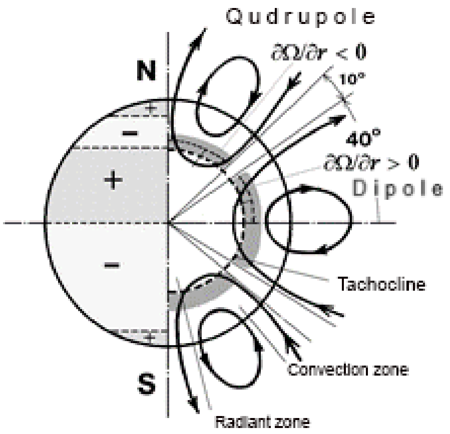

Figure 3: The structure of the global magnetic field excited by the $\alpha\Omega$ dynamo mechanism in the deep layers of the solar convection zone near the tachocline.

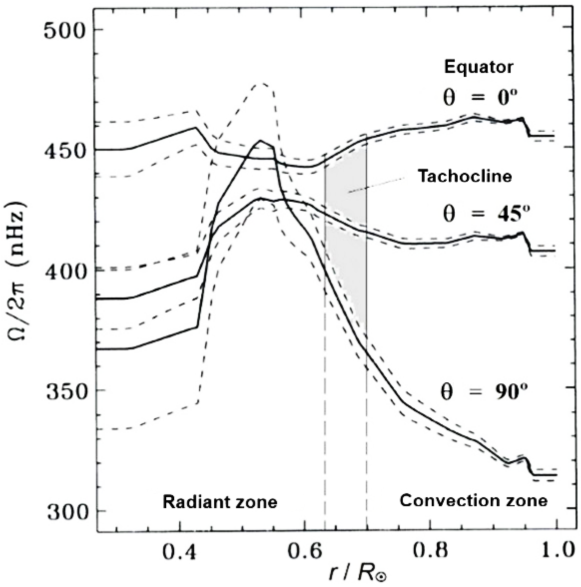

Figure 4: Radial profiles of the Sun's internal rotation velocity for three heliolatitudes θ, $\Omega/2\pi$ is the rotation frequency in nanohertz, $r/R_\odot$ is the relative heliocentric radius. It is relevant that $\partial\Omega/\partial r \neq 0$ in the radiant zone.

a predominance of the intensity of sunspot formation in one of the hemispheres of the Sun.

A key role in the proposed scenario is played by the special mode of the Sun's internal rotation, revealed as a result of helioseismological experiments. According to helioseismological data, the SCZ is divided into polar and near-equatorial regions with opposite signs of the radial angular velocity gradient $\partial\Omega/\partial r$ (Howe, 2009). If we take into account helioseismological data on $\partial\Omega/\partial r$, the $\alpha\Omega$ dynamo excites two harmonics of the toroidal field in the SCZ (including the tachocline). The first harmonic is a dipole (polar region $\partial\Omega/\partial r > 0$), the second is a quadrupole (near-equatorial region $\partial\Omega/\partial r < 0$) (Fig. 3). These dynamo toroidal magnetic harmonics change their direction with the period of the solar cycle.

It is relevant that the radial angular velocity gradient $\partial\Omega/\partial r$ penetrates into the deep layers of the stable radiant zone (Howe, 2009), below the SCZ and the tachocline (Fig. 4).

The radial gradient of the angular velocity $\partial\Omega/\partial r$ acts on the primary poloidal magnetic field, and thereby excites a toroidal magnetic field of constant direction in time (deep Ω effect of the radiant zone). This second toroidal component penetrates to the SCZ due to magnetic buoyancy. Then the summary toroidal field in the SCZ will consist of two components: variable (the dynamo-field of the SCZ) and stationary (the field rising from the radiant zone).

Conclusion. The first toroidal magnetic component (which consists two dynamo harmonics) is excited by the dynamo process in the convection zone. This component ***cyclically changes its direction (polarity)***. The second toroidal magnetic component is excited by deep Ω effect in the radiant zone. This component ***has a constant direction in time***. The deep magnetic component, rising to the convective zone, can lead here to a predominance of the summary toroidal magnetic field in one of the hemispheres of the Sun. The summary toroidal field, when rising onto the solar surface, can contribute to the north-south asymmetry of the sunspot formation process. Thus, continuous "feeding" of the dynamo process in the solar convection zone by additional toroidal flow emanating from the deep radiant zone can lead to the north-south asymmetry of the sunspot distribution on the surface, which was characteristic of the Maunder Minimum.

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