EVOLUTION OF CHANGES IN THE STRUCTURE OF THE SOLAR CORONA WITH THE PHASE OF SOLAR

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Abstract: *The structure of the solar corona is investigated in relation to the dynamics of the heliospheric current layer (HCL) during the 25th Schwabe-Wolf cycle of solar activity, using a series of images of the solar corona taken during the total solar eclipse of April 8, 2024, observed from Kerrville, Texas, USA. A relationship is sought in the distribution of the radial component of coronal structures (at a height above 2.5 solar radii). The conclusion reached earlier by other authors that the configuration of the HCS determines the main structural features of the white corona is confirmed.*

ЕВОЛЮЦИЯ НА ПРОМЕНИТЕ В СТРУКТУРАТА НА СЛЪНЧЕВАТА КОРОНА С ФАЗАТА НА СЛЪНЧЕВАТА АКТИВНОСТ

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Ключови думи: *Форма на слънчевата корона, хелиосферен токов слой, цикличност на слънчевата активност*

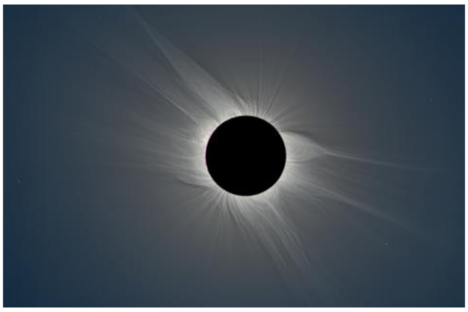
Резюме: *Изследвана е структурата на слънчевата корона, свързана с динамиката на хелиосферния токов слой (ХТС) по време на 25-ия цикъл на Швабе-Волф на слънчевата активност, използвайки серия от снимки на слънчевата корона, направени по време на пълното слънчево затъмнение на 8 април 2024 г., наблюдавано от гр. Кервил, щат Тексас, САЩ. Потърсена е връзка в разпределението на радиалния компонент на коронални структури (на височина над 2,5 слънчеви радиуса). Потвърждава се заключението, до което са стигнали по-рано и други автори, че конфигурацията на ХТС определя основните структурни характеристики на бялата корона.*

Introduction

More than 40 years ago, the idea was proposed that a collection of large helmet-shaped coronal rays forms a closed belt around the Sun, and that this belt is the base of the heliospheric current layer (see, for example, [1]). It is known that the heliospheric current layer (HCL) divides the solar space into two parts with opposite (away from and towards the Sun) directions of the interplanetary magnetic field. A detailed justification of the idea that the helmet-shaped radiation belt is identical to the base of the HCL is provided in [2], but the analysis carried out there is statistical in nature. Observations of several total solar eclipses (1932, 1991, 2012) have provided a unique opportunity to directly compare the structure of the corona with the orientation of the heliospheric layer.

The shape of the corona changes with the phase of the 11-year solar cycle. Figure 1 shows a schematic representation of typical coronal shapes for the minimum and maximum periods of the 11-year solar cycle, according to canonical concepts in solar physics.

At minimum activity (Figure 1a), the corona has two systems of helmet-shaped rays ("fans"), elongated along the equator, and in the north and south, systems of short rays, the so-called polar brushes, are observed (TSE - 2006).



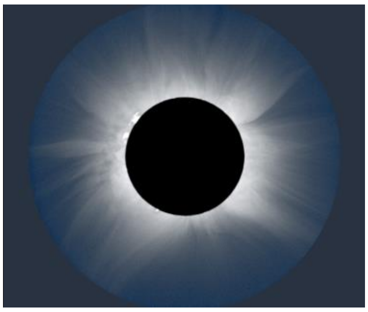
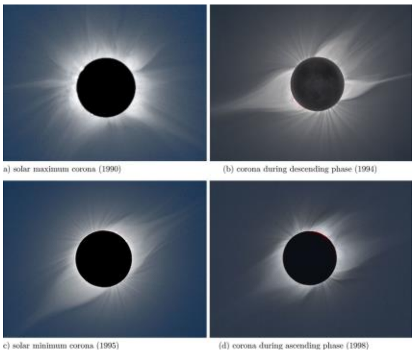


Fig. 1 a

Fig. 1 b

At maximum activity (Figure 1b), the helmet-shaped rays are distributed relatively evenly throughout the solar limb (TSE – 1990). During the transition from minimum to maximum activity, the appearance of the corona, according to generally accepted concepts, should gradually evolve from one extreme form to another.

The concept of the relationship between the solar corona and the heliospheric coronal current layer, developed in [2], allows us to approach the evolution of coronal shapes from a new perspective. At the minimum of the 11-year cycle, the HCL is located close to the plane of the solar equator, and an observer on Earth should see the base of the HCL practically as an edge. This determines the characteristic shape of the “minimum” corona. During other periods of the 11-year cycle, the inclination of the HCL to the equator varies widely, up to 90° at the maximum of the cycle, and its orientation relative to the observer can be arbitrary. This, in particular, explains the variety of coronal shapes during total solar eclipses (Figure 2, a, b).



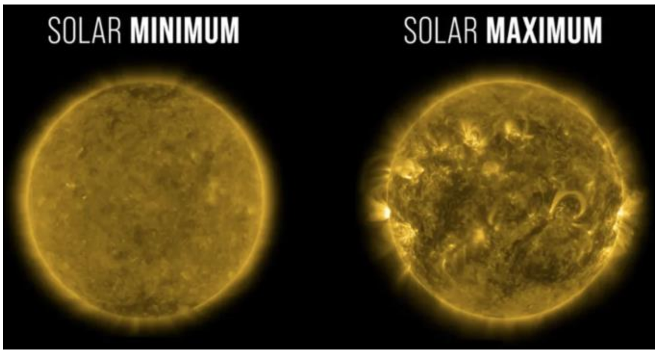


Fig. 2 a

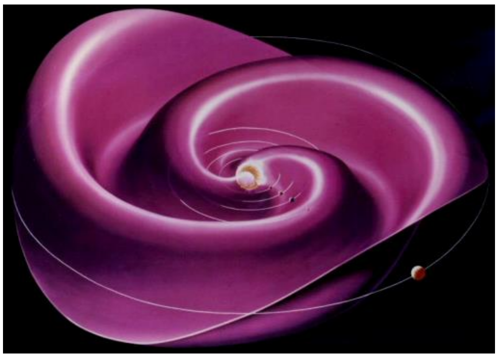
Fig. 2 b

Images from NASA's SDO satellite (Fig. 2b) show the appearance of the Sun during solar minimum (left, December 2019) compared to solar maximum (right, May 2024).

In certain cases, the heliospheric layer is tilted towards the equator, but oriented along the line of sight, i.e., edge-on to the observer. In such a position, a completely unusual pattern from a canonical point of view should be observed: a "minimal" corona tilted towards the equator. However, since the orientation of the heliospheric layer can be arbitrary, and total solar eclipses on Earth are rare, the probability of observing such a pattern is low. A similar situation occurred during the eclipses of August 31, 1932, and July 11, 1991 (also in [2]).

Heliospheric current layer (HCL)

The heliospheric current layer is a surface in the Solar System across which the polarity of the solar magnetic field reverses. This surface extends along the equatorial plane of the Sun and reaches the boundaries of the heliosphere. The shape of the current sheet is determined by the influence of the Sun's rotating magnetic field on the plasma in interplanetary space. The thickness of the current sheet is approximately 10,000 km. Within the current sheet, a weak electric current (hence the name!) is observed - approximately 10^{-10} A/m². The resulting current is part of the heliospheric current circuit. The heliospheric current sheet is sometimes called the interplanetary current layer. The HCL is a relatively thin, large-area current configuration embedded in a wider plasma sheet (Figure 3 a, b).



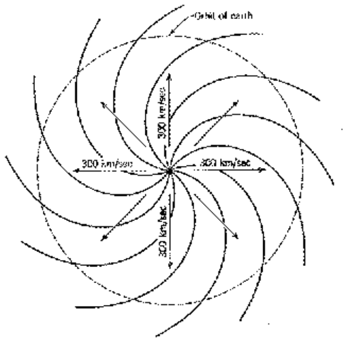


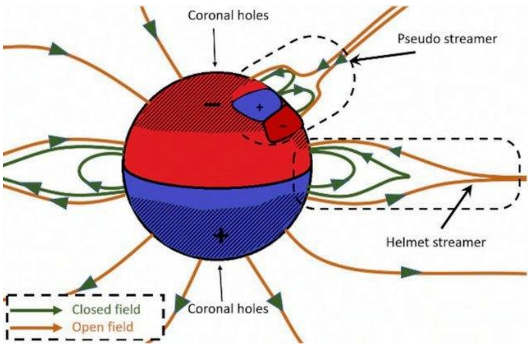
Fig. 3 a Fig. 3 b

In addition, the HCL usually contains a shear (along the streamlines) component of the magnetic field. The presence of high-energy solar cosmic particles in the HCL can change its structure, leading to the formation of nested plasma structures and the appearance of extremely large coronal structures. Current equilibrium in the HCL is achieved at different temperatures of the solar cosmic rays and different high-energy plasma concentrations. The heliospheric current sheet rotates with the Sun, making one rotation every 27 days. During this period, the Earth, together with its magnetosphere, passes through the maxima and minima of the current sheet, interacting with it. At this time, the magnetic induction at the surface of the Sun is approximately 10^{-4} Tesla. If the magnetic field were in the form of an ideal dipole, its strength would decrease proportionally to the cube of the distance and would be 10^{-11} Tesla near Earth's orbit.

Solar corona as an optical manifestation of the heliospheric current layer

Based on its structural properties, the solar corona is clearly divided into two parts: the inner, consisting mainly of contour structures, and the outer. Contour structures in the solar corona are contour-like structures formed by the magnetic field confining relatively cold solar plasma. The main examples of such structures are prominences, as well as loops and filaments, which are visible as curved shapes above the solar surface and in the corona. The main structural element of the outer corona, determining the global scale pattern of the entire corona, are the helmet-shaped rays extending far into interplanetary space. The transition from the inner to the outer corona occurs in the range of heliocentric distances r from 1.5 to 2 solar radii.

On the other hand, the heliospheric current layer (HCL) is the surface of separation of the polarity of the interplanetary magnetic field (IMF). The configuration of the base of the HCL is well described by the neutral line of the IMF on the "source surface" (r ≈ 2.5 Sun radius), calculated by extrapolating magnetic field measurements on the photosphere. Studies in recent years have shown that the helmet-shaped coronal rays are not randomly distributed over the Sun, but rather form a closed belt around it, and this belt corresponds to the base of the HCS (High Common Sunset – Coronal System of the Sun). It can be said more precisely: the helmet-shaped coronal ray belt is a visible (optical) manifestation of the HCS near the Sun, and the rays themselves are structural elements of the HCS (Fig. 4a, b).



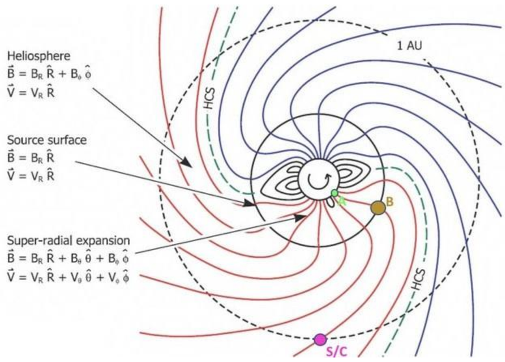


Fig. 4 a Fig. 4 b

To study the evolution of the spatial orientation of the HCS, the concept of a HCS midplane has been introduced [4]. The position of the midplane, determined purely geometrically, for example by the configuration of the neutral line on the surface of the source, corresponds well to the dipole component of the solar magnetic field. The perpendicular to the midplane passing through the center of the Sun can be considered the HCS axis, and the points of its intersection with the solar surface are the HCS poles or the magnetic poles of the Sun. A number of patterns have been identified in the change in the orientation of the HCS during the 11-year solar activity cycle. In particular, the inclination of the HCS midplane to the plane of the solar equator varies from almost zero at the minimum of the cycle to ~70° at times approximately 1 year before and ~1 year after the maximum of the cycle [4]. During the approximately 2-year period of maximum solar activity, the configuration of the HCS is so complex and changes so rapidly that defining the midplane becomes impossible and the very concept of a midplane apparently loses its meaning.

The analysis shows that for most of the 11-year cycle, the actual configuration of the HCS base deviates little from the mean plane. Analysis of a 15-year time interval, including all phases of the 11-year cycle except the maximum, shows that for 43% of the time the standard deviation of the HCS base from the plane does not exceed 10°, and for 73% it does not exceed 15°. Thus, the HCS base and therefore the helmet beam belt can be considered to be largely a flat structure. It is likely that some analogy can be drawn between the appearance of the corona in 3D space and the shape of spiral galaxies [5, 6].

It is this impressive variability of the solar corona that is well known to observers of total solar eclipses during their phase evolution. At the minimum of the 11-year cycle, the corona has two systems of helmet-shaped rays, elongated along the equator; at the maximum, the helmet-shaped rays are distributed more or less evenly throughout the entire solar halo. According to generally accepted ideas, during the transition from the minimum to the maximum of the cycle, the appearance of the corona should gradually evolve from one extreme form to another. Repeated attempts have been made to classify the structure of the corona depending on the phase of the 11-year cycle, but it has not been possible to establish a completely unambiguous connection between these two phenomena.

The fact of the small deviation of the outer corona from the equatorial plane allows us to formulate a new view of the evolution of the corona in the 11-year cycle. During most of the cycle, the shape of the corona in 3D space changes little, while the observed variety of coronal shapes is determined primarily by changes in the orientation of the corona relative to the observer. The above should be considered as a first approximation, characterizing the most general properties of the global structure of the corona. The real picture, of course, is richer and more complex. In particular, during a quarter of the period under consideration, the root-mean-square deviation of the base of the CTS from the plane exceeds 15°, reaching 45°. This is mainly due to the contribution of the enhanced quadrupole component of the magnetic field, and a consequence of this situation may be a four-sector structure of the MMF in the ecliptic plane. The “flat” state of the corona, existing for most of the 11-year cycle, can be arbitrarily called (by analogy with atomic systems) the ground state of the corona, and all other states can be called excited states [7].

Observations and image processing

To observe the solar eclipse of 2024 (with a total phase of up to 2.5 minutes), the Astronomical Observatory and Planetarium in Stara Zagora organized an observation expedition to Argentina. One of the scientific tasks of the expedition team was to study the structure of the corona in white light [8]. To analyze the structure, direct images of the inner and middle corona (observer P. Maglova) and images of the outer corona obtained by special photometric processing were used, which show a detailed structure of the corona in the radial direction. Figures 4a and 4b show two of the composite images of the outer corona of the Sun, where the general appearance of the structure of the white corona is visible.

Fig. 5 a

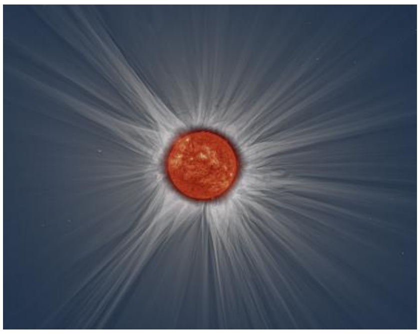


Fig. 5 b

The moment of the eclipse coincides with the beginning of the maximum of the 25th 11-year solar cycle. Therefore, based on generally accepted concepts, one would expect the corona to have a shape close to the “maximum” type. Figures 5a and 5b show that the true shape of the 2024 corona has numerous elements of coronal structures characteristic of a minimal type of corona. These coronal structures of the “minimal type” are associated with two diametrically opposed systems of multiple plumes (brushes, rays), as well as polar brush-like structures between them. Interestingly, this corona with elements of a minimal also shows a serious inclination towards the solar equator. Thus, Fig. 4b demonstrates the inconsistency of the canonical scheme of coronal shape evolution applied to the 2024 corona. At the same time, the observed picture fits very well into the situation outlined above.

To determine the orientation of the mean plane of the heliospheric current layer near the Sun, we used synoptic maps of the magnetic neutral line at a heliocentric distance of 2.5 to about 8 solar radii, published in the Solar Geophysical Data (USA) bulletin. The method for determining the mean plane of the HCL is described in [9, 10]. Calculations based on data from preliminary ephemerides show that the mean plane of the HCL on the day of the eclipse was inclined by 34° to the plane of the solar equator and at the same time was oriented at a relatively small angle to the observer's line of sight. In other words, in 2024 the rare case of orientation of the HCL discussed above actually occurred.

Conclusion

As can be seen from Figure 4a, the solar surface along the midplane of the heliospheric current layer on the day of the eclipse. This shows that there is an excellent correspondence between the orientation of the heliospheric current layer and the directions of the coronal rays. Thus, the observations of the 2024 solar eclipse provide once again experimental confirmation of the idea that the helmet-shaped coronal ray belt is identical to the base of the heliospheric current layer. In other words, the systems of helmet-shaped ray structures can indeed be considered a visible (optical) manifestation of the heliospheric current layer. We believe that in light of the above, existing methods for predicting the structure of the coronal layer should be optimized taking into account the orientation and instantaneous state of the heliospheric current layer.

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