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The form of sunspots in Cycle 24

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The analysis of the form of sunspots in the 24 cycle of activity was performed according to the observations of the SDO/HMI space observatory. The boundaries of sunspots were detected on images in a continuumTo study the connection of the shape of the spots with the magnetic field, the contours of the sunspots were combined with magnetograms. The analysis of the averaged forms of sunspots is carried out. It was found that sunspots, as a rule, have an ellipsoid shape, with the major axis of the ellipse, as a rule, elongated along longitude. The major axis of the ellipse has a predominant inclination to the equator, different in the northern and southern hemispheres. The angle of inclination of the sunspots corresponds to the angle of inclination of the magnetic bipoles of the sunspot groups. The eastern parts of individual sunspots are on average closer to the poles, and the western parts are closer to the equator. Such an elongated shape corresponds not only to the photosphere-penumbra boundary, but also of sunspots umbra.

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1. Introduction

The first telescopic observations of sunspots by Galileo, Steiner and others were made around 1611, which was the beginning of a systematic study of the Sun. Over time, the prevailing view of the nature of sunspots has undergone major changes. A breakthrough in understanding the nature of sunspots occurred in 1908, when George Ellery Hale first measured the magnetic field in sunspots [1]. Since then, the magnetic field has firmly established itself as the root cause of the phenomenon of sunspots.

Sunspots are regions of concentrated magnetic fields that appear dark on the surface of the Sun. Each spot is characterized by a dark core, umbra, and a less dark halo, penumbra. The existence of penumbra distinguishes sunspots from usually smaller pores. The discovery of the Wilson effect in 1769 influenced the picture of the structure of the entire Sun that had developed in the past. Since the dark regions of the sunspots appear to lie deeper than the remaining part of the solar surface, it has been widely believed for some time that all the inner regions of the Sun are dark and therefore cool compared to the bright photosphere outside the sunspots [2]. The brightness and temperature of a sunspot depend on its spatial position. They change in the umbra and penumbra of the sunspot. The umbra is $1000 - 1900\ K^o$ colder than the quiet Sun, the penumbra is $250 - 400\ K^o$ colder. It is believed that the temperature decreases due to the suppression of convective energy through a magnetic field [3].

The formation of sunspots is closely related to the formation of active areas in general. As an increasing magnetic flux appears, individual pores begin to form. Pores are dark photospheric formations without penumbra, usually with a diameter of $d \leq 500$ km. Penumbra begins to develop around pores with a diameter of $d \geq 3.5$ Mm or a magnetic flux $\Phi \geq (1 - 1.5) \times 10^{20}$ Mx. Later, these pores grow and simultaneously converge and merge, forming a larger sunspot. The time scale of the formation of a large spot ranges from several hours to several days.

Currently, it is believed that sunspots on average have a round form. Perhaps this approach is related to model assumptions in which it is easier to model axisymmetric magnetic flux tubes [4].

Previously, when processing a large number of contours of sunspots, it was found that the form of sunspots differs from the round one. In the article [5], a method was used to study the average profile of a sunspot on a disk by scaling and superimposing images of all spots and constructing a histogram of the brightness distribution of the combined image. It was shown that the average form of sunspots is elongated in the longitude direction.

In this paper, we will investigate the forms of sunspots depending on the intensity of magnetic fields and other factors.

2. Observational data and processing method

In this paper, the analysis of images in the continuum of the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamcis Observatory (SDO) telescope is performed. The choice of data from the space observatory provided high-quality images, without the influence of the atmosphere. For the analysis, we used 4 observations per day of the SDO/HMI of observations with an exposure of 45 seconds, at times close to 0:00; 5:00; 10:00; 15:00; 20:00 UT in the period 2010-2021 . Magnetic field data were selected at the same time in order to most accurately combine measurements in the

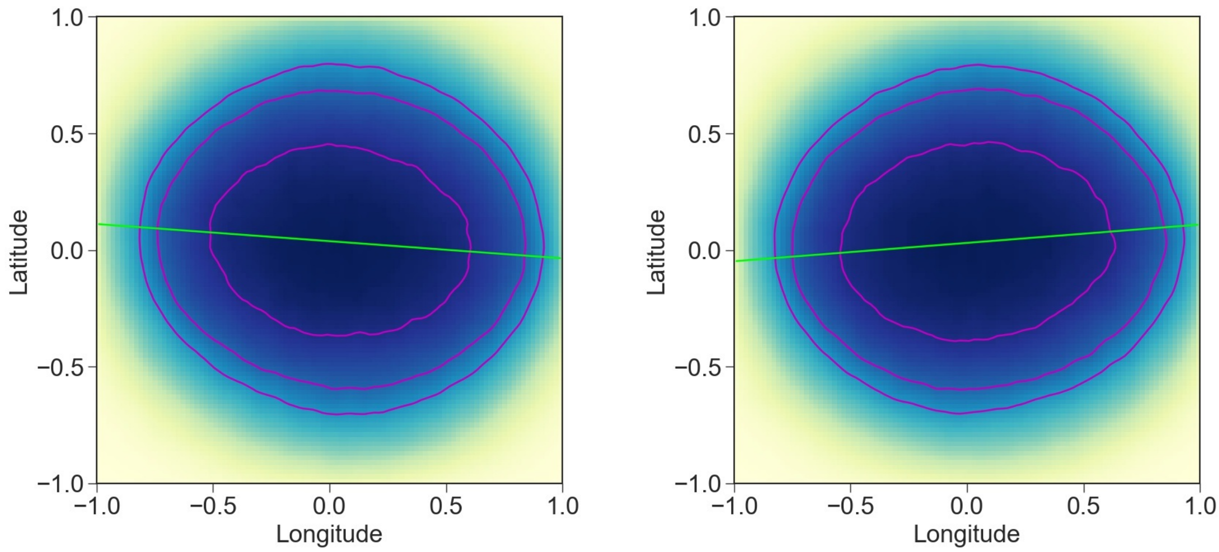

Figure 1: The form of sunspots in the north (Left) and the southern (Right) hemispheres for sunspots with an area of $S: 30 - 50$ μhm. The isodensities (purple) are fitted in the distribution density and the direction of the major axis of the fitted ellipse (green) is drawn.

continuum with observations of magnetic fields. For a comparative analysis of the characteristics of dark objects, it is necessary to know the typical contrast distributions for sunspots and pores. Observations of sunspots have been carried out at the Kislovodsk Mountain Astronomical Station (KMAS) since 1947. Since 2010, observations have been conducted on digital detectors. Detection of sunspots, umbra and pores according to synoptic ground observations is performed using a computer program in semi-automatic mode [6]. The experience of isolating sunspots, pores and nuclei of sunspots was used to allocate these according to SDO/HMI observation data. We used a modified image processing procedure [7].

To study the form of sunspots, we identified statistical features of the form of sunspots by constructing its averaged profile. To do this, all sunspots recorded in heliographic coordinates are reduced to the same scale, and a two-dimensional density diagram is constructed. Normalization occurs as follows: all radius vectors drawn from the center to the points of the spot are normalized by the distance of the maximum length in the latitudinal or longitude direction. Thus, the sunspot is "inscribed" in a single square. Next, we consider the density of the distribution of points in this circle after superimposing all the sunspots.

3. Results of the analysis of the form of sunspots

The density of the distribution of the inner points of the sunspots in the given latitude-longitude coordinates turned out to be different from the correct circle (Figure 1 and Figure 2). To study the form of sunspots, we used the isodensit method in the distribution density matrix. To do this, we determined the average I_{av} distribution density and then constructed isodensit contours. Figure 1 and Figure 2 show the contours of isodensits for values 1.0, 1.3 and 1.5 $\times I_{av}$. The shape of the contour line is close to the shape of an ellipse. To quantify the form features, we fitted an ellipse into

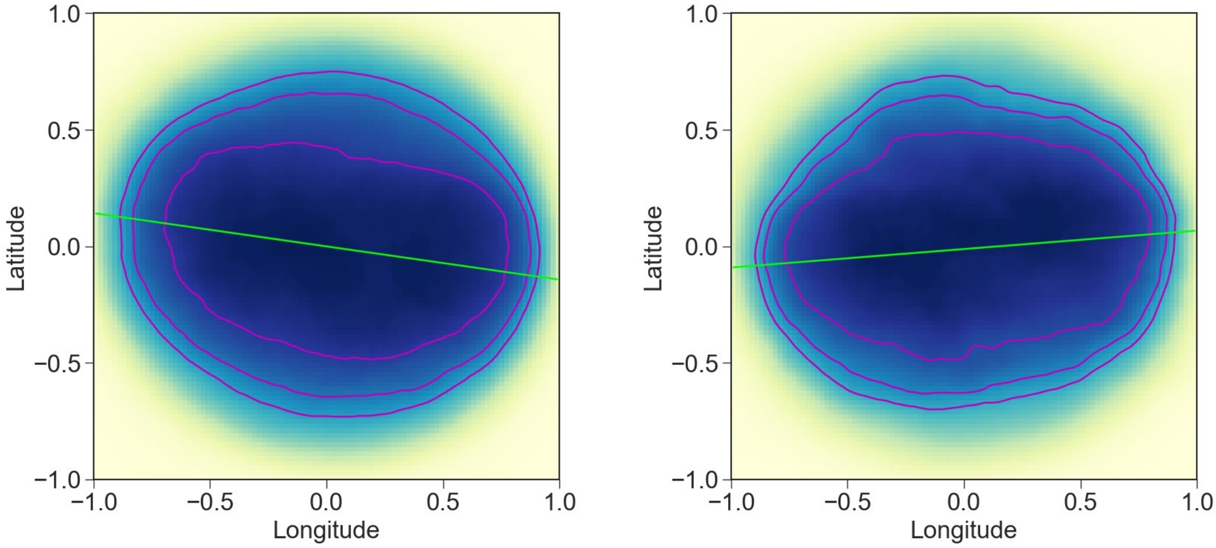

Figure 2: The same as in Figure 1, but for sunspots with an area of $S > 200$ μhm.

the distribution density and found the ratio of the sizes of the small and large axes of the ellipse e, as well as the angle of inclination of the large axis of the ellipse μ with respect to the solar equator.

After applying this procedure separately to the sunspots of the northern and southern hemispheres, we find that the sunspots have an elongated shape, close to an ellipse with a large axis stretched along the solar equator. But there is also a tilt of the major axis with an angle of μ. The angle of inclination of the sunspots μ is on average such that the eastern parts of the sunspots are closer to the poles, and the western parts are closer to the equator. Note that this corresponds to the τ-angle of inclination of the magnetic axes of the bipoles for sunspots group. Figure 1 and Figure 2 show the forms of sunspots for different sizes. For small-area sunspots $S : 30 - 50\mu$hm (Figure 1), the parameter $e \approx 0.8$ turned out to be greater than for large sunspots $S > 200\mu$hm (Figure 2) $e_N \approx 0.75$, $e_S \approx 0.73$. It means that small sunspots have a rounder shape, and with the increase in the area of sunspots, their elongation increases.

Figure 3 shows the change in parameter e from the area of sunspots. The maximum of parameter e is observed for the area of sunspots $S \approx 100$ μhm. For large spots with an area greater than $S > 10^3$ μ hm, the parameter is $e \approx 0.6$. The dependence of the parameter y on the area of sunspots can be expressed by the formula $e = -0.07 + 8.86 \times 10^{-1} \times lg(S) - 2.18 \times 10^{-1} \times lg^2(S)$. For the angle μ, the dependence on the area is not unambiguous (Figure 4). To plot the graph, we reduced the orientation of the ellipse in the southern hemisphere to the orientation in the northern hemisphere. The angle μ varies in the range from $\mu \approx -1^o$ to -7^o.

Figure 5 and Figure 6 show the dependences of the sunspot form parameter e on the magnitude of the magnetic field. Various parameters can be used to describe the characteristics of the magnetic field. Figure 5 shows the dependence on the maximum intensity of the magnetic field B_{mx} in sunspots. As well as for the area, the approximation can be represented by a second-order curve with a maximum near the values of $B_{mx} \approx 1500$ G: $e = 0.65 + 1.51 \times 10^{-4} \times B_{mx} - 4.62 \times 10^{-8} \times B_{mx}^2$.

The dependence of the parameter e on the average intensity of the magnetic field is not so

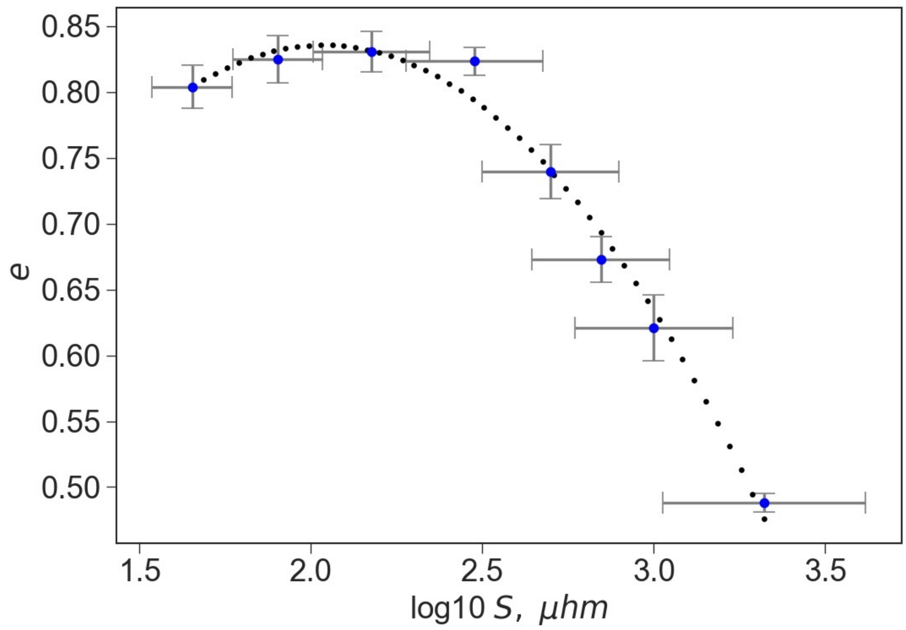

Figure 3: Change of the parameter e, the ratio of the minor and major axes of the ellipse depending on the logarithm of the area of sunspots.

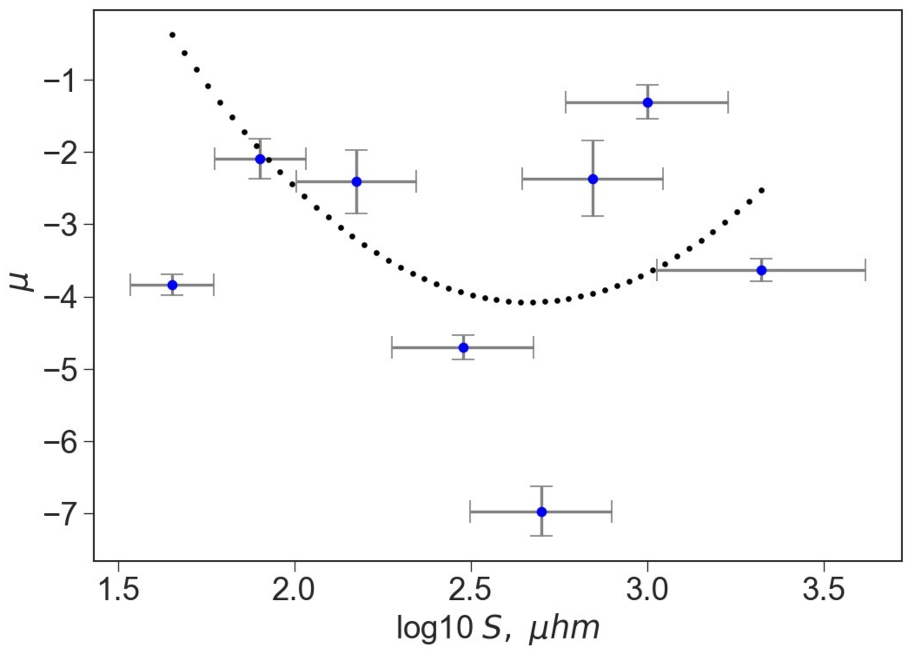

Figure 4: Change in the angle of inclination of the sunspots μ in degree depending on the logarithm of the area.

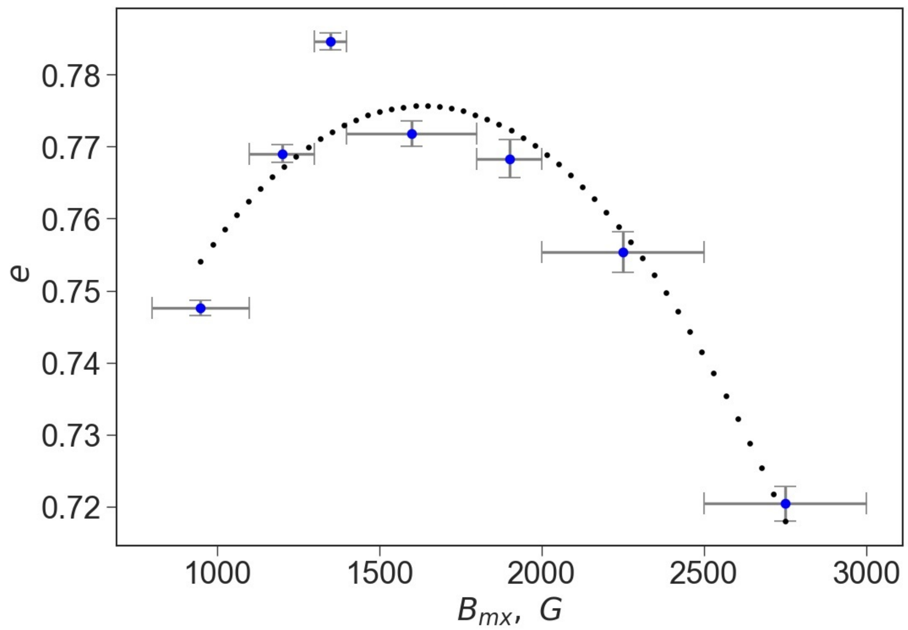

Figure 5: . Dependence of parameter e on the maximum magnitude of the magnetic field B_{mx} in sunspots.

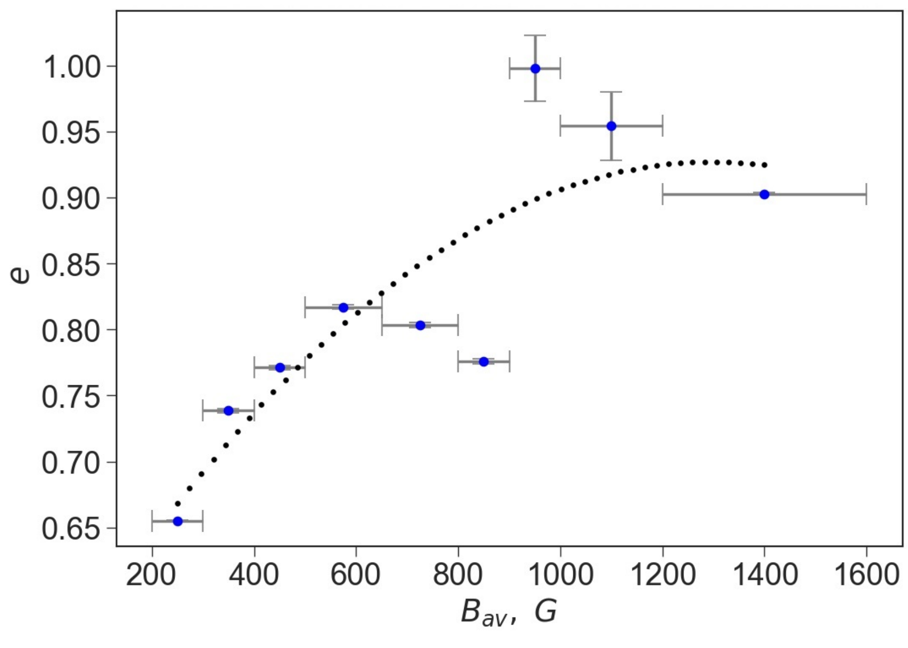

Figure 6: Dependence of parameter e on the average magnitude of the magnetic field B_{av} in sunspots.

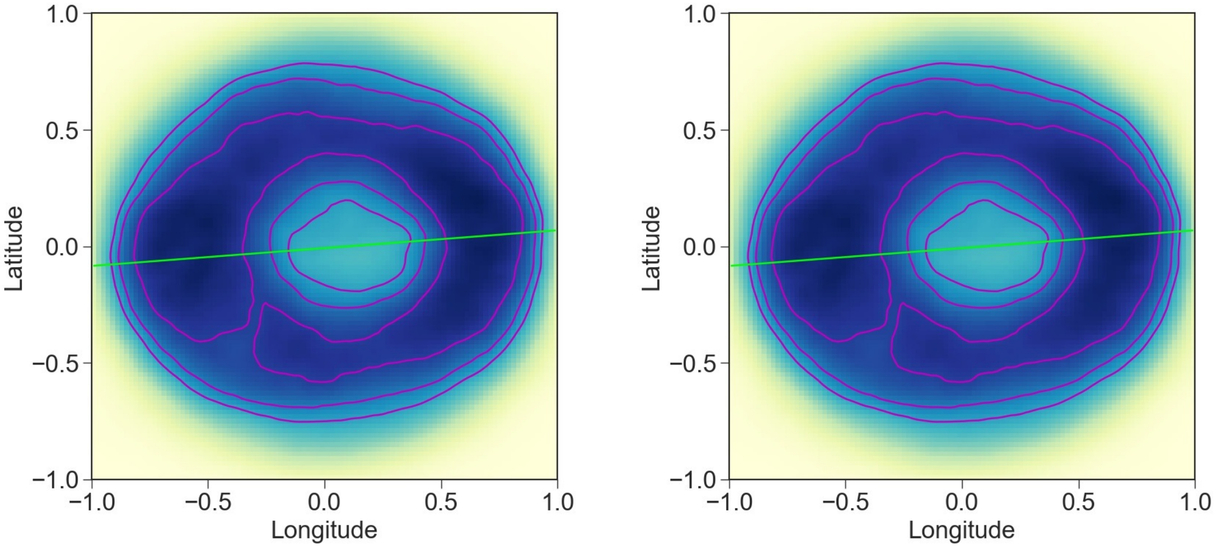

Figure 7: The average form of the penumbra of sunspots in the northern (left) and southern (right) hemispheres.

unambiguous. It is possible that the dependence has different trends for sunspots of high and low intensity of the average magnetic field B_{av} (Figure 6).

4. Discussion

The shape of sunspots on average differs from the regular round shape. The sunspots are elongated along the direction of longitude and correspondingly compressed along latitude (Figure 1, 2). This effect cannot be explained by the Wilson effect. The Wilson effect was established in 1769 by A. Wilson and consists in the fact that near the limb, the penumbra on the side closer to the center of the disk decreases by a greater amount than the width of the penumbra on the limb side. The estimation of the depth of the depression in the centers of sunspots for the Wilson effect gives a value of $Z_W = 400 - 800$ km for developed sunspots and reaches values of $Z_W = 1500 - 2100$ km for large sunspots [2].

To eliminate the influence of the Wilson effect, we limited the selection of sunspots by the distance from the center of the disk to the value $r < 0.7 \cdot R_{Sun}$. Note that since the latitude of sunspots is usually less than 40^o, it is manifested for sunspots near the limb by the fact that the sunspots are pulled along the latitude. In our case, we found that the sunspots are on average elongated along the longitude.

There are still many questions. One of them is whether the elongation along the longitude is a consequence of the deformation of the penumbra of sunspots and how much it effects of sunspots umbra, where magnetic fields have maximum intensities. To clarify this issue, we have divided the sunspots separately into penumbra and the umbra region. Figure 7 shows the averaged forms of penumbra of sunspots. In the centers of the diagrams we see areas of low intensity density. This is due to the elimination of the sunspots umbra. These regions can use to estimate the shape of the sunspot umbrae. We see that the averaged formes of the umbrae, as well as the photosphere-penumbra boundary, have an elongated form along the longitude and the angle of inclination µ is approximately the same as for the entire sunspot.

5. Conclusions

In this work, based on the processing of daily observation data from the SDO/HMI space Observatory, it is confirmed that the average profiles of sunspots are elongated along longitude ($e < 1.0$). The magnitude of the flatness of y depends on the area of the sunspots and on the intensity of the magnetic field in the sunspots.

Also, for sunspots, there is a small angle of inclination of the axis, at which the eastern parts of the sunspots are farther from the equator than the western regions. This may indicate the effect of differential rotation on sunspots. Indeed, with differential rotation, the high-latitude parts of the sunspots will shift relative to the low-latitude parts. With this shift, the angle of inclination of the axis of the sunspots will appear.

Acknowledgements

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