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Differential rotation of sunspots of different magnetic polarity

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Abstract. The rotation rate was analyzed depending on the latitude of individual sunspots of different magnetic polarity. To identify sunspots, we used observations of the SDO/HMI space observatory in the period 2010-2024 in the continuum and observations of magnetic fields at the same time. It was found that the rotation rate of sunspots depends on the magnetic polarity in the 22-year Hale magnetic cycle. The dependence of the rotation rate of sunspots on latitude can be written for sunspots of leading polarity, the rotation rate can be approximated by the formula: $\omega_{\rm ld}(\theta) = \ 14.574 - 2.225\sin^2\theta - 0.02\sin^4\theta$ deg/day. For sunspots of trailing polarity $\omega_{\rm tr}(\theta) = 14.216 - 2.60\sin^2\theta - 0.01\sin^4\theta$ deg/day. Thus, sunspots of leading polarity rotate more than $\sim 2\%$ faster than sunspots of trailing polarity. For sunspots with magnetic flux $\Phi > 2 \cdot 10^{20}$ Mx, the rotation rate practically does not change with increasing magnetic flux.

Keywords: Sun: sunspots; rotation

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1 Introduction

Sunspots are often used to study long-term rotation variations. Sunspots rotate at a different rate than non-magnetic plasma. The most available data for studying long-term variations in the rotation of the Sun are data on sunspot groups. Based on the analysis of Mount Wilson observations from 1921 to 1982 Howard et al. (1984), the law of rotation of sunspot groups $\omega(\theta) = 14.52 - 2.84\sin^2\theta$ deg/day was found. According to the processing of the Greenwich Photoheliographic Results 1874-1976 (Balthasar et al. 1986), the law of rotation was found $\omega(\theta) = 14.557 - 2.85\sin^2\theta$

There are much fewer studies based on the analysis of the movement of individual sunspots. Newton & Nunn (1951), studying the movements of 139 single unipolar recurrent sunspots for 1934 – 1944, found the dependence of the sidereal velocity of rotations of the sine of latitude: $\omega(\theta) = 14.38 - 2.38\sin^2\theta$ deg/day. In Kutsenko (2021) the rotation rate was found for unipolar sunspots $\omega(\theta) = 14.28 - 2.4\sin^2\theta - 2.24\sin^4\theta$ deg/day. In Howard et al. (1984) it was found that sunspot groups rotate about 1% slower than individual sunspots.

Gilman & Howard (1984, 1985) performed the analysis of the rotation rate variation of individual sunspots according to the Mount Wilson Observatory. They processed photographic plates of observations in "white" light for the period 1917 – 1983. Gilman & Howard (1984) showed that there are rotation variations with the phase of the solar activity cycle. In Gilman & Howard (1985) sunspots with a lifetime of at least 2 days were taken for analysis. It was found that the leading sunspots rotate faster than the following sunspots, by about 0.1 deg/day, or 14 m/s.

In this study, we will consider the speed of longitudinal movement of individual sunspots depending on the magnetic properties of sunspots.

2 Data and Method

For the analysis, we used Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI), with a cadence of 45 seconds of the hmi.Ic_45s and hdmi.M_45s series made at the same time. We took 5 images for each day. The observation data were processed automatically. To identify sunspots and pores, we used a sunspot detection procedure similar to that used at the Kislovodsk Mountain Astronomical Station (KMAS) to identify sunspots for synoptic observations (Tlatov et al. 2014).

To determine the velocity of movement, we tracked sunspots on neighboring time images. We have created tables of the characteristics of sunspots and pores, including their geographical coordinates, area, magnetic field characteristics, type of spot and others. Next, we determined the rate of movement of the geometric center of sunspots and pores $\omega = \Delta\phi/\Delta t$, where $\Delta\phi$ is the longitude shift, Δt is the time interval. The procedure for determining the sequence in application to determining the lifetime of sunspots and pores is described in Tlatov (2023). In total, about 250 thousand pairs were allocated in neighboring images of the Sun with a time difference of 5 hours.

3 Analysis results

Sunspots can be classified according to the polarity of their magnetic field. To determine the polarity of the field, we used the superimposition of the boundaries of the spots selected in the continuum on the magnetograms of the magnetic field made on the same telescope at the same time. The Hale law was used to determine the polarity sign of the leading and trailing sunspots.

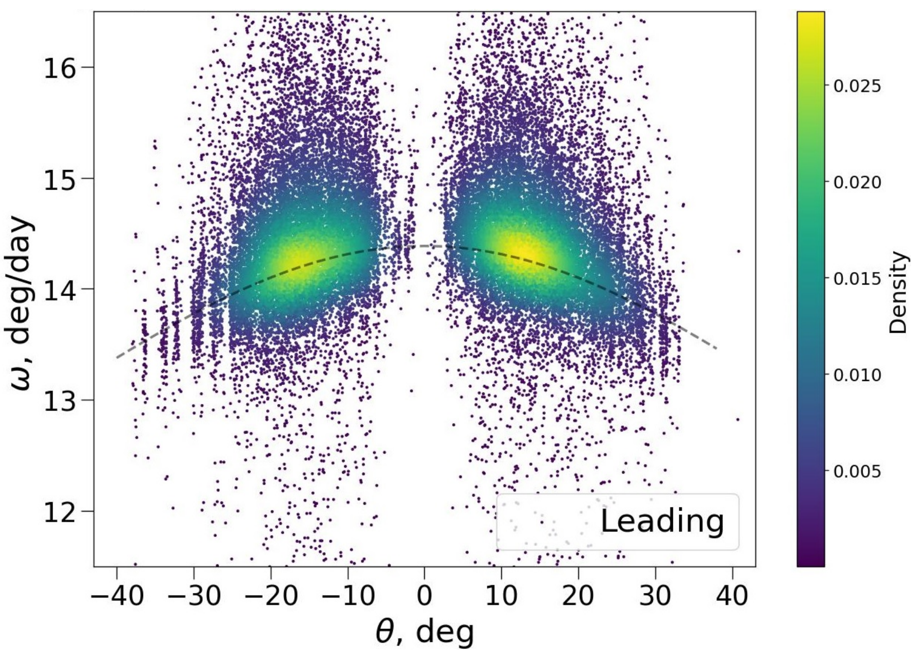

Fig. 1. Scatter plot of the rotation rate of sunspots of the leading magnetic polarity. The dotted line shows the rotation rate according to (Newton & Nunn 1951).

In total, $\approx$ 117 thousand sunspots of the leading polarity and $\approx$ 95 thousand of the trailing polarity were identified, in which the rotation rate was determined. Figure 1 shows the scatter diagram of the rotation rate of sunspots of the leading polarity, and Fig. 2 shows same diagram for sunspots of the trailing polarity. Here we consider sunspots with an area greater than $S > 20$ μhm. This limitation allowed us to exclude solar pores from consideration. For comparison, the dotted line on the graphs shows the rotation rate of unipolar sunspots from the work (Newton & Nunn 1951). It can be noted that the center of gravity of the diagram for sunspots of the leading polarity is higher, and for spots of the trailing polarity is lower than the rotation rate of unipolar spots according to the (Newton & Nunn 1951) formula. For sunspots of leading polarity, the rotation rate can be approximated by the formula: $\omega_{\rm ld}(\theta) = 14.574 - 2.225\sin^2\theta - 0.02\sin^4\theta$. For sunspots of trailing polarity, $\omega_{\rm tr}(\theta) = 14.216 - 2.60\sin^2\theta - 0.01\sin^4\theta$ deg/day. Sunspots of leading polarity rotate $\approx 2.3\%$ faster than sunspots of trailing polarity.

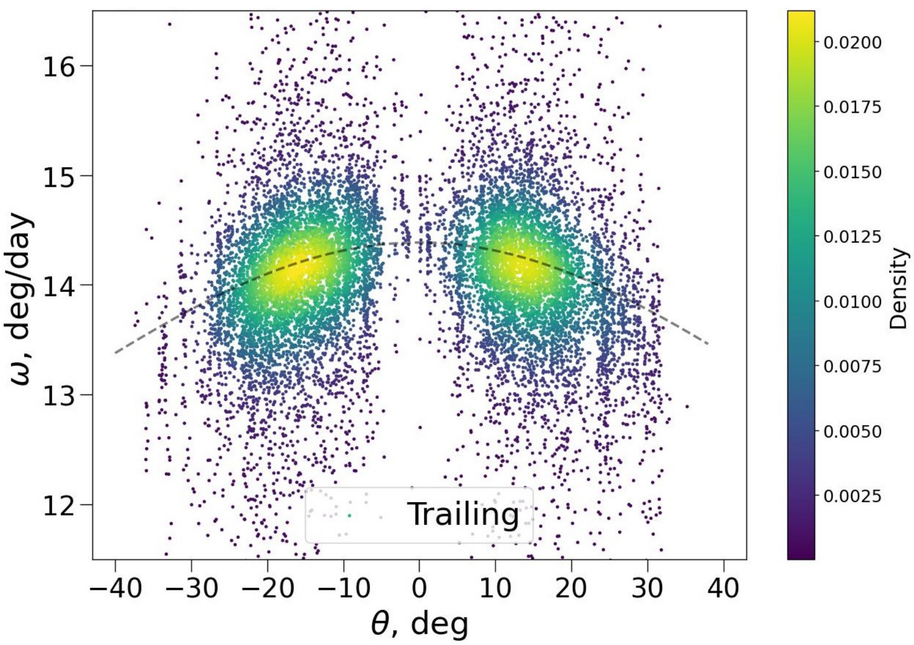

Fig. 2. Same as in Fig. 1 but for sunspots of trailing polarity.

The dependence of the differential rotation rate of sunspots of different magnetic polarity on the magnetic flux is shown in Fig. 3. Here, spots near the equator $\theta < \pm 15^o$ are considered. The following can be noted. Sunspots with low magnetic flux $\Phi < 2 \cdot 10^{20}$ Mx rotate more slowly than sunspots with large areas. For sunspots of trailing polarity with flux $\Phi > 2 \cdot 10^{20}$ Mx, the rotation rate practically does not change with increasing flux. For spots of leading polarity, with increasing flux $\Phi > 1 \cdot 10^{21}$ Mx, the rotation rate decreases.

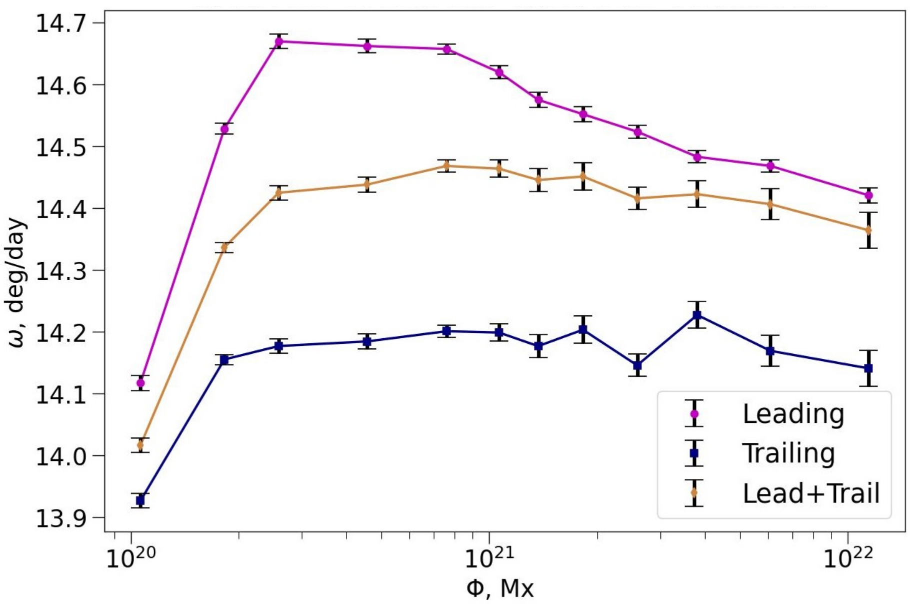

Fig. 3. Rotation rate of sunspots of different magnetic polarity depending on their magnetic flux with latitude in the range $\theta : \pm 15^o$.

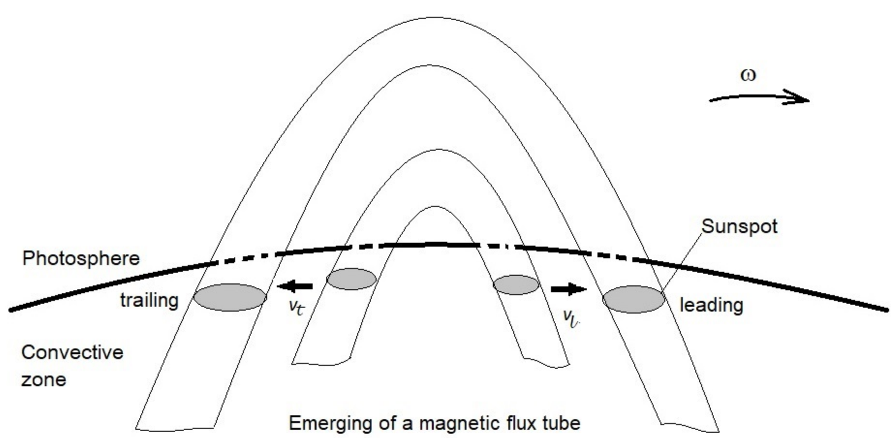

Fig. 4. Simplified diagram of the possible formation of additional speed of longitudinal displacement of sunspots during the emergence of a magnetic flux tube.

4 Discussion

Leading polarity sunspots have rotation rate $\sim$ 2.3% faster than trailing polarity sunspots, or 0.26 deg/day or 36 m/s (Fig. 1, 2). A similar result was obtained earlier (Gilman & Howard 1985). However, they did not use information about magnetic polarity and took leading and trailing spots when processing the plates in “white” light. Such a difference in speeds may be due to additional factors affecting the horizontal movement of the sunspots. Sunspots are visible as the exits of the arch of magnetic flux tubes on the photosphere. At the initial stage of ascent, the distance between the sunspots is less than in the later stages, since the distance between the legs of the arches fixed on the photosphere increases with distance from its top. This leads to the appearance of an additional observable velocity v_l for the leading sunspot directed along the rotation. For the trailing sunspots of the part, the v_t velocity is directed against rotation, which creates the effect of a slow rotation rate (Fig. 4).

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