ON THE ROTATION OF SUNSPOTS AND THEIR MAGNETIC POLARITY

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ABSTRACT

The rotation of sunspots of 2 yr in two different solar cycles is studied with the data from the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory and the Michelson Doppler Imager instrument on board the Solar and Heliospheric Observatory. We choose the \(\alpha\) sunspot groups and the relatively large and stable sunspots of complex active regions in our sample. In the year of 2003, the \(\alpha\) sunspot groups and the preceding sunspots tend to rotate counterclockwise and have positive magnetic polarity in the northern hemisphere. In the southern hemisphere, the magnetic polarity and rotational tendency of the \(\alpha\) sunspot groups and the preceding sunspots are opposite to the northern hemisphere. The average rotational speed of these sunspots in 2003 is about \(0.65\) hr\(^{-1}\). From 2014 January to 2015 February, the \(\alpha\) sunspot groups and the preceding sunspots tend to rotate clockwise and have negative magnetic polarity in the northern hemisphere. The patterns of rotation and magnetic polarity of the southern hemisphere are also opposite to those of the northern hemisphere. The average rotational speed of these sunspots in 2014/2015 is about \(1.49\) hr\(^{-1}\). The rotation of the relatively large and stable preceding sunspots and that of the \(\alpha\) sunspot groups located in the same hemisphere have opposite rotational direction in 2003 and 2014/2015.

Key words: magnetic fields – Sun: rotation – sunspots

1. INTRODUCTION

The magnetic field, to which almost all solar active phenomena are related, plays an important role in solar physics. Sunspots are the most obvious characteristics of the magnetic field on the Sun (Thomas & Weiss 2008). Although the earliest observation of sunspots with telescopes dates back to the time of Galileo, the magnetic field was found in 1908 by George Hale, who observed line splitting and polarization in sunspot spectra by solar tower at the Mount Wilson Observatory (Hale 1908). The 11 yr activity cycle, based on the variation of the sunspot numbers and known since the mid-nineteenth century (Schwabe 1844), is a prominent feature of the Sun. Newly emerged sunspots in an early solar cycle are located on midlatitudes of the Sun and successively appear closer to the solar equator as the cycle progresses. The latitudinal distribution of sunspots and its progression over the sunspot cycle follow a butterfly diagram. Hale et al. (1919) further studied the polarity and distribution of sunspots and established Hale’s laws. Sunspots generally appear as pairs that contain a preceding sunspot and a following sunspot. The preceding and following sunspots have opposite magnetic polarity, and each polarity is reversed in the two hemispheres (Hale’s law). In about 11 yr, the preceding sunspots in one hemisphere (e.g., the northern hemisphere) keep one magnetic polarity; in the next 11 yr, preceding sunspots switch to opposite magnetic polarity. So the magnetic cycle of sunspots is about 22 yr (Hale & Nicholson 1925), which is also known as the Hale Cycle. Although the periodic change of sunspots is well observed, our understanding of its physical nature is still evolving.

The twist, shear, linking, and kinking of magnetic field are often described by magnetic helicity. Helicity was studied for more than 20 yr (Pevtsov 2008). Some statistical studies of active regions showed that the helicity tended to be negative in the northern hemisphere and positive in the southern hemisphere, which is known as the hemispheric helicity rule (Pevtsov et al. 2014). The hemispheric preference is statistically weak for active regions (e.g., Seehafer 1990; Pevtsov et al. 1995, 2001, 2008; Abramenko et al. 1997; Bao & Zhang 1998; Hagino & Sakurai 2004, 2005; Zhang 2006; Hao & Zhang 2011; Liu et al. 2014), from \(\sim58\%\) to \(82\%\), and it does not vary with the solar cycle.

Besides the magnetic field, rotation seems to be the prominent property of sunspots. The rotational motions exist on the solar surface and atmosphere ubiquitously and constantly (see, e.g., Komm et al. 2007; Attie et al. 2009; Zhang & Liu 2011; Wedemeyer-Böhm et al. 2012). Sunspot rotation was first observed by Evershed (1910) a century ago. Recently, more and more rotating sunspots have been identified. Yan & Qu (2012) gave the definition of rotating sunspots: a sunspot can be regarded as a rotating sunspot when it rotates around its umbral center or it rotates around another sunspot within the same active region. Subclasses of six rotational types were given by Yan et al. (2008a). Zhang et al. (2007) reported a large rotational angle of sunspots up to \(240^\circ\). Min & Chae (2009) found that a small sunspot of positive polarity in AR 10930 rotated counterclockwise about its center by \(540^\circ\) within 5 days using a nonlinear affine velocity estimator. Yan et al. (2009) also found this sunspot rotating \(259^\circ\) over 4 days before an X3.4 flare. Brown et al. (2003) studied statistically seven sunspots using white-light Transition Region and Coronal Explorer (TRACE) data and found that they rotated between \(40^\circ\) and \(200^\circ\) within 3–5 days. Besides, Yan et al. (2008b) found 182 rotating sunspots among 2959 active regions from 1996 to 2007 December. The number of rotating sunspots with positive polarity was more than the number of those with negative polarity in the northern hemisphere, while the pattern was opposite in the southern hemisphere. Zhu et al. (2012) studied the relationship between rotating sunspots and emergence of magnetic flux tubes and
found that the rotational angular velocities of sunspots in active regions with flux emergence were larger than those without flux emergence. Theoretically, Sturrock et al. (2015) simulated photospheric footprints or sunspots of the flux tube and found that they are undergoing rotation.

Our study is motivated by the following questions about the rotational motion of sunspots: Why do some sunspots rotate? Is there any relation between the rotation and magnetic field of sunspots? Is there periodicity about rotation of sunspots? To seek answers to these questions, we use the data of two solar cycles, cycle 23 from 1997 to 2008 and cycle 24 from 2008 to 2019, to obtain the statistical results. The paper is organized as follows. The data we use are described in Section 2. The method of analysis of the rotation of sunspots is presented in Section 3. Section 4 shows data processing. We summarize and discuss the results in Section 5.

2. OBSERVATIONAL DATA

The data used in our study are taken from the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) spacecraft (Scherrer et al. 1995) and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO).

The MDI made observations in the Ni I line at 6768 Å; longitudinal magnetograms were constructed by measuring the Doppler shift of the line separately with right and left circularly polarized wave plates. The difference between these two is a measure of the Zeeman splitting and is roughly proportional to the magnetic flux density, the line-of-sight (LOS) component of the magnetic field averaged over the resolution element. The 1024 × 1024 pixel continuum and magnetogram images have pixel resolution of 2″.

The spatial resolution of HMI is 0″.5 pixel−1, and the spectral line is at Fe I 6173 Å. We use the continuum and magnetogram images of HMI to study rotation of sunspots. Continuum intensity and LOS magnetic field strength are two of the LOS observables that were obtained by reconstructing the spectral line profile from the measurements at the six positions (Couvidat et al. 2012).

Basically, the sunspots under study can be divided into two classes: the α sunspot groups and the complex sunspot groups. The magnetic structures of the α sunspot groups are relatively simple. The complex sunspot groups usually have preceding sunspots and following sunspots. The sunspots within each group are interacting with each other. The eruptive events like coronal mass ejections and flares occur much more frequently in the complex active regions. We select the sunspots with the following principles: First, sunspots with radius larger than about 8 Mm (about 10″) and the α sunspot groups with simple magnetic structure are chosen. Perhaps limited by spatial resolution, very tiny sunspots are not showing the rotational property obviously. Large sunspots show rotational properties at a different scale. Second, their structure should be relatively stable. There is no interaction with other sunspots, and they keep their features for several days. Next, we choose the sunspots close to the center of the solar disk from about E30 to W30. The locations of sunspots are obtained from the website http://www.solarmonitor.org/. When the sunspots are roughly located on the center of the solar disk, we record the maximum magnetic field from the data. The maximum strength of sunspots has a value on the order of a kilogauss within several days in our study.

The data are obtained through the Joint Science Operations Center Web server (http://jsoc.stanford.edu/). The intensitygrams of MDI are obtained with the MDI Full Disk Intensity Continuum, and the magnetograms of MDI are obtained with the MDI Full Disk 96 m Magnetogram at a cadence of 96 minutes. The data of sunspots are from 2003 January to December, which contains 5α sunspots group and 37 preceding sunspots of complex active regions. The intensitygrams and magnetograms of HMI are obtained from HMI Active Region patches at a cadence of 12 minutes. The data of these sunspots are from 2014 January to 2015 February, which contain 18α sunspot groups and 6 preceding sunspots and 10 following sunspots of complex active regions.

3. THE ANALYSIS METHODOLOGY

3.1. Time-slice Method

First, from the images of the photosphere, the regions of interest within active regions are chosen. The image that is close to the center of the solar disk is used as a reference image, because of its smaller projection effect. We align the time-sequence continuum intensitygram and LOS magnetogram data to the reference image with the “rot_xy” procedure, which takes into account the solar differential rotation effect. After repeating this procedure, we then create a movie from these time-series images to make sure that the regions are in the frame. The movie can also be used to visualize rotation of sunspots.

The α sunspot group has a simple structure, but complex active regions contain sunspots with different polarities. Thus, analysis of individual sunspots is needed.

In order to derive the rotational parameters of the sunspots, we follow the procedure developed by Brown et al. (2003). It is also used by many other authors (e.g., Brown et al. 2003; Jiang et al. 2012; Li & Liu 2015). As sunspots on the photosphere move, merge, deform, and disappear, we follow the center of umbra. There are two ways to determine the center of the sunspot: (1) the point of minimum intensity in the white-light images, and (2) the point with absolute maximum value in the magnetograms. In our images, we choose the points with the maximum value of the absolute magnetic field.

We uncurl the circular region of the sunspot in the white-light image by transforming from the Cartesian (x−y) frame to the polar (r−θ) frame, that is, cutting off the circular region of the sunspot and unfolding it into the r−θ plane. In this process, the original location to cut off is parallel to the x-axis, and then we uncurl it counterclockwise from 0° to 360°. Then we get the intensitygram of the sunspot in the r−θ frame. Following this process on all the time-series images, one can obtain the θ variation of characters as a function of time. We can extract one line at each time by fixing the radius on the r−θ plane. The time series lines will be formed by the intensitygrams at the circle with fixed radius r_c in the time−θ plane, and the rotational trend can be found.

The radius r_c is chosen with the following principles: when there are enough characteristic points to show the trend, r_c is near and in the umbra of the sunspot. The reason is discussed in Section 3.2. The rotational characters of sunspots can be obtained, and angular velocity can be evaluated.
3.2. Radius Chosen in Time-slice Method

About the radius chosen for the rotational sunspots, Brown et al. (2003) suggested that the penumbra is rotationally feature-rich, and thus feature-tracking results can be obtained easily. Close to the umbra, there is a less prominent rotational feature to trace. However, as the motion of the penumbra is complicated and the structure of the penumbra changes more rapidly, there are some uncertainties in the determination of rotation. But the umbra is relatively stable and may present a global rotating structure. So, we analyze the different parts (umbra and penumbra) of sunspots to determine which one is better for obtaining the real rotation. In the following, we present two examples to show how to analyze the sunspot rotation.

3.2.1. AR 11158—a Complex Active Region (Evolving Sunspots)

NOAA AR 11158 first emerged on 2011 February 11 and then grew rapidly and developed into a $\beta\gamma\delta$-type active region on 2011 February 13. The AR consists of four main sunspots: “P1” and “P2” with positive magnetic polarity, and “Fa” and “Fb” with negative magnetic polarity, shown in Figure 1. The data are obtained from HMI/SDO. At the beginning of February 14, the four sunspots are forming. On February 15 and 16, these four sunspots can be distinguished clearly.

We analyze the four sunspots individually. The radii are fixed in inner umbra, outer umbra, and penumbra to produce time slices. Figure 2 shows the fixed radii of time slices.

In the time-slice figures, Figure 3(a), $r = 30'$; Figure 4(a), $r = 30'$; Figure 5(a), $r = 30'$; Figure 6(a), $r = 30'5$, they are all located in the umbra. Diagonal lines in the time-slice images show a clear pattern of rotation. When the radii are located in the outer edge of the umbra, as in Figure 3(b), $r = 60'$; Figure 4(b), $r = 60'$; Figure 5(b), $r = 60'$, the trends are complicated. Some points show clockwise motion and others counterclockwise motion. When the radii are located in the regions of penumbrae, as in Figure 3(c), $r = 120'$; Figure 4(c), $r = 110'$; Figure 5(c), $r = 100'$; Figure 6(c), $r = 120'$, the situations are the same as in the outer edge of the umbra. The trends are even more complicated, and it is hard to determine the real rotational directions of the sunspots.

![Figure 1](image1.png)

**Figure 1.** HMI continuum intensity image of AR 11158 on 2011 February 15. The AR consists of four main sunspots, “P1,” “P2,” “Fa,” and “Fb.” “P1” and “P2” have positive magnetic polarity, and “Fa” and “Fb” have negative magnetic polarity.

![Figure 2](image2.png)

**Figure 2.** Four sunspots (“P1,” “P2,” “Fa,” and “Fb”) in AR 11158. The white circles in the sunspots are the radii to produce time-slice figures.
The green lines of Figure 3(a) show sunspot P1, which rotates counterclockwise. They all show a uniform rotational tendency at different areas and on different time periods (from 14 00:00 UT to 16 00:00 UT). However, there are streaks showing different rotational tendency in Figure 3(b). The red lines represent the clockwise rotation. The green lines mark the counterclockwise rotational features, and the yellow lines mark the nonrotational features. Different rotational tendencies (lines with different colors) exist at the same time, as shown in the figure. This indicates that the motion of the outer umbra is complicated. It is not easy to determine the rotational direction from this part. In the region of the penumbra, the situation is the same as in panel (b).

In Figure 4(a), the green lines show counterclockwise uniform rotation of sunspot P2. The red and green lines in (b) and (c) show that there are clockwise and counterclockwise rotations in the same time period. The rotational tendency in (b) and (c) is complicated and cannot be determined. The rotational features in the inner umbra may reflect the real rotation of the sunspot.

The green lines of Figure 3(a) show sunspot P1, which rotates counterclockwise. They all show a uniform rotational tendency at different areas and on different time periods (from 14 00:00 UT to 16 00:00 UT). However, there are streaks showing different rotational tendency in Figure 3(b). The red lines represent the clockwise rotation. The green lines mark the counterclockwise rotational features, and the yellow lines mark the nonrotational features. Different rotational tendencies (lines with different colors) exist at the same time, as shown in the figure. This indicates that the motion of the outer umbra is complicated. It is not easy to determine the rotational direction from this part. In the region of the penumbra, the situation is the same as the outer umbra, which is shown in Figure 3(c). There are lines with different colors in the same time period. This means that there are features with different rotational patterns at the same time. So we cannot obtain the uniform rotational tendency of the sunspot from the region.

In Figure 4(a), the green lines show counterclockwise uniform rotation of sunspot P2. The red and green lines in (b) and (c) show that there are clockwise and counterclockwise rotations in the same time period. The rotational tendency in (b) and (c) is complicated and cannot be determined. The rotational features in the inner umbra may reflect the real rotation of the sunspot.

Sunspot Fa mainly rotates clockwise in the umbra, which is shown in Figure 5(a) with red lines. The black streaks in the figure mainly have the tendency to move down (i.e., rotate clockwise). The red lines, green lines, and yellow lines in (b) and (c) show that there are clockwise and counterclockwise rotations (and nonrotating parts) at the same time. It means that the motion in the large radius (penumbra) is complicated. The rotational tendency in the penumbra may not be the same as the rotational tendency in the umbra. The analysis in the umbra may be suitable for obtaining rotation of the sunspot.

In Figure 6(a), the red lines show that sunspot Fb rotates clockwise. At the beginning (before February 14), there are some features (black streaks) that show clockwise rotation. Starting from February 14, many C class flares occurred. The motion in this area is much larger. In the time-slice figure, there are some black streaks showing clockwise rotation, and there are also some white streaks showing counterclockwise rotation. After February 14, there are also some black streaks showing clockwise rotation. However, there are clockwise and counterclockwise rotations at the same time in Figures 6(b) and (c). It is hard to determine the rotational tendency of the sunspot. In Figure 6(c), there are some clockwise and counterclockwise rotation features, but not obvious. According to the above discussion, we find that the umbra rotates clockwise. The motion in the penumbra mainly comes from the consequence of the flares. It may be different from the rotation of the umbra.
From these time-slice figures, we can see that the rotational tendency is uniform at small radius (inner umbra) with black streaks. However, at large radius (penumbra), the rotational tendency is complicated. Some points show clockwise rotation, but other points show counterclockwise rotation at the same time. For the complicated sunspots, we suggest that the small radius (in the umbra) shows the true rotation. The large-radius cases may contain the flow motion of the penumbra. It may not be the true rotation of the sunspots.

3.2.2. AR 12005—α Sunspot Group (Relatively Stable Sunspot)

NOAA AR 12005 is always an α-type active region from 2014 March 16 to 20 (Figure 7). Its structure changes very little during this period. The rotational tendency is shown in Figure 8. When \( r = 4^\circ 0 \) (Figure 8(a)), the rotational features traced are located in the inner umbra. The red line shows that the sunspot rotates clockwise. The rotation of larger radii (penumbra) are also analyzed (Figures 8(b) and (c); their radii are \( r = 10^\circ 0 \) and \( r = 15^\circ 0 \), respectively), and the rotational trend is the same as those at small radii. So the rotational tendencies on the small and large radii are always the same and show that this sunspot rotates clockwise.

For the α sunspot groups (the relatively stable sunspots), the rotational trends can be obtained from the umbra or penumbra. According to the above discussion, we choose the radius \( r_c \) to be near or inside the umbra for the complicated sunspots.

4. DATA ANALYSIS RESULT

With the aligned data, we use the method described in Section 3 to analyze the rotation of sunspots.

4.1. A Case Study: AR 12061

NOAA AR 12061 is located in the southern hemisphere (S24E02), and its magnetic polarity is positive. Figure 9(a) is the HMI intensity map of AR 12061, and the LOS magnetic field contours are overlaid (red represents positive polarity).

After choosing the point of maximum intensity of the magnetograms as the center of the circle with a radius of 35 pixels (17.5), shown in Figure 9(b), we uncurl the whole sunspot from the Cartesian frame to the polar frame. Some images at different times on the \( r-\theta \) plane are shown in Figure 10. From Figure 10, some features varying with time can be seen, indicating that the sunspot was rotating. To display the rotational properties better, we select the circles with radii ranging from 3 pixels (1.5) to 32 pixels (16.0) (Figure 9(b)) to obtain time slices.

Figure 11 shows the time slices at \( r = 8^\circ 5 \) of Figure 10, which is taken from 4 days of data that contain 432 intensitygrams with a cadence of 12 minutes. There are some bright and dark streaks in the figure. The obvious dark streak, which has a tendency to move up, reveals the rotation of the sunspot. This indicates that AR 12061 rotates counterclockwise. The red dashed line indicates the trend shown in...
The sunspot rotates about 100° within 4 days. In other words, the angular speed is about $1°.04\text{hr}^{-1}$. The rotational tendency is checked by comparing with the time-sequence image movies carefully. As Li & Liu (2015) pointed out, this method did not measure the average rotation of a sunspot but obtained the rotation of the specific feature traced. However, we can get the rotational directions of sunspots and analyze their evolution.

4.2. The Polarity and Rotation Relationship

In order to obtain the relation between the rotation and magnetic polarity, we deal with sunspots from 2014 January to 2015 February, as in Section 4.1, and use the time slices of the sunspots to find the trends of the sunspots' rotation.

The sunspots' rotational directions and angular speeds can be obtained from the trends. Figures 12 and 13 show the counterclockwise and clockwise rotation of the $\alpha$ sunspot groups, respectively. The sunspots of Figure 12 are located in the southern hemisphere, and the sunspots of Figure 13 are located in the northern hemisphere. The red dashed line in the figures represents the approximate trend. So the approximate angular speeds within the corresponding interval can be evaluated. Figures 14–17 present the rotations of sample complex sunspot groups ($\beta, \gamma, \delta, \beta\gamma, \beta\gamma\delta$ class). Figure 14 shows that the following sunspots with negative magnetic polarity rotate clockwise. These sunspots are located in the southern hemisphere. In the northern hemisphere, the following sunspots with positive polarity rotate counterclockwise, which is shown in Figure 15. The examples of preceding sunspots are shown in Figures 16 and 17.

Table 1 lists the characteristics of these sunspots. It shows that there is a certain relationship between rotational direction and magnetic polarity for sunspots. For the $\alpha$ sunspot groups, sunspots located in the southern hemisphere rotate counterclockwise, and their magnetic polarities are positive. The sunspots located in the northern hemisphere rotate clockwise, and their magnetic polarities are negative. Closer to umbras, we can obtain the main rotational trends more easily. We list the radii we choose to estimate the angular speeds.

The complex active regions evolve fast and have two or more sunspots with different magnetic polarities. We choose the sunspot with singular polarity to analyze the rotation. The results are also listed in Table 1. The polarities and rotational directions of the preceding sunspots are the same as the $\alpha$ sunspot groups located in the same hemisphere. But sunspots with negative polarity located in the southern hemisphere (the following sunspots) rotate clockwise in general, which is contrary to the $\alpha$ sunspot groups located in the same hemisphere. Similarly, the trend of sunspots located in the northern hemisphere is also contrary to the northern hemispheric $\alpha$ sunspot groups. They rotate counterclockwise while their magnetic polarities are positive.
We plot the maximum of magnetic field strengths versus angular speeds of all sunspots in Figure 18. It shows clearly that sunspots with positive polarity rotate counterclockwise, and sunspots with negative polarity rotate clockwise.

4.3. The Cycle of Sunspots’ Rotation

In order to seek probable periodicity of rotation, we study sunspot data (the $\alpha$ sunspot groups and the preceding sunspots) of 2 yr in two different solar cycles with the method described in Section 3. The MDI data of 2003 in solar cycle 23 (from 1997 to 2008) and HMI data of 2014/2015 in solar cycle 24 (from 2008 to 2019) are used in our study.

There are 42 sunspots in 2003 (22 of them are located in the northern hemisphere, and 20 of them are located in the southern hemisphere) in our sample. Figure 19 shows the rotation of the $\alpha$ sunspot groups and the preceding sunspots located in the northern hemisphere. These sunspots rotate counterclockwise and have positive polarity. The 20 sunspots located in the southern hemisphere rotate clockwise, as shown in Figure 20. Their magnetic polarities are negative. We obtain the angular speeds, locations, and magnetic strengths of these sunspots as shown in the tables. Table 2 lists the sunspots in 2003 (cycle 23). The rotational directions of these sunspots have
Figure 8. Time slices at different radii of AR 12005. (a) $r = 40^\circ$; the time slice is taken from the inner umbra, and the red line marks the rotational tendency of the sunspot. (b) $r = 100^\circ$; the time slice is taken from the outer edge of the umbra. (c) $r = 150^\circ$; the time slice is taken from the penumbra. The regimes all show the clockwise rotation of the sunspot. The rotational tendency can be obtained from the umbra or penumbra.

Figure 9. (a) HMI intensity image of AR 12061 overlaid by LOS magnetogram contour (in Gs). (b) Region to be uncurled. The uncurling starts at the westward direction and proceeds counterclockwise about the spot.
hemispheric preference: sunspots in the northern hemisphere rotate counterclockwise, and sunspots in the southern hemisphere rotate clockwise.

The polarities reverse their sense 11 yr later, as listed in Table 1. These sunspots were observed in 2014/2015 (cycle 24) and contain 24 sunspot groups (we just focus on the α sunspot groups and the preceding sunspots), 10 of which are located in the northern hemisphere and 14 of which are located in the southern hemisphere. According to the study of Section 4.2, sunspots in the northern hemisphere rotate clockwise, and sunspots in the southern hemisphere rotate counterclockwise.

We can see from Tables 1 and 2 that all the α sunspot groups and preceding sunspots with positive polarity rotate counterclockwise and sunspots with negative polarity rotate clockwise.

Figure 10. Examples of $r$–θ intensitygrams in different times. The X-axis refers to the θ coordinate in degrees.

Figure 11. Time slice of AR 12061 taken from the $r$–θ plot at $r = 8^\circ.5$. Rotation of the features can be seen by some diagonal streaks. We display the features as a red dashed line. The X-axis refers to the observational time period. The Y-axis refers to the θ coordinate in degrees.

The Astrophysical Journal, 826:6 (18pp), 2016 July 20 Zhong et al.
Figure 12. 10 α sunspot groups (from (a) to (j)) are located in the southern hemisphere in the year of 2014/2015. Their magnetic polarity is positive. They rotate counterclockwise, and the tendency is marked as red dashed lines. The X-axis refers to the observational time period of these sunspots, and the Y-axis refers to the $\theta$ coordinate in degrees.

Figure 13. 8 α sunspot groups (from (a) to (h)) are located in the northern hemisphere in the year of 2014/2015. Their magnetic polarity is negative. They rotate clockwise, and the tendency is marked as red dashed lines.
et al. 2012), which allows us to detect the rotational features more easily. Figure 21 reveals that the sunspots with positive polarity rotate counterclockwise and sunspots with negative polarity rotate clockwise in both solar cycles. The rotational direction corresponds to the magnetic polarity, independent of the solar cycle.

The $\alpha$ sunspot groups and the preceding sunspots in the northern and southern hemispheres have opposite polarities (Hale’s law), which is shown in Figure 22. In 2003, the $\alpha$ sunspot groups and the preceding sunspots have positive polarity in the northern hemisphere and negative polarity in the southern hemisphere (star symbols), but the situation is
reversed in the year of 2014/2015 (filled circles). The polarity of the \( \alpha \) sunspot groups and the preceding sunspots in each hemisphere reverses the sense every 11 yr.

The polarity of sunspots reverses its sense every 11 yr solar cycle, and that makes the 22 yr period magnetic (Hale) cycle. The rotational directions and magnetic polarities have a certain relationship, so the change of the rotational directions seems to have the same pattern as the cycle. The angular speed of the \( \alpha \) sunspot groups and preceding sunspots is shown in Figure 23. In the year of 2003, the \( \alpha \) sunspot groups and the preceding sunspots rotate counterclockwise in the northern hemisphere and rotate clockwise in the southern hemisphere. From 2014 January to 2015 February, the \( \alpha \) sunspot groups and the preceding sunspots rotate clockwise in the northern hemisphere and rotate counterclockwise in the southern hemisphere. So rotational directions of \( \alpha \) sunspot groups and preceding sunspots change with magnetic polarities (Hale Cycle). In the northern hemisphere, sunspots in 2003 of Cycle 23 rotate counterclockwise and sunspots in 2014/2015 of Cycle 24 reverse their rotational direction (clockwise). In the southern hemisphere, the sunspots in different solar cycles also have opposite rotational directions.

**5. SUMMARY AND DISCUSSION**

The relatively large and stable sunspots rotate with a variety of angular velocities. Some sunspots rotate obviously, and the rotational features can be followed or seen from the movies easily and qualitatively. However, for some sunspots, the
### Table 1
Sunspots in 2014/2015

| Number | NOAA AR | Location | Hale Class | Angular Speed (deg hr⁻¹) | Magnetic Polarity (Maximum Field) |
|--------|---------|----------|------------|--------------------------|----------------------------------|
| 1      | 11948   | N06      | α/α        | +1.77 (4°5)              | N (−2144.60 Gs)                  |
| 2      | 12005   | N13      | α/α        | +1.46 (6°0)              | N (−2384.30 Gs)                  |
| 3      | 12022   | N17      | α/α        | +1.25 (2°5)              | N (−1333.50 Gs)                  |
| 4      | 12033   | N12      | α/α        | +1.42 (15°0)             | N (−1882.80 Gs)                  |
| 5      | 12050   | N12      | α/α        | +1.67 (2°5)              | N (−1674.40 Gs)                  |
| 6      | 12079   | N12      | α/α        | +1.04 (7°5)              | N (−2265.90 Gs)                  |
| 7      | 12218   | N16      | α/α        | +1.25 (8°0)              | N (−2271.30 Gs)                  |
| 8      | 12272   | N12      | α/α        | +2.67 (3°0)              | N (−1338.50 Gs)                  |
| 9      | 11973   | N06 (preceding) | β/β | +1.46 (4°5) | N (−1829.20 Gs) |
| 10     | 12017   | N09 (preceding) | β/β | +1.25 (6°5) | N (−1816.10 Gs) |

| Number | NOAA AR | Location | Hale Class | Angular Speed (deg hr⁻¹) | Magnetic Polarity (Maximum Field) |
|--------|---------|----------|------------|--------------------------|----------------------------------|
| 1      | 11946   | N09 (following) | βγ/βγ | −2.58 (18°5) | P (2098.60 Gs)                  |
| 2      | 11968   | N10 (following) | βγ/βγ | −1.95 (8°5) | P (1851.80 Gs)                  |

| Number | NOAA AR | Location | Hale Class | Angular Speed (deg hr⁻¹) | Magnetic Polarity (Maximum Field) |
|--------|---------|----------|------------|--------------------------|----------------------------------|
| 1      | 11949   | S16      | α/α        | −1.46 (5°5)              | P (2034.90 Gs)                  |
| 2      | 11955   | S14      | α/α        | −1.67 (3°5)              | P (1788.20 Gs)                  |
| 3      | 12061   | S24      | α/α        | −1.04 (8°5)              | P (1685.50 Gs)                  |
| 4      | 12075   | S09      | α/α        | −2.08 (4°5)              | P (1821.80 Gs)                  |
| 5      | 12151   | S08      | α/α        | −1.35 (7°0)              | P (2239.10 Gs)                  |
| 6      | 12194   | S12      | α/α        | −0.94 (4°0)              | P (1851.10 Gs)                  |
| 7      | 12200   | S16      | α/α        | −1.80 (3°0)              | P (1373.10 Gs)                  |
| 8      | 12227   | S04      | α/α        | −0.73 (5°5)              | P (2079.40 Gs)                  |
| 9      | 12252   | S20      | α/α        | −1.77 (4°0)              | P (1972.60 Gs)                  |
| 10     | 12261   | S11      | α/α        | −1.04 (4°5)              | P (1772.90 Gs)                  |
| 11     | 11974   | S13 (preceding) | βγ/βγ | −0.43 (9°0) | P (2062.40 Gs)                  |
| 12     | 11977   | S10 (preceding) | βγ/βγ | −0.29 (18°5) | P (1921.60 Gs)                  |
| 13     | 11991   | S24 (preceding) | βγ/βγ | −0.52 (4°5) | P (1889.60 Gs)                  |
| 14     | 12002   | S18 (preceding) | βγ/βγ | −1.60 (5°5) | P (2001.20 Gs)                  |

| Number | NOAA AR | Location | Hale Class | Angular Speed (deg hr⁻¹) | Magnetic Polarity (Maximum Field) |
|--------|---------|----------|------------|--------------------------|----------------------------------|
| 1      | 11967   | S13 (following) | βγ/βγ | +1.84 (19°0) | N (−2660.40 Gs)                  |
| 2      | 11974   | S13 (following) | βγ/βγ | +2.94 (6°0) | N (−1645.20 Gs)                  |
| 3      | 11977   | S10 (following) | βγ/βγ | +1.73 (5°0) | N (−1946.40 Gs)                  |
| 4      | 11982   | S10 (following) | βγ/βγ | +1.14 (15°0) | N (−2458.30 Gs)                  |
| 5      | 11991   | S24 (following) | βγ/βγ | +2.62 (11°5) | N (−2129.40 Gs)                  |
| 6      | 12002   | S18 (following) | βγ/βγ | +0.63 (10°5) | N (−1630.70 Gs)                  |
| 7      | 12010   | S15 (following) | βγ/βγ | +2.43 (8°0) | N (−1822.70 Gs)                  |
| 8      | 12049   | S07 (following) | βγ/βγ | +1.00 (8°5) | N (−1832.30 Gs)                  |

**Notes.** Data are from HMI. In the “Location” column, “N” stands for northern hemisphere and “S” stands for southern hemisphere; in the “Angular Speed” column, “+7°” stands for rotating clockwise and “−7°” stands for rotating counterclockwise; in the “Magnetic Polarity” column, “P” stands for positive and “N” stands for “negative.”

**Figure 18.** Magnetic field vs. angular speed $\Omega$ of the rotating sunspots in 2014/2015. The rotational direction is related to the magnetic polarity. The sunspots marked with red filled circles rotate counterclockwise, and they have positive magnetic polarity. The sunspots marked with blue plus signs rotate clockwise, and they have negative magnetic polarity.
Figure 19. 22 $\alpha$ sunspot groups and preceding sunspots of 2003 located in the northern hemisphere rotate counterclockwise, and their polarity is positive.
features are not so obvious, and their rotational trends cannot be obtained easily. Thus, sunspots are uncurled from the Cartesian frame to the polar frame. Then the radius of the uncurled circle is fixed to obtain time slices. The trends of time slices indicate the rotational directions, and the ranges of the trends are rotational magnitudes in degrees. In our study, we focus on the rotational directions of sunspots. The rotations of the ρ sunspot groups have continuity as structures evolving smoothly. The specific features of the ρ sunspot groups have enough lifetime to be traced. By calculating from the trends of the time slices, the angular speeds of about ±1°31 hr⁻¹ are found (the ρ sunspots rotate a little more than 100° within 4

Figure 20. 20 ρ sunspot groups and preceding sunspots of 2003 located in the southern hemisphere rotate clockwise, and their polarity is negative.
The Astrophysical Journal, 826:6 (18pp), 2016 July 20  
ZHENG ET AL.

Table 2

Sunspots in 2003

| Number | NOAA AR | Location | Hale Class | Angular Speed (degree hr⁻¹) | Magnetic Polarity (Maximum Field) |
|--------|---------|----------|------------|-----------------------------|----------------------------------|
| 1      | 10258   | N07 (preceding) | $\alpha/\beta$ | $-0.18$ | P (2535.67 Gs) |
| 2      | 10288   | N13 (preceding) | $\beta/\alpha$ | $-0.98$ | p (2244.02 Gs) |
| 3      | 10290   | N17 (preceding) | $\beta_2/\beta_1$ | $-0.48$ | P (2464.84 Gs) |
| 4      | 10296   | N12 (preceding) | $\beta_3/\beta_2$ | $-0.30$ | P (3214.95 Gs) |
| 5      | 10306   | N07 (preceding) | $\beta_3/\beta_2$ | $-0.21$ | P (3227.82 Gs) |
| 6      | 10319   | N13 (preceding) | $\beta_3/\beta_2$ | $-0.92$ | P (2771.54 Gs) |
| 7      | 10325   | N10 (preceding) | $\beta_3/\beta_2$ | $-0.31$ | P (3038.31 Gs) |
| 8      | 10330   | N07 (preceding) | $\beta_3/\beta_2$ | $-0.35$ | P (3070.89 Gs) |
| 9      | 10346   | N16 (preceding) | $\beta/\alpha$ | $-0.35$ | P (2687.02 Gs) |
| 10     | 10351   | N08      | $\alpha/\alpha$ | $-0.12$ | P (2622.57 Gs) |
| 11     | 10373   | N07 (preceding) | $\beta/\alpha$ | $-0.76$ | P (2715.43 Gs) |
| 12     | 10375   | N12 (preceding) | $\beta_3/\beta_2$ | $-1.05$ | P (2733.37 Gs) |
| 13     | 10377   | N04 (preceding) | $\beta_3/\beta_2$ | $-0.56$ | P (2180.81 Gs) |
| 14     | 10387   | N18 (preceding) | $\beta_3/\beta_2$ | $-0.62$ | P (2425.00 Gs) |
| 15     | 10390   | N14 (preceding) | $\alpha/\beta$ | $-1.23$ | P (2501.51 Gs) |
| 16     | 10420   | N11      | $\alpha/\alpha$ | $-2.34$ | P (2758.44 Gs) |
| 17     | 10463   | N09      | $\alpha/\alpha$ | $-0.72$ | P (2428.32 Gs) |
| 18     | 10465   | N00 (preceding) | $\beta/\beta$ | $-0.21$ | P (2593.09 Gs) |
| 19     | 10484   | N04 (preceding) | $\beta_3/\beta_2$ | $-0.49$ | P (2472.54 Gs) |
| 20     | 10488   | N09 (preceding) | $\beta/\beta$ | $-1.28$ | P (2869.35 Gs) |
| 21     | 10513   | N13      | $\alpha/\alpha$ | $-0.42$ | P (2507.05 Gs) |
| 22     | 10528   | N09 (preceding) | $\beta_3/\beta_2$ | $-0.25$ | P (2993.30 Gs) |

Notes. Data are from MDI. In the “Location” column, “N” stands for northern hemisphere and “S” stands for southern hemisphere; in the “Angular Speed” column, “+” stands for rotating clockwise and “-” stands for rotating counterclockwise; in the “Magnetic Polarity” column, “P” stands for positive and “N” stands for negative.

The rotations of the sunspots in complex active regions are more complicated. For example, we can see from the movie that the sunspots rotate clockwise; however, in the time-slice figures, there are not only streaks indicating clockwise rotation but also streaks indicating counterclockwise rotation. This makes it difficult to determine their rotational directions. Besides, uniform rotation of the whole sunspot does not last for a long time. So in our sample, we try to choose the relatively large and stable sunspots that have relatively few eruptive events in these regions. The rotational features have enough lifetime to allow us to trace. After calculating, the mean angular speed is about $\pm0.91$ hr$^{-1}$.

From the statistical analysis of rotating sunspots in the year of 2014/2015 in Section 4.2, we find the following relations between rotation and magnetic polarities:

i. The $\alpha$ sunspot groups. These sunspots tend to rotate counterclockwise and have positive magnetic polarity in the southern hemisphere, whereas in the northern hemisphere, the $\alpha$ sunspots tend to rotate clockwise and have negative magnetic polarity.

ii. The preceding sunspots in the complex sunspot groups. These sunspots and the $\alpha$ sunspot groups show the same tendency between magnetic polarities and rotational
Figure 21. Sunspots’ magnetic field vs. angular speed $\Omega$. The star symbols represent the sunspots in the year of 2003, and the filled circles represent the sunspots in the year of 2014/2015.

Figure 22. Maximum of magnetic field strengths of the $\alpha$ sunspots and the preceding sunspots in both hemispheres. The star symbols represent the sunspots in the year of 2003, and the filled circles represent the sunspots in the year of 2014/2015. The sunspots with positive polarity rotate counterclockwise, and the sunspots with negative polarity rotate clockwise.

Figure 23. Scatter of sunspots about the latitude and angular speed. The star symbols represent the sunspots in the year of 2003, and the filled circles represent the sunspots in the year of 2014/2015.
directions. In the southern hemisphere, they tend to rotate counterclockwise and have positive polarity. The results are opposite in the northern hemisphere. But those sunspots evolve in a much more complicated pattern than the α sunspot groups.

iii. The following sunspots in the complex sunspot groups. These complex sunspots have negative magnetic polarity and tend to rotate clockwise in the southern hemisphere, whereas in the northern hemisphere, the sunspots have positive magnetic polarity and tend to rotate counterclockwise.

According to the above results, in our sample the sunspots corresponding to negative magnetic polarity tend to rotate clockwise, and sunspots corresponding to positive magnetic polarity tend to rotate counterclockwise, no matter whether they are in the northern or southern hemisphere.

With the data from two solar cycles, we find that the rotational direction of sunspots follows periodicity. It is the same as magnetic polarity of sunspots. In this study, we choose the sunspot data of two solar cycles from MDI/SDO and HMI/SOHO. In the year of 2003, 5 α sunspot groups and 37 preceding sunspots of complex sunspot groups are studied. There are 22 sunspots located in the northern hemisphere and 20 sunspots located in the southern hemisphere. In the northern hemisphere, the sunspots have positive polarity. They are rotating counterclockwise. The 11 sunspots in the southern hemisphere rotate clockwise and have negative polarity. The results agree with the conclusion that sunspots with positive magnetic polarity rotate counterclockwise and sunspots with negative magnetic polarity rotate clockwise.

From 2014 January to 2015 February, there are 10 α sunspot groups and 4 preceding sunspots with positive polarity rotating counterclockwise in the southern hemisphere. In the northern hemisphere, 8 α sunspot groups and 2 preceding sunspots with negative polarity rotate clockwise.

We study sunspots of 2 yr in two successive solar cycles. The polarities of the α sunspot groups and preceding sunspots in both hemispheres reverse in these 2 yr. This is the result of the 22 yr magnetic cycle of sunspots. The directions of sunspots’ rotation are also reversed.

It is recognized that the magnetic field of sunspots is connected to the solar dynamo, but it is still not well understood. Through the study on the rotation of sunspots, we find the correlation of rotation and magnetic polarity of sunspots. This may help us to understand the solar dynamo in future studies.

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