First Asia-Pacific Solar Physics Meeting
ASI Conference Series, 2011, Vol. 2, pp 175–180
Edited by Arnab Rai Choudhuri & Dipankar Banerjee

Long-term variation of solar surface differential rotation

L. Zhang[1,2*], K. Mursula[2], I. Usoskin[3], H. Wang[1] and Z. Du[1]

[1]*Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Datun Road 20A ChaoYang District 100012, Beijing, China*
[2]*Department of Physics, University of Oulu, Finland*
[3]*Sodankylä Geophysical Observatory, University of Oulu, Finland*

Abstract. Recently, the surface differential rotation parameters were found to vary differently with time for the northern and southern hemispheres of the Sun. Both sunspots and flares strongly suggest that the northern hemisphere rotated considerably faster than the southern during the last three solar cycles, showing a strong north-south asymmetry in solar surface rotation. In order to study the long-term variation of solar surface differential rotation, the location of sunspots during 1877-2009 is analyzed separately in the two hemispheres. The variation of the rotation of the northern hemisphere is found to have an anti-correlation with that of the southern hemisphere and the variation suggests a period of 10-12 cycles.

Keywords : Sun: rotation – Sun: activity

1. Introduction

Differential rotation of solar surface was noted a few centuries ago. Scheiner presented evidence as early as in 1630 that the passage of sunspots across the solar disc took a slightly longer time at high latitudes than near the equator. However, it took 250 years before Carrington established the differential rotation equation

$$\Omega(\phi) = A + B \sin^{7/4} \phi, \tag{1}$$

which came to the following form for convenience of calculation,

$$\Omega(\phi) = A + B \sin^2 \phi + C \sin^4 \phi. \tag{2}$$

*email: zhangliyun@bao.ac.cn

Table 1. Different tracers of solar rotation with faster hemisphere indicated in cycles 12-23. LBT stands low-brightness-temperature and PMF for photospheric magnetic fields.

authors	tracers	solar cycles	faster hemisphere
(Javaraiah 2003)	sunspot groups	12	South
...	sunspot groups	13	North
...	sunspot groups	14-20	South
(Gigolashvili et al. 2003)	Hα filaments	20, 22	North
...	Hα filaments	19, 21	South
(Scherrer et al. 1987)	PMF	20-21	North
(Hoeksema & Scherrer 1987)	coronal magnetic field	21	North
(Antonucci et al. 1990)	PMF	21	North
(Brajša et al. 1997)	Hα filaments	21-22	North
...	LBT regions	21-22	North
(Knaack et al. 2005)	PMF	21, 23	North
...	PMF	22	South
(Hathaway et al. 1996)	Doppler velocities	22	South
(Bai 2003)	major flares	19-23	North

ϕ denotes the latitude and A is the equatorial rotation rate. A, B, and C are constants to be determined from observations.

Besides sunspots many other tracers, e.g., Doppler shifts, coronal holes and surface magnetograms have been used to determine the differential rotation parameters. The measured rotation parameters differ from each other not only for different solar tracers but also for the same objects. The discrepancy of the obtained velocities for different tracers can be explained by their different heights in the solar atmosphere, because of the radial gradient. The discrepancy for the same objects is probably caused by different time data binning since many works suggest that solar surface rotation and torsional oscillations change from cycle to cycle, even within one cycle (Balthasar, Vazquez & Woehl 1986; Javaraiah, Bertello & Ulrich 2005; Knaack & Stenflo 2005; Balthasar 2007; Howard & Labonte 1980; Antia, Basu & Chitre 2008).

Solar surface rotation shows evidence for north-south (N-S) asymmetry. Several studies suggest that northern hemisphere does not rotate at the same rate as southern hemisphere. A summary of different tracers with the suggested faster hemispheres for cycles 12-23 is presented in table 1.

Recently, using a dynamic, differentially rotating coordinate system, Usoskin, Berdyugina & Poutanen (2005) found two persistent (on century scale) active longitudes separated by 180°. These longitudes migrate with differential rotation and the rotation parameters can be determined by optimization. Applying the same system to solar X-ray flares, Zhang et al. (2007) found two significant active longitudes in all

three (C, M, and X) classes of flares. However, the obtained rotation parameters for one class of flares differed significantly from those for another class. The analysis was improved by Zhang, Wang & Du (2008) and Zhang et al. (2010). The rotation parameters were found to be consistent among all the three classes of X-ray flares and also in agreement with the proposed parameters for sunspots for the common time period.

Applying the refined method to sunspots in 1877-2010, Zhang et al. (2011) noted that the long-term variation of solar surface rotation is roughly opposite in the northern and southern hemispheres. However, the long-term period of the variation of the solar surface rotation in the two hemispheres was not very clear. In order to study the long-term period, a detailed analysis is done in this work. The method is described in section 2 and the result is presented in section 3.

2. Method to determine solar surface differential rotation parameters - using solar active longitudes

The method is illustrated in Fig. 1. Let us assume that one active longitude appears at Carrington longitude Λ_{01} in the beginning (first day of the first rotation) and its rotation rate follows the solar surface differential rotation. It will move to Λ_{ik1} on the kth day of the ith rotation when a sunspot (or a sunspot group) occurs at Carrington longitude λ_{ik}. Meanwhile, the opposite active longitude which is at $\Lambda_{02} = \Lambda_{01} \pm 180^\circ$ in the beginning will migrate to $\Lambda_{ik2} = \Lambda_{ik1} \pm 180^\circ$. The angular rotation rate in the ith rotation can be simply expressed as (neglecting the small quartic term)

$$\Omega_{\phi_i} = A + B \sin^2 < \phi_i > \tag{3}$$

where ϕ_i is the area weighted mean latitude of sunspots observed in this rotation. Then one can obtain

$$\Lambda_{ik1} = (\Lambda_{01} + T_c \sum_{j=0}^{i-1} (\Omega_{\phi_j} - \Omega_c) + k(\Omega_{\phi_i} - \Omega_c)) \bmod 360^\circ, \tag{4}$$

where $T_c = 27.2753$ days is the time step, synodic Carrington rotation period, Ω_c is the angular velocity of Carrington frame (in sidereal frame 14.1844 deg/day and in synodic frame 13.199 deg/day), and k is the time of sunspot observation given as a fractional day of the Carrington rotation. The velocity and rotation parameters are in sidereal frame in this work.

The distance between the sunspot and a nearer active longitude (Λ_{ik1} or Λ_{ik2}) can be measured by

$$\Delta_{ik} = \min(|\lambda_{ik} - \Lambda_{ik1}|,\ 360^\circ - |\lambda_{ik} - \Lambda_{ik1}|,\ |180^\circ - |\lambda_{ik} - \Lambda_{ik1}||). \tag{5}$$

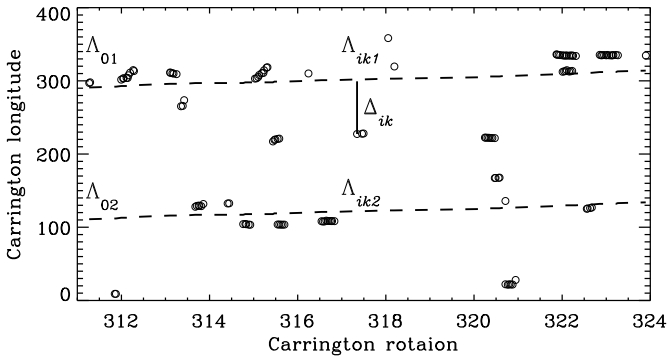

Figure 1. Demonstration of the method. Circles stand for sunspots and two dash lines are expected migration routes of the two active longitude.

One can define the merit function

$$\epsilon(\Lambda_{01}, A, B) = \frac{1}{n} \sum_i \sum_k \Delta_{ik}^2, \tag{6}$$

where n stands for the total number of sunspots. The merit function has three parameters Λ_{01}, A, and B. One can search for the best fit parameters in a reasonable range where the merit function reaches minimum. The search interval for the value of Ω_0 is within [13.5, 15.0] (deg/day) in steps of 0.01 (deg/day), B within [0.0, 5.0] (deg/day) in steps of 0.01 (deg/day) and Λ_{01} within [0°, 360°] in steps of 1°. Applying the obtained rotation parameters for each hemisphere, one can calculate the rotation rate at dominant latitude 17° of sunspots, i.e., Ω_{17}, which can be considered as the surface rotation rate for each hemisphere. Greenwich data in 1877-2009 has been used and the time interval was chosen to be three solar cycles, which was stepped forward by one cycle. The rotation parameters for each cycle are obtained from this 3-cycle running intervals, e.g., the rotation parameters for cycle 13 are obtained from the data in cycles 12-14 and for cycle 14 from the data in cycles 13-15.

3. Result

The rotation rates of solar surface in cycles 13-22 show a clear oppositely variation in the northern and southern hemispheres. Values of rotation rates Ω_{17} for cycles 13-22 obtained from 3-cycle running intervals are demonstrated in the top panel in Fig. 2. The errors (±0.005 deg/day) were measured in the same way as in Zhang et al. (2011), which are too small to be seen outside of the circles of the figure. The values of Ω_{17} show that the rotation rates for the two hemispheres deviate from each other significantly in the beginning, come close in the following three cycles and change signs in cycle 17. They depart again thereafter and come to close in the end. The variation in the nine cycles suggests a period of about 10-12 cycles.

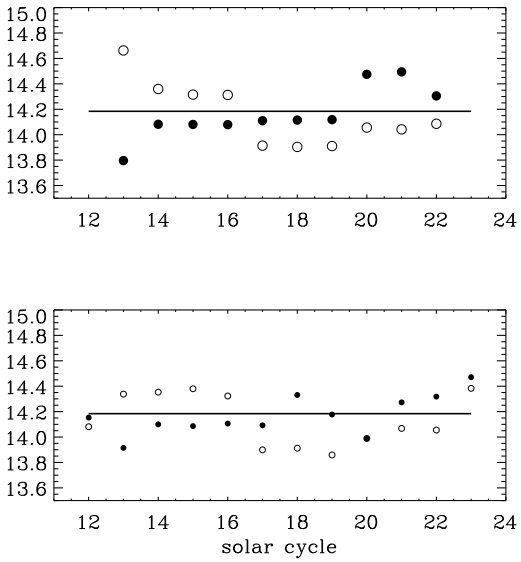

Figure 2. Dominant rotation rates Ω_{17} for northern (filled circles) and southern (open circles) hemispheres in cycles 12-23. Top panel is for 3-cycle intervals and bottom for 1-cycle intervals. The horizontal lines stand for sidereal Carrington rotation rate Ω_c = 14.1844 (deg/day).

The rotation parameters obtained from 1-cycle intervals shown in bottom panel in Fig. 2 are taken from earlier work by Zhang et al. (2011). It happens to see that the rotation rates in the two hemispheres are very close to each other in the first cycle 12 and in the last cycle 23. This implies that the long-term period of N-S asymmetry in solar surface rotation is 11 cycles. However, the rotation parameters obtained for 1-cycle intervals do not vary so smoothly as for 3-cycle intervals since the method has a benefit from long time and large amount of samples. For example, the bottom panel shows that the two hemispheres have a equal rotation rate in cycle 20. Thus, considering the results from 1-cycle and 3-cycle intervals, the long-term period of N-S asymmetry in solar surface rotation is expected to be around 10-12 cycles.

The mean rotation rate of Ω_{17} over the twelve cycles is 14.189±0.005 (deg/day) in northern hemisphere and 14.169±0.005 (deg/day) in southern hemisphere. Both are very close to Carrington frame rotation velocity 14.1844 (deg/day). This is consistent with Zhang et al. (2011) that the mean rotation rate in northern hemisphere is slightly larger than in southern hemisphere in the last twelve cycles.

The variation of solar surface differential rotation with time has also been studied by Heristchi & Mouradian (2009) and Plyusnina (2010), but no N-S asymmetry was found. This is probably due to the data they used. They took daily sunspot number and sunspot areas as indices. These daily values are smoothed over the whole disc.

They do not carry longitude information with high accuracy. Thus they are not very good indices for studying surface differential rotation.

Acknowledgements

The research leading to these results has received funding from the European Commission's Seventh Framework Programme (FP7/2007-2013) under the grant agreement no 218816 (SOTERIA project, www.soteria-space.eu). We also acknowledge the financial support by the Academy of Finland to the HISSI research project no. 128189. This work is jointly supported by the National Natural Science Foundation of China through grants 10973020, 10733020, 10921303 and 40890161, and the National Basic Research Program of China (Program 973) through grant 2011CB811406.

References

Antia H. M., Basu S., Chitre S. M., 2008, ApJ, 681, 680-692
Antonucci E., Hoeksema J. T., Scherrer P. H., 1990, ApJ, 360, 296
Bai T., 2003, ApJ, 485, 1114
Balthasar H., Vazquez M., Woehl H., 1986, A&A, 155, 87
Balthasar H., 2007, A&A, 471, 281
Brajša R., Ruždjak V., Vršnak B., Pohjolainen S., Urpo S., Schroll A., Wöhl H., 1997, Solar Phys., 171, 1
Gigolashvili M. Sh., Mdzinarishvili T. G., Japaridze D. R., Chargeishvili B. B., 2003, NA, 8, 529
Hathaway D. H. et al., 1996, Sci., 272, 1306
Heristchi D., Mouradian Z., 2009, A&A, 497, 835
Hoeksema J. T., Scherrer P. H., 1987, ApJ, 318, 428
Howard R., Labonte B. J., 1980, ApJ, 239, L33
Javaraiah J., 2003, Sol. Phys., 212, 23
Javaraiah J., Bertello L., Ulrich R. K., 2005, Solar Phys., 232, 25
Knaack R., Stenflo J. O., 2005, A&A, 438, 349
Knaack, R., Stenflo J. O., Berdyugina S. V., 2005, A&A, 438, 1067
Plyusnina L. A., 2010, Solar Phys., 261, 223
Scheiner C., 1630, Rosa Ursine sive Sol (Andreas Phaeus, Italy), book 4, part 2
Scherrer, P. H., Hoeksema J. T., Antonucci E., 1987, BAAS, 19, 935
Usoskin I. G., Berdyugina S. V., Poutanen J., 2005, A&A, 441, 347
Zhang L. Y., Wang H. N., Du Z. L., Cui Y. M., He H., 2007, A&A, 471, 711
Zhang L. Y., Wang H.N., Du Z.L., 2008, A&A, 484, 523
Zhang L., Mursula K., Usoskin I., Wang H., 2010, JASTP, 73, 528
Zhang L., Mursula K., Usoskin I., Wang H., 2011, A&A, 529, A23