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AN ANALYSIS OF THE SOLAR DIFFERENTIAL ROTATION FROM THE KANZELHÖHE SUNSPOT DRAWINGS

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Abstract. We present here the results of the behaviour of the solar differential rotation during solar cycles no. 20 and no. 22, derived from Kanzelhöhe sunspot drawings (Kanzelhöhe Observatory for Solar and Environmental Research, University of Graz, Austria). The positions of sunspot groups were determined using a special software Sungrabber. Sunspot groups were identified with the help of the Greenwich Photoheliographic Results (GPR) and Debrecen Photoheliographic Data (DPD) databases, covering solar cycles no. 20 and no. 22, respectively. In order to calculate the sidereal angular rotation rate ω and subsequently solar rotation parameters A and B we used two procedures: a) daily motion of sunspot groups and b) linear least-square fit from the function $CMD(t)$ for each tracer, where CMD denotes the Central Meridian Distance. The sample was limited to $\pm 58^\circ$ in CMD in order to avoid solar limb effects. We mainly investigated velocity patterns depending on the solar cycle phase and latitude.

Key words: solar rotation - sunspots

1. Introduction

Within the project intended to investigate the behaviour of the solar differential rotation during several solar cycles we plan to process Kanzelhöhe sunspot drawings (Kanzelhöhe Observatory for Solar and Environmental Research, University of Graz, Austria) for solar cycles nos. 20 - 24. As part of this analysis, we present here the results for the solar cycles no. 20 and no. 22.

Kanzelhöhe Observatory is the only observatory in Austria for solar and environmental research being part of the Institute of Physics, at the Karl-Franzens University of Graz. The Kanzelhöhe Observatory online service began in February 2000 and is updated daily with new scanned drawings. The drawings are digitized since 1944.

For the time period 1874 - 1976 many analyses of high-precision positions and rotational velocities of sunspot groups were performed. For example, the dependence of the differential rotation of sunspot groups on the phase of the cycle was analysed by Balthasar *et al.* (1986), the dependence of solar rotation on time was analysed by Brajša *et al.* (2006) and relationship between the solar rotation and activity was researched by Brajša *et al.* (2007).

The main aim of this work is to extend the analysis 1977 - present and to compare the following data sets:

a) *Greenwich Photoheliographic results* (GPR, 1874 - 1976) and *Solar Optical Observing Network, United States Air Force, National Oceanic and Atmospheric Administration* (SOON/USAF/NOAA, 1977 - present) - also known as the *Extended Greenwich results* (EGR, 1874 - present)

b) *Debrecen Photoheliographic Data* (DPD, 1974 - present),

c) *Kanzelhöhe sunspot drawings*[1] (1944 - present) - in this work processed in part, the results for the solar cycles no. 20 and no. 22. only.

We note that some results (meridional motions, torsional oscillations, Reynolds stress) concerning the EGR dataset have been presented in Sudar *et al.* (2014).

The main reason for the selection of these data sets among other data sets is the fact that the DPD, GPR and SOON/USAF/NOAA showed the lowest deviation in heliographic coordinates and calculated velocities in relation to the Kanzelhöhe data set (Poljančić *et al.*, 2011). In Poljančić *et al.* (2011), the comparison of selected data sets was done for the years 1972 and 1993 belonging to similar declining phases of the solar cycles no. 20 and no. 22, respectively. For this reason, here we analyse the whole solar cycles no. 20 and no. 22, considering the years specified in Table 1 from Brajša *et al.* (2009) as their starting and ending points (solar cycle 20: 1964.8 - 1976.3; solar cycle 22: 1986.7 - 1996.4).

[1] <http://cesar.kso.ac.at/synoptic/draw_years.php>

Table I: Number of velocities calculated for different solar cycles and methods, as noted.

Cycle	Method	Number of velocities calculated
20	DS	5399
20	LSQ	1619
22	DS	8346
22	LSQ	2097

2. Methods

The positions of sunspot groups were determined using a special software for determination of tracer′s positions in full disk solar images - *Sungrabber* (Hržina *et al.*, 2007)[2]. Sunspot groups were identified with the help of the GPR and DPD databases, covering solar cycles no. 20 and no. 22, respectively. In order to calculate the sidereal angular rotation rate ω and solar rotation parameters A and B we used two methods:

a) the daily-shift method (DS) - rotation velocities were calculated from the daily differences of the Central Meridian Distance (CMD) and the elapsed time:

$$\omega_{syn} = \frac{\Delta CMD}{\Delta t} \tag{1}$$

b) the linear least-squares fit method (LSQ) from the function $CMD(t)$ for each tracer.

In order to avoid solar limb effects, we limited the data to $\pm 58°$ in CMD which covers about 85% of projected solar radius (Balthasar *et al.*, 1986). With such a cutoff we obtained a sample of 17461 calculated sidereal rotation velocities (numbers of sidereal velocities calculated for each solar cycle and each method are given in Table I). Conversion of rotation velocities from synodic to sidereal ones was done using the procedure described in Roša *et al.* (1995) and Brajša *et al.* (2002). Calculated sidereal velocity values have been used in the fitting to the solar differential rotation law:

$$\omega(B) = A + B \sin^2 b \quad . \tag{2}$$

[2] <http://www.zvjezdarnica.hr/sungrabber>

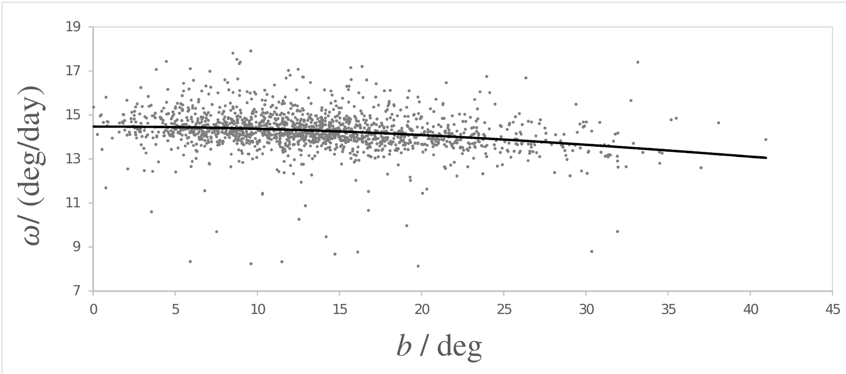

Figure 1: Values of rotational velocities calculated by the LSQ method for the solar cycle no. 20 with the corresponding fit (Eq. 3).

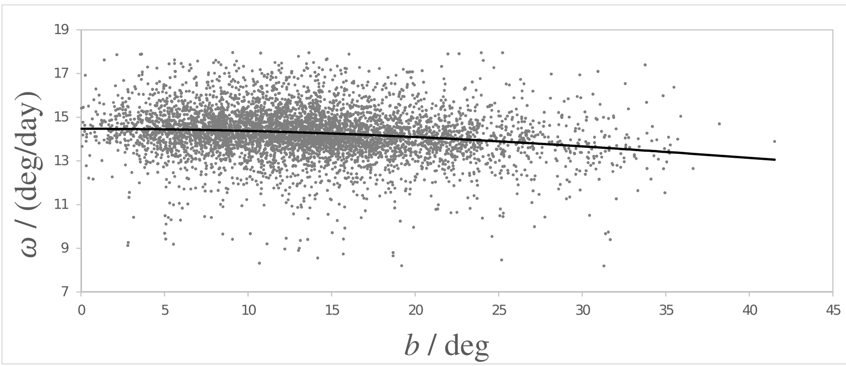

Figure 2: Values of rotational velocities calculated by the DS method for the solar cycle no. 20 with the corresponding fit (Eq. 4).

We limited calculated sidereal rotation velocities to 8 - 18° per day (to eliminate any gross errors resulting from misidentification of sunspot groups). Thereby the elimination of 2% of the calculated velocities was done reaching the numbers from Table I. In the DS method, we assigned the velocity to the latitude and time of the first measurement of position. Olemskoy and Kitchatinov (2005) showed that by using average latitude false flows can be detected due to non-uniform distribution of the tracers in latitude.

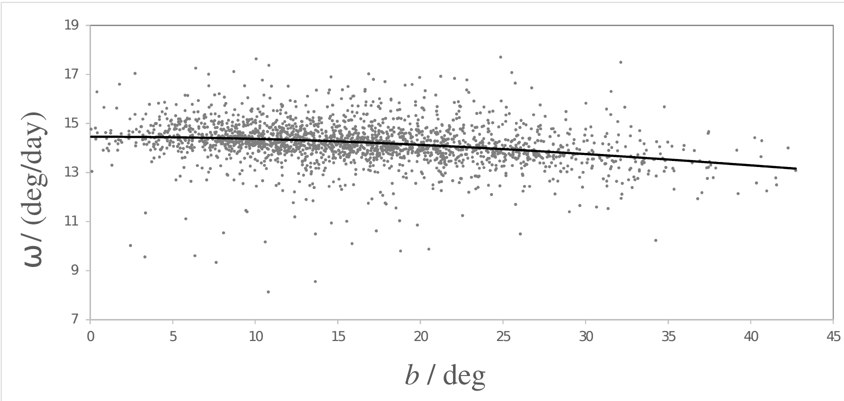

Figure 3: Values of rotational velocities calculated by the LSQ method for the solar cycle no. 22 with the corresponding fit (Eq. 5).

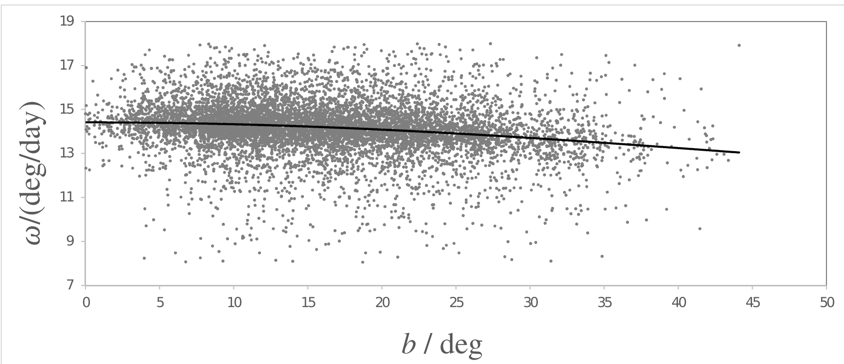

Figure 4: Values of rotational velocities calculated by the DS method for the solar cycle no. 22 with the corresponding fit (Eq. 6).

3. Results, discussions and conclusion

The solar differential rotation law (Eq. 2) is determined for solar cycles no. 20 and no. 22 treating the northern and southern hemispheres together ($|b|$ is used). Results of fittings for each solar cycle and each method:

$$Cycle20(LSQ): \quad \omega(B) = (14.47 \pm 0.03) + (-3.30 \pm 0.36)sin^2b \qquad (3)$$

$$Cycle20(DS): \quad \omega(B) = (14.47 \pm 0.02) + (-3.22 \pm 0.26)sin^2b \qquad (4)$$

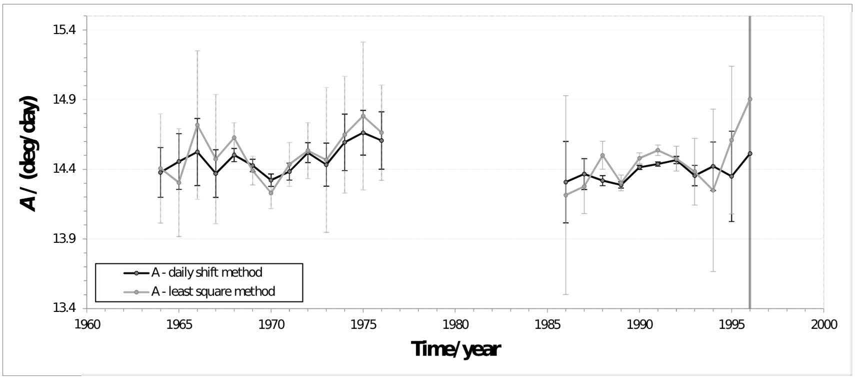

Figure 5: Time variation of the equatorial rotation rate during the solar cycles no. 20 and no. 22.

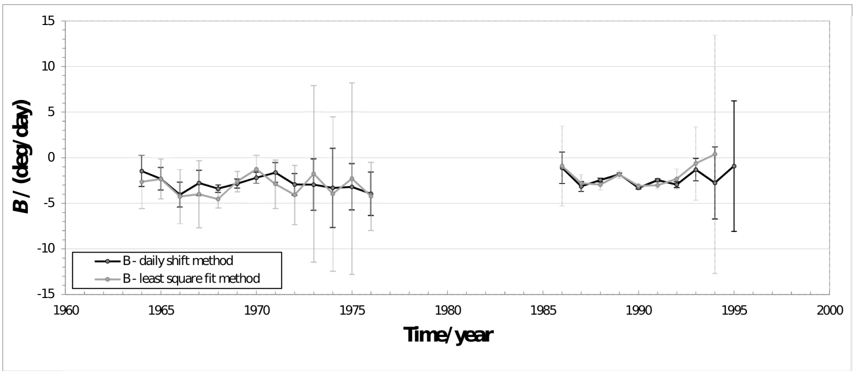

Figure 6: Time variation of the differential rotation coefficient B during the solar cycles no. 20 and no. 22.

$$Cycle22(LSQ): \quad \omega(B) = (14.46 \pm 0.03) + (-2.82 \pm 0.23) sin^2 b \tag{5}$$

$$Cycle22(DS): \quad \omega(B) = (14.41 \pm 0.02) + (-2.83 \pm 0.17) sin^2 b \tag{6}$$

In Figures 1 - 4 rotational velocity values and corresponding fits (Eq. 3 -6) are shown.

Our results for both solar cycles are in a qualitative agreement with earlier investigations (Balthasar *et al.*, 1986; Pulkkinen and Tuominen, 1998; Khutsishvili *et al.*, 2002).

Our results indicate slightly higher values of the equatorial rotation velocity toward the end of the cycles (activity minimum), although the errors show that these changes are not significant (Figure 5). Rotation parameter B toward the end of cycle no. 20 shows lower values (Figure 6). This can indicate anticorrelation of A and B (Balthasar and Wöhl, 1980).

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