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Angular velocity of sunspot-groups during the activity cycle deduced using the age selection methodology

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Abstract. Using Greenwich Photoheliographic Results collected during the period 1874-1981 and the Age Selection Methodology (Zappalá & Zuccarello (1991)), we have studied the variability of the sunspot-groups angular velocity in different phases of the activity cycle. The results indicate that during minima, all sunspot-groups, independently of their age, show the same increase in angular velocity, i.e. ∼ 0.16 degrees/day. Comparing our results with those regarding the internal angular velocity as deduced by p-mode oscillations, it is possible to conclude that the observed higher angular velocity during minima concerns several layers beneath the solar photosphere.

Key words. Sunspot-groups angular velcity – Activity cycle – Age Selection Methodology

1. Introduction

In previous works we pointed out that, when using sunspot-groups as tracers of the solar rotation, it is possible to minimize errors in the angular velocity determination if the Age Selection Methodology (ASM) (Zappalá & Zuccarello (1991)) is applied.
In particular, using the ASM, we found that sunspots-groups characterized by an age ≤ 3 days show, at all latitude strips, an angular velocity which is ∼ 0.3 degrees/day higher than that deduced by recurrent sunspots. Moreover, the angular velocity difference between young sunspots (hereinafter called Young Sunspot-Groups, i.e. YSG) and recurrent sunspots (RSG) decreases with time, until when the sunspots angular velocity reaches the values characteristic of the photospheric plasma (Zappalá & Zuccarello (1991)). Therefore, the differences in angular velocity of sunspot-groups characterized by different areas and different Zurich type can be interpreted as due to a single cause : the sunspot-group evolutionary state.
Moreover, if we suppose that the angular velocity of young sunspots corresponds to that of the layer where sunspots are initially anchored, the different angular velocity of variously aged sunspots is indicative of a variation of the solar angular velocity

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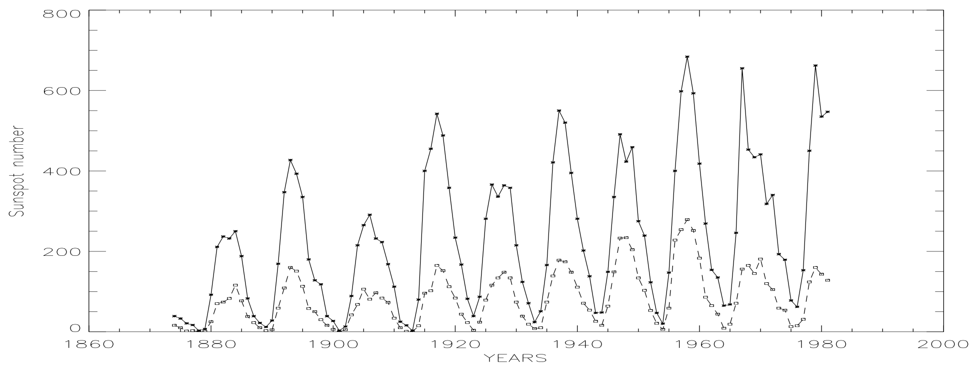

Fig. 1. Number of sunspot-groups as a function of the year. The continuous line indicates the number of YSG; the dashed line indicates the number of RSG.

with the solar radius. In this paper we focus our attention on the dependence of the sunspots angular velocity on the phase of the cycle : during minima, the sunspots rotation rate seems to be higher than during other phases of the cycle (Balthasar et al (1986)).

However, we stress that the above mentioned result has been obtained without taking into account the sunspot-groups evolutionary state, therefore it might be possible that it is affected by bias due to rotation rate determination obtained by non-homogeneous tracers.

In this context, the ASM can throw some light on this problem, in fact, if we take into account that YSG have a higher angular velocity compared to RSG, the higher rotation rate during minima can have two possible explanations : a) during minima the number of YSG is much higher than the number of RSG; b) the higher angular velocity during minima reflects a global behaviour of the Sun.

In order to verify whether one or both hypotheses are correct, we have used the ASM to calculate the rotation rate of differently aged sunspots over the solar cycle.

2. The Age Selection Methodology

The analysis has been performed using sunspot group data acquired during the period 1874 - 1981 and reported in Greenwich Photoheliographic Results (GPR) . The following daily parameters are given for each sunspot group : (i) observation time; (ii) Greenwich sunspot group number through 1976; NOAA/USAF group number after 1976; (iii) Mt. Wilson magnetic classification; (iv) Greenwich group 0-9 type through 1976; (v) observed umbral area in millionths of the solar disk; (vi) observed whole spot area in millionths of the solar disk; (vii) heliographic coordinates.

The data analysis is limited to a part of the solar disk bounded by $\pm 70°$ heliographic longitude from the central meridian and $\pm 40°$ latitude.

The Age Selection Methodology (ASM) is based on two fundamental steps (Zappalá & Zuccarello (1991)):

1) determination of the time of birth of the sunspot group; 2) selection in three classes : a) All Sunspot Groups (ASG); b) Young Sunspot Groups (YSG), i.e. $\leq$ 3-day old sunspots; c) Recurrent Sunspot Groups (RSG), i.e. $\geq$ 1 rotation;

The total number of phenomena reported in GPR is $\sim$ 35000, and, using the ASM, we have selected 34893 ASG, 25060 YSG ($\sim$ 72 %) and 8831 RSG ($\sim$ 25 %). The discrepancy between the sum of YSG and RSG and the numebr of ASG is due to the fact that, for some sunspot groups, it was not possible to determine the date of birth,

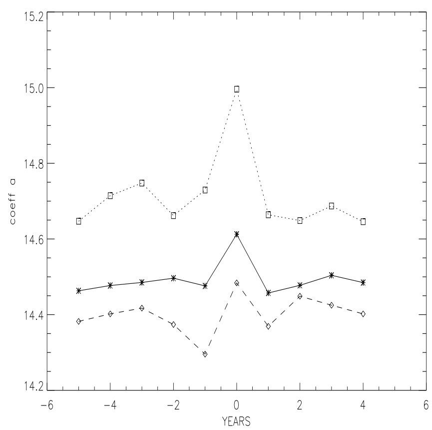

Fig. 2. Average value of coefficient a over 8 solar cycles as a function of the year in the cycle (year = 0 corresponds to the minimum) for ASG (continuous line), YSG (dotted line), RSG (dashed line).

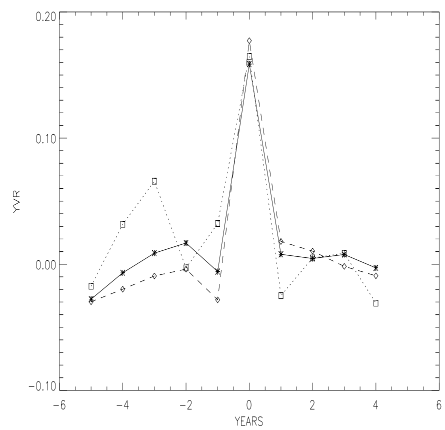

Fig. 3. Yearly Velocity Residuals over 8 solar cycles as a function of the phase in the cycle (in years) for ASG (continuous line), YSG (dotted line), RSG (dashed line).

neither to determine whether they were recurrent.
We found that the number of RSG is sistematically lower than the number of YSG during all the phases of the cycle. Moreover, the number of RSG is extremely low during minima (it is zero in the years 1878, 1901, 1913) and it increases when maxima are approaching (see Fig. 1).
In order to study the dependence of angular velocity of differently aged sunspots on the phase of the cycle, we have carried out an analysis concerning the determination of the following parameters :
1) coefficients a and b of the rotation law $\Omega(\theta) = a + b sin^2\theta$;
2) residuals of the annual average sunspot group rotation rate (Gilman & Howard (1984)).

As to coefficients a and b, these have been calculated, for each year and for each class of sunspot groups, by the least square method.
In order to calculate the residuals, we have determined, for each class of objects, the annual average rates in bins of 5° latitude ($\bar{v}_{i,l,k}$, where i is the year, l is the latitude strip and k is the class). Then we have determined the "grand" average sunspot angular velocity $< V >_{l,k}$ on the entire period of observation (108 years) for every latitude bin. Successively, we have determined the difference between the annual average rates for each bin and class and the grand average sunspot angular velocity, obtaining the value of the annual average residuals for each latitude strip :

$$\Delta v_{i,l,k} = \bar{v}_{i,l,k} - < V >_{l,k} \quad (1)$$

Then we have combined the yearly average residuals for different bins (i.e. $\sum_{l=1}^{n} v_{l,k}$) weighed according to the number of observations in each bin. This parameter is indicated as Yearly Velocity Residual (YVR). The results obtained from the angular velocity determination can be summarized as follows :

- for all the three classes of objects examined, parameter a, averaging over 8 solar cycles, has its maximum value when the minimum of activity occurs (see Fig. 2);
- the average value of a over 108 years is : $a_{ASG} = 14.6$ degrees/day, $a_{YSG} = 14.8$

degrees/day, $a_{RSG} = 14.4$ degrees/day. Therefore it is $a_{RSG} < a_{ASG} < a_{YSG}$;
- the average value of YVR at minima is the same for ASG, YSG and RSG ($\sim$ 0.16 degrees/day), indicating that for each class of objects, independently of their age, there is the same increase in the angular velocity during minima (see Fig. 2);
- the values of a and of the YVR are anticorrelated with the sunspot group number for ASG, YSG and RSG;
- the analysis of parameter a for YSG shows that the angular velocity is higher during cycles with a lower number of sunspot groups;
- for all the three classes of objects examined, the analysis of parameter b over 108 years shows a tendency to a less differential rotation when minima are approaching.

The main conclusion we can draw from these results is that, during minima, the angular velocity increases of the same amount for all the three classes.

3. Conclusions

Beck (1999) has compared the rotation rates deduced by several authors who used sunspots as tracers with the rotation rates of supergranulation cells and he found that young sunspots and supergranulation cells where characterized by higher angular velocity. Moreover, Beck (1999) compared the rotation curves at various depths obtained by the inversion of heliosmeismological data acquired by MDI and GONG. From this comparison it was inferred that the rotation rate increases from the solar surface toward the internal layers and reaches the maximum value at $0.93R_\odot$. Moreover, the layer at the depth of $0.71R_\odot$, which corresponds to the base of the convection zone, rotates slower than the surface. The comparison between the rotation curves deduced by the inversion of helioseismological data and the surface rotation rate deduced by YSG and supergranulation cells shows that the last ones have a higher rotation rate.

An artifact of inversions is that possible velocity variations on narrow ranges are averaged, therefore the difference between the velocity of supergranulation cells and of young sunspot-groups and that deduced by oscillations may be due to this problem. On the basis of this hyothesis, we obtain that YSG are indicative of the rotation rate at a depth of $0.93R_\odot$, corresponding to $\sim$ 50000 km from the solar photosphere, while RSG are indicative of the rotation rate at a depth of $0.98R_\odot$, corresponding to $\sim$ 14000 km. Moreover, we recall the result, obtained from the analysis of the rotational splitting of p-mode oscillations, concerning the higher rotation rate at minima at a depth of $0.4R_\odot$ (Goode & Dziembowski (1991)).

We have therefore indications that at least three layers, at different solar radii, show an acceleration when the magnetic activity is reduced to the minimum.

Therefore, despite the fact that during minima the number of RSG is lower than during other phases of the cycle, and consequently $\Omega(\theta)$ deduced by non-selected sunspot-groups might be affected by the greater statistical weight of young and short-lived objects, we conclude that the higher angular velocity during minima is due to a process which involves several internal layers of the Sun.

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