Differential rotation of sunspot groups as A function of their area

Bashir K. Abuzeid*

Faculty of Science, Misurata University, Libya

*b.abuzeid@sci.misuratau.edu.ly

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Abstract:

The rotation velocity of sunspot groups of two different area classes (small groups having an area A < 100-millionths of the solar hemisphere (msh) and large groups having an area A > 100 msh) were investigated using data from *the Greenwich Photoheliographic Results* (GPR) 1964 until 1976, that cover the solar cycle no. 20. It was found that the rotation velocity of the sunspot groups of both classes divide the rotation profile into two parts, the north hemisphere in which the small groups (A < 100 msh) move up to about 1.8 % more rapidly than the large groups (A > 100 msh) and the south hemisphere in which the small groups move down to about 2.5% less rapidly than the large groups at about –30 deg. At the equator the rotation rate of the small groups is about 1.4 % faster than the large groups.

Keywords: Sunspot groups, Solar Differential Rotation, Area of Sunspots, Solar Cycle, and Sun.

الدوران التفاضلي لمجموعات البقع الشمسية كدالة على مساحتها

بشير خليفة أبوزيد*
كلية العلوم - جامعة مصراتة
*b.abuzeid@sci.misuratau.edu.ly

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الملخص:

تم التحقيق في سرعة دوران مجموعات البقع الشمسية من فئتين مختلفتين من حيث المساحة، (مجموعات صغيرة مساحتها $A < 100$ msh (مليون جزء من نصف الكرة))، و(مجموعات كبيرة مساحتها $A > 100$ msh). باستخدام بيانات نتائج التصوير الضوئي الشمسي لغرينتش (GPR)، خلال الفترة الزمنية ما بين عام 1964م وعام 1976م، والتي تغطي الدورة الشمسية رقم 20. وقد وجد أن سرعة دوران مجموعات البقع الشمسية من كلا الفئتين تقسم منحنى الدوران إلى قسمين. حيث وجد أنه في حالة نصف الكرة الشمالي تتحرك المجموعات الصغيرة ($A < 100$ msh)، بنحو 1.8% أسرع من المجموعات الكبيرة ($A > 100$ msh)، وفي نصف الكرة الجنوبي حيث تتحرك المجموعات الصغيرة بنحو 2.5% أقل سرعة من المجموعات الكبيرة عند حوالي (30−) درجة. أما عند خط الاستواء، يكون معدل دوران المجموعات الصغيرة أسرع بنحو 1.4% من المجموعات الكبيرة. كذلك تم حساب ورسم منحنى سرعة دوران المجموعات الشمسية التي تم اختيارها حسب الشروط التي تم تحديدها، (عمر المجموعة لا يقل عن ثلاثة أيام وفقط المجموعات الواقعة بين ±30 درجة)، حيث اتضح أن سرعة دوران المجموعات الشمسية عند خط الاستواء $\omega(\varphi) = 14.5$ يوم/درجة، وتقل السرعة باتجاه الأقطاب لتصل $\omega(\varphi) = 14.0$ يوم/درجة عند 30 درجة شمالاً و $\omega(\varphi) = 13.8$ يوم/درجة عند 30 درجة جنوبًا.

الكلمات المفتاحية: مجموعات البقع الشمسية، الدوران التفاضلي الشمسي، مساحة البقع الشمسية، الدورة الشمسية، الشمس.

1. Introduction:

The rotation of the sunspots is a very important phenomenon provided us by the information about how the sun works, Where, Christoph Scheiner in 1863, studied the rotation of the sunspots and discovered that at the equator the sunspots move faster than sunspots at higher latitudes (Paterno, 2009). Using long-period data, Christoph Scheiner derived a differential rotation equations in the function of latitude. However, the idea of the sun's differential rotation has not been received and appreciated at that time. In 1860, Richard Christopher

Carrington observed the Sun and determined the rotation period of the Sun based on latitude. So, it is known that Sunspots around the equator have 25-day rotation period, while sunspots at about ±45 deg latitude have 28-day rotation period. Since the work of Carrington (1863), many studies have been concentrated on the field of the sunspot group rotation especially in the latest years (for some analysis of older observational data, (Abarbanell & Wöhl, 1981), (Arevalo et al., 1982), (Balthasar et al., 1986), (Eddy et al., 1976), (Herr, 1978), (Yallop et al., 1982)). Solar differential rotation is one of the main effects that play a role in the solar dynamo mechanism, (Nagovitsyn et al., 2018). Also, solar rotation profile is one of the key inputs of the solar dynamo model, which provides an important constraint for the solar dynamo model, (Kutsenko, 2021), (Ruždjak et al., 2017). The rotation of the sunspot groups can be influenced by some factors like their lifetime, (Newton & Nunn, 1951), their position on the solar surface, (Howard & Gilman, 1984), (Hoyng, 1992), and their area, (Abuzeid & Marik, 1997), (Arevalo, 1982), (Godoli & Mazzuconi, 1979), (Howard, 1984), (Howard & Gilman, 1984), (Nagovitsyn et al., 2018), (Newton & Nunn, 1951), (Permata & Herdiwijaya, 2019), (Ward, 1966), (Zappalá & Zuccarello, 1991). Ward (1966) used the Greenwich observations to measure the rotation rate of sunspot groups observed between 1905 and 1954. He concluded that large groups tend to rotate more slowly than small ones, and sunspot groups with large areas move less rapidly on average than small groups. Godoli and Mazzucconi (1979), analyzed the Greenwich sunspot data for Solar Cycle no. 18 and discovered that larger sunspot groups rotate at slower rates.

In this paper our main point is to show the effect of the area of a sunspot group on the rotation velocity by using a large number of sunspot groups taken from the Greenwich Photoheliographic Results (GPR), for the years 1964 until 1976, (time interval of solar cycle no. 20). The rotation curve of the cycle no. 20 is also investigated and shown in Figure (2), and the data are given in Table (2).

The data and the method are described in the next section. The results are presented in Section 3. The discussion and conclusions are in Sections 4,5.

2. Data and Method:

The analysis is based on sunspot data reported in the Greenwich Photoheliographic Results (GPR), for the years 1964-1976 that cover the solar cycle no.20. Due to the comments given in the Greenwich sunspot group reports 1874-1981, the informations about the time, coordinates, magnetic classification, type, area and the distance from the center of the solar disk for the sunspots are given. As a condition of our research, not all sunspot groups were interesting for our investigation, only those sunspot groups have at least three days lifetime and located between latitudes ±35 deg. These conditions make the determination of rotation velocity of the sunspot groups more precisely and easy, because the method we used can't decide a good result if a sunspot group is observed twice (two days life-time), and the number of groups over ±35 deg is small, that sometimes we could not calculate the mean value which gives a good approximate result for the rotation rate. According to our conditions, through this research in the given period (Total = 3308 sunspot groups), it was found a number N=1327 of sunspot groups which were located between the latitudes ±35 deg, (~ 40% of the total number), and by using a computer technique it was separated the whole sample into two parts according to two area classes; Class I includes all spot groups with an area A < 100 msh (corrected whole area in millionths of solar hemisphere) and Class II includes all spot groups with an area A > 100 msh. N_S=1151 groups were classified as small groups and only N_L =176 were large groups. The sidereal rotation rate $\omega(\varphi)$ is obtained for each data point by determining the daily shift in longitude, then the averaged rotational rate $\omega(\varphi)$ for each latitude belt was calculated for the two classes. The least mean-squares method is used for the two classes (I,II), to fit a rotation with a latitude dependence given by the expression;

$$\omega(\varphi) = A + B \sin^2\varphi \qquad (1)$$

Here, φ is the latitude, A and B are parameters determined for the period of each class (Gupta et al. 1999), (Herr, 1978). The selected number (N=1327) of sunspot groups is again used to investigate the rotation rate of sunspot groups of the solar cycle no. 20.

3. Results:

3.1. Rotation Profiles for Tow Different-area Sunspot Groups.

By using a least-squares fitting method to fit Equation (1), we obtain differential rotation profiles for the tow different-sized sunspot groups, (Class I, Class II). Both sidereal rotation rates for the selected area classes of the given period (1964-1976), are presented in Figure 1. The lines through these data points represent the fits obtained using the expression $\omega(\varphi) = A + B \sin^2\varphi$. The fitted law of the differential rotation for the small sunspot groups (Class I with A < 100 msh), eq.(2), and the large sunspot groups (Class II with A > 100 msh), eq.(3), are, respectively:

$$\omega(\varphi) = 14.55 - 2.61 \sin^2\varphi \qquad (2)$$

$$\omega(\varphi) = 14.45 - 2.07 \sin^2\varphi \qquad (3)$$

Looking at Figure (1), it is clear that the sunspot groups for both classes show the usual rotation curve (being latitude dependent). At about +30^o the rotation velocity of the small groups is $\omega(\varphi)$ = 13.97 deg/day (faster), and for the large groups $\omega(\varphi)$ = 13.70 deg/day (slower). At the equator the small groups rotate with a rotation velocity $\omega(\varphi)$ = 14.54 deg/day and the large groups rotate with a rotation velocity $\omega(\varphi)$ = 14.44 deg/day. At about –30^{o} the situation is different (reverse), the small groups rotate with rotation rate $\omega(\varphi)$ = 13.83 deg/day (slower), and the large groups rotate with rotation rate $\omega(\varphi)$ = 14.16 deg/day (faster), this lead us to an interesting result, (In the southern hemisphere, the rotation rate of both classes is reverse). The graph can be divided into nearly two equal parts. The right hand part contains sunspot groups of the north hemisphere in which the small groups rotate faster than the large groups in all the latitude belts with a difference $\Delta(\varphi)$ ~ 1.8 %, this difference becomes smaller near the equator to about $\Delta(\varphi)$ = 1.4 %. The left hand side of the graph contains almost sunspot groups of the south hemisphere showing an interesting and very significant result that large groups rotate faster than the small groups and this is an unusual result (usually large groups rotate slower), the difference $\Delta(\varphi)$ ~ 2.5% is the maximum at about –30 degrees. This unusual behavior of the sunspot groups can lead us to an important effect which cannot be explained yet.

In addition, regarding the values of the rotation velocities of both small and large groups, in general the rotation velocity of the groups in the southern hemisphere show faster rotation than in the northern one.

In Table (1) the mean values of the sidereal rotation velocities of both classes are given for zones of 5 deg in latitude with the considered numbers N_S of the small sunspot groups and N_L of the large sunspot groups. Considering our results, it is clear that the rotation velocity of sunspot groups depends very strongly on their area as well as other factors like their life-time and their coordinates.

3.2. Rotation Profile for Sunspot Groups of Solar Cycle no.20.

In this section we show the profile of the investigated rotation rate of sunspot groups of the solar cycle no. 20. From the Greenwich Photoheliographic Results (GPR) we selected sunspots of the period 1964-1976 that cover the solar cycle no. 20 to our investigation. According to the GPR, the whole period contain about 3308 sunspot groups. We selected only sunspot groups have at least 3 days life-time and those located between latitudes ±35 deg. According to these conditions we could select 1327 sunspot groups, that is about 40% of the whole sunspot groups observed during the given period. The least mean-squares method is used to fit a rotation with a latitude dependence given by the formula $\omega(\varphi) = A + B \sin2 \varphi$. we get sidereal rotation rates of the latitude belts from the selected sunspot groups. Table (2) lists the rotation rates given in deg/day for each latitude belt of 5 deg and the number N of considered sunspot groups in each belt. The rotation rate profile with a mean error bars have been plotted for the latitude belts, and shown in Figure (2). The circles shown in the figure represent the averaged rotation rate taken for the considered sunspot groups in each latitude belt, where the curve represents the fit obtained by using the rotation law $\omega(\varphi) = A + B \sin^2 \varphi$. The fitted rotation law in this case is given by the following formula:

$$\omega(\varphi) = 14.52 - 2.48 \sin^2 \varphi \qquad (4)$$

The rotation curve indicates a latitude dependence profile. At the equator it is found that the sunspot groups rotate with $\omega(\varphi) = 14.5$ deg/day, this value changes to smaller as we move toward the poles. In the north hemisphere at about 30 deg, the rotation rate $\omega(\varphi) \sim 14.0$ deg/day, while in the southern hemisphere at about -30 deg, the rotation rate is slower, $\omega(\varphi) \sim 13.8$ deg/day. Looking to the curve, it is clear that at the equator the sunspot groups rotate with 40% faster than sunspot groups at ±30 deg. In general, sunspot groups in the northern hemisphere rotate about 1.4% faster as compared with sunspot groups of southern hemisphere. From the values listed in Table (2), it is clear that the number of considered sunspots in the northern hemisphere (N=714) is larger than in the southern hemisphere (N= 613).

4. Discussion:

Sunspot groups data collected during 13 years of observations (GPR), have been analyzed using a least mean-squares method. The usual behavior of the rotation speed of sunspot groups, which depends on the difference in latitude, as this difference leads to a change in the speed depending on the location of the group. More precisely, small groups rotate faster than large groups because they suffer smaller drag force of the surrounding plasma, (Godoli & Mazzuconi, 1979), (Howard & Gilman, 1984), (Jha et al., 2021), (Petrovay et al., 1990), (Ward, 1966). It can be also that some of them are young groups connected to deep faster rotating layers, (Balthasar et al., 1986), (Livingston et al., 2006). On the other side large groups rotate slower than the small ones because of the larger resistant drag force. In the case of the north hemisphere our results of the rotation velocities confirm with those obtained by, Arévalo et al. (1982), and Balthasar et al. (1986). Ward (1966), declared that large groups move up to 2 % less rapidly than small groups for the period 1905-1954. The results of Arévalo et al. (1982) for the period 1874-1902 and the results of Balthasar et al. (1986), for the period 1874-1976 show the same qualitative behavior as the results obtained by us. Also Gupta et al. (1999) used the Kodaikanal sunspot data set for the period 1906–1987 to examine the differential rotation of different-sized sunspots and they discovered that smaller sunspots rotate more quickly than bigger ones. This result is in good agreement with our results. In our results, the differences in the values of the rotation velocity is small because we investigating a different period and using a different method. In the case of the south hemisphere our result show an interesting behavior of the groups as the large groups move more rapidly than the small groups, this opposite result may be explained by the opposite direction of the magnetic field in both hemispheres as the sunspot groups follow the direction of the magnetic field, (Hale & Nicholson, 1925). This can be decided in another investigation. The above mentioned investigators gave the mean rotation velocities between the north and south hemispheres while we calculated the rotation velocity of both hemispheres separately.

We therefore believe that from now on, it will be necessary to take into account the influence of the sunspot group area on the solar rotation curves determination. It is also clear that we still need other investigations to declear the asymmetry-hemisphere rotation velocity.

Table (1): Rotation Velocity for both Classes

The sidereal rotation velocities of the sunspot groups (in deg/day) for the two area classes (Class I with A <100 msh and Class II with A >100 msh), and the considered number of sunspot groups N_S, M_L for small and large groups of each latitude belt during the investigated period 1964-1976, (time interval of solar cycle no. 20).

Latitude Belts ***(deg)***	**Class I** ***(A<100 msh)***	**Class II** ***(A>100 msh)***	N_S ***(A<100 msh)***	N_L ***(A>100 msh)***
30 - 35	14.06	13.57	26	4
25 - 30	14.08	13.60	48	1
20 - 25	14.04	14.25	102	16
15 - 20	14.22	14.12	144	24
10 - 15	14.40	14.21	143	30
5 - 10	14.66	14.45	97	25
0 - 5	14.45	14.55	49	5
0 - –5	14.65	14.54	41	7
–5 - –10	14.51	14.36	112	18
–10 - –15	14.38	14.25	153	22
–15 - –20	14.35	14.32	104	15
–20 - –25	14.04	14.26	73	6
–25 - –30	14.04	14.22	48	1
–30 - –35	13.64	14.31	11	2

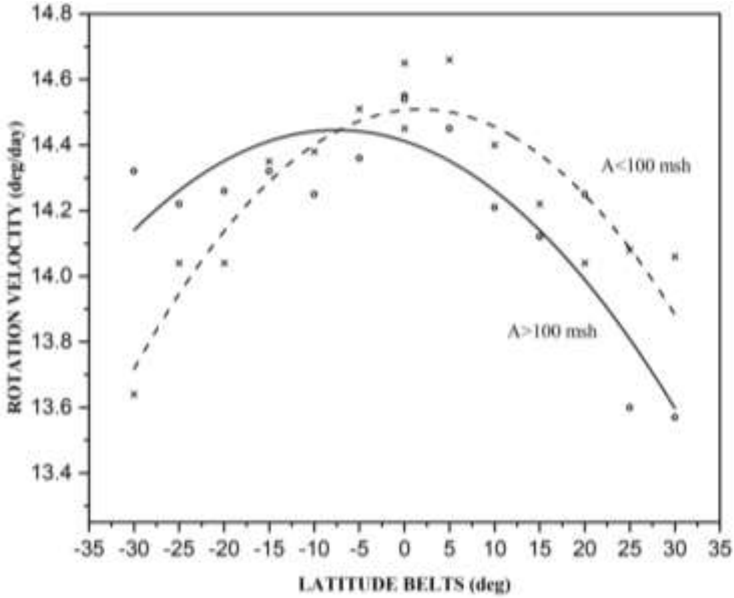

Figure (1): Differential Curves for both Classes

Figure 1. Sidereal rotation velocity for both area classes plotted against solar latitude belts. The dashed line with crosses belongs to the small sunspot groups (Class I with area A <100 msh). The solid line with circles belongs to the large sunspot groups (Class II with area A >100 msh). In the period 1964-1976, (time interval of solar cycle no.20).

Table (2): Rotation Velocity during Solar Cycle no. 20

Rotation rates of the selected sunspot groups through the period 1964-1976, cover the solar cycle no. 20.

Latitude Belts *(deg)*	Rotation Rate *ω(φ) (deg/day)*	Number of sunspot groups *(N)*
30 - 35	13.99 ± 1.75	30
25 - 30	14.06 ± 1.82	49
20 - 25	14.07 ± 2.62	118
15 - 20	14.20 ± 1.97	168
10 - 15	14.36 ± 2.28	173
5 - 10	14.61 ± 2.35	122
0 - 5	14.46 ± 1.88	54
0 - –5	14.63 ± 1.05	48
–5 - –10	14.49 ± 2.31	130
–10 - –15	14.36 ± 2.22	175
–15 - –20	14.34 ± 2.43	119
–20 - –25	14.05 ± 2.69	79
–25 - –30	14.04 ± 1.74	49
–30 - –35	13.74 ± 1.42	13

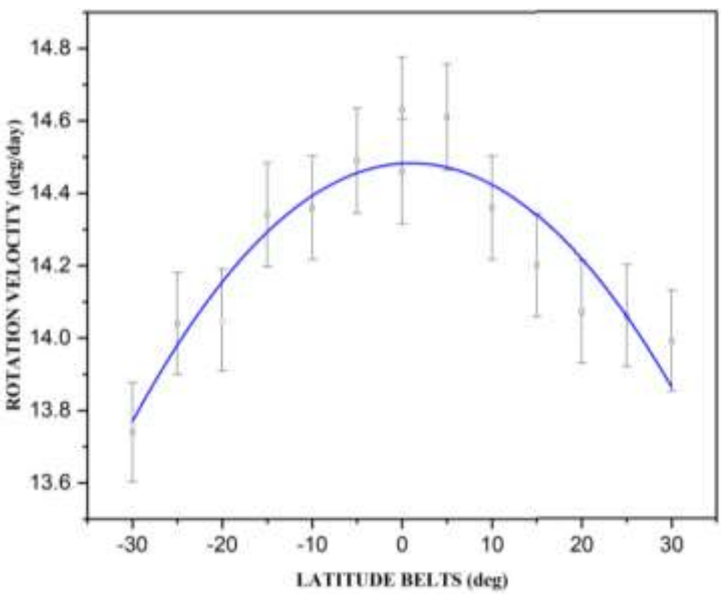

Figure (2): Differential Rotation Curve of the Solar Cycle no. 20

Figure 2. The differential rotation curve of the selected sunspots through the period 1964-1976, (time interval of solar cycle no.20).

5. Conclusion:

With an emphasis on how this rotation varies according to the area of sunspot groups, the manuscript investigates “Differential rotation of sunspot groups as A function of their area”. This is a useful study that clarifies solar dynamics and advances our knowledge of sunspot evolution and solar magnetic activity. To identify patterns in differential rotation concerning the sunspot group areas.

In conclusion, the study makes a significant contribution to solar physics, particularly because it focuses on sunspot group area and rotation rates in a novel way. With a few improvements, especially in the data's interpretation and visualization, this effort will yield even more significant discoveries.

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