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Change of rotation rates of sunspot groups during their lifetimes: Clues to the sites of origin of different flux tubes

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Abstract. From 103 years of data of non-recurrent sunspot groups and for the two sets (area <100 millionths of hemisphere and >100 millionths of hemisphere), irrespective of their life span, we compute rotation rates and rate of change of rotation rates during their lifetime. It is found that variation of rotation rates of sunspot groups with respect to their lifetime is approximately similar to the radial variation of internal rotation inferred by helioseismology and it is confirmed that all the spot groups decelerate as they evolve into later phases of their lifetime.

After classification according to different life spans, for the same two data sets, we compute initial rotation rates and rate of change of initial rotation rates of sunspot groups. For the two data sets, variation of initial rotation rates of sunspot groups with respect to their life spans is similar to the radial variation of internal rotation of solar plasma inferred from helioseismology. We also obtain the rate of change of initial rotation rates for two sets of spot groups and the results are as follows: (i) for the area <100, spot groups are accelerated for the life spans of 6–12 days and decelerated for the life spans of 3–6 days; (ii) for the area >100, acceleration for the life spans of 9–12 days and deceleration for the life spans of 3–9 days.

Interpreting these results, an attempt is made to locate the sites of origin of spot groups of different sizes and life spans in the convection zone.

Key words. Sun: sunspot – Sun: rotation

1. Introduction

It is believed that sunspots are formed near the base of the convection zone where the seat of the dynamo is supposed to be situated and are brought to the surface by buoyancy forces (Parker 1979). While rising towards the surface in the convection zone, the structure and dynamics of sunspots are influenced by external forces such as the Coriolis force, drag force, convective and turbulent forces, etc. Thus sunspots are reliable tracers that may yield information regarding structure and dynamics of the plasma beneath the surface. Several studies on rotation rates of sunspot groups indicate their relevance to underlying plasma dynamics. Ward's (1966) analysis indicates that groups having large areas rotate more slowly than the small spot groups. From the analysis of Greenwich sunspot data for the cycle No. 18, Godoli & Mazzucconi (1979) conclude that rotation rates of sunspot groups are independent of their lifetime and interpret that all the spot groups may originate from the same depth. Gokhale & Hiremath (1984), from the analysis of Greenwich sunspot data for the solar cycles 1923–1933, 1934–1944 and 1945–1954, find a general trend that spot groups accelerate during their initial phase and decelerate during their late phase, yielding a net deceleration over their lifetime. Balthasar et al. (1986) show that old spots rotate slower than young ones and further conclude that the rotation rates of initial phases of sunspots may yield crucial information about the depth of anchoring of the sunspot group. Recent studies (Touminen & Virtanen 1987; Zappala & Zuccarello 1991; Zuccarello 1993) give information regarding plasma rotation beneath the surface. Very recent studies (Javaraiah & Gokhale 1997, hereafter JG97; Javaraiah 2001) indicate that variation of rotation rates of sunspot groups with respect to their life spans is almost the same as the radial variation of internal plasma rotation as inferred by helioseismology (Antia et al. 1997). Though previous studies of rotation rates of sunspot groups provide some information on the rotation of the plasma beneath the surface, it is not clear whether all the spot groups of different sizes originate at a particular place, say near base of the convection zone as expected by dynamo theories, or spot groups of different sizes originate at different places in the convective envelope. In order to confirm and delineate these views, for different areas of sunspot groups and irrespective of their life spans, we determined average rotation rates and rate of change

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of rotation rates. We also compute initial rotation rates and rates of change of initial rotation rates of the sunspot groups with respect to their different life spans. For interpretation of the results obtained in the following analysis, we use the plasma rotation inferred by helioseismology. Using a crude approximation to the momentum equation, we compute rate of change of rotation of the plasma and compare to the results obtained by the sunspot groups. This analysis enables us to speculate regarding the sites of origin of sunspot groups of different sizes and of different lifetimes. In Sect. 2, we describe the data used and the method of analysis. We present results in Sect. 3 and conclusions and discussion in Sect. 4.

2. Data and analysis

For the present analysis, we use the data of the Greenwich Photoheliographic Results obtained from `http://wwwssl.msfc.nasa.gov/ssl/pad/solar/greenwich.htm` which is accessible by the public. We adopt almost all the criteria, as used in the previous studies (Balthasar 1986; JG97), in the selection of non recurrent sunspot groups for the analysis. However, we use the additional criterion that the spot groups whose rotation rates lie between 11–16 deg/day only are considered. Thus this will avoid the spot groups which have been influenced by torsional oscillations (Howard & LaBonte 1980) yielding only a steady part of the large-scale rotation. After selecting the proper data, we compute rotation rate ω and rate of change of rotation rate AD (acceleration or deceleration) as follows:

$$\omega_i = \frac{(l_{i+1} - l_i)}{(t_{i+1} - t_i)} \quad (1)$$

and

$$AD_i = \frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{(\omega_{i+1} - \omega_i)}{(\delta t_{i+1} - \delta t_i)}, \quad (2)$$

where l is the heliographic longitude from the central meridian, t is the time of observation, $\delta t_i = (t_{i+1} + t_i)/2.0$, $i = 1, 2, 3, ...n$, and n is the age of the spot group. We define life span of a spot group as the total number of days between the first and the last appearance on the same part of the solar disk satisfying the aforementioned criteria. We classify the data into two groups, viz., small spot groups which have areas <100 millionths of hemisphere (here afterwards *mh*) and large spot groups which have areas >100 mh. It is to be noted that this classification of area is not adhoc, since it has been established (Gokhale & Sivaraman 1981) that the distribution of sunspot groups with respect to areas falls distinctly into two groups viz., areas having <100 mh and areas having >100 mh. For a particular size of spot groups, we compute rotation rate ω and rate of change of rotation rate AD (acceleration if it is positive and deceleration if it is negative) as in Eq. (1) and (2) respectively.

3. Results

In the following analysis we use the combined data of 1874–1976, for the whole region of heliographic latitudes of 0° to 40° in both the hemispheres. This will ensure better statistics i.e., more data and hence less uncertainty in the results of rotation rates and rate of change of rotation rates. Another aspect of taking combined data in this region (0° to 40°) is that we want to compare the variation of rotation rates of the sunspot groups with the radial variation of rotation inferred by helioseismology. Though solar rotation varies from the equator to the latitude zone of 40° (∼1 degree/day corresponding to ∼30 nHz; see Balthasar et al. 1986; Zappala & Zuccarello 1991), the radial variation of the gradient of rotation (inferred by helioseismology) in the belt of sunspot latitude zone is similar. Hence we combined the data set of rotation rates of the sunspot groups for the latitude zone of 0° to 40°. It is to be noted that, in addition to Greenwich data available from 1874 to 1976, data are also available up to the present date on the web site. However, for the sake of easy computer programming and in order to keep the continuity of group numbers, we use the data from 1874–1976 only. For the sake of comparison with the solar internal rotation, as inferred by helioseismology, rotation rates of sunspot groups are computed in units of nHz. Errors quoted in the following rotation rates are computed as: $\frac{\sigma}{N^{1/2}}$, where σ is the standard deviation and N is the number of data points.

3.1. The results of ω and AD independent of life span of the sunspot groups

Firstly we classify the data into two data sets (<100 mh and >100 mh) and using Eqs. (1) and (2), we compute ω and AD. In Fig. 1a, we present the number of spot groups with respect to their age. The dotted line represents the area <100 mh and dashed line represents area >100 mh. In Fig. 1b, we present average rotation rates ω with the age of sunspot groups that are independent of their life spans. By dividing the convective envelope from the base ($0.695\,R_\odot$) to the surface ($1\,R_\odot$) into equally 11 parts and with an equal interval of $0.03\,R_\odot$, in the same Fig. 1b, we plot the internal rotation for the latitude of 15° as inferred by helioseismology. The reason that we have to select a rotation profile at the latitude of 15° only is as follows. The radial variation of the gradient of rotation profile inferred by helioseismology is similar for the latitude zones 0° to 40° and the maximum number of sunspot groups during the solar cycle emerge near this belt. We present the rate of change of rotation rates AD in Fig. 2a. The results presented in Fig. 1b are in agreement with the results of previous studies (Balthasar et al. 1986; Touminen & Virtanen 1987) that the old spot groups rotate slower than the young spot groups resulting in a net deceleration (see Fig. 2a) of rotation rates during their lifetimes. It is crucial to note that in Fig. 1b both the curves of rotation rates of spot groups, except rotation rates of spot groups which have an age ≤4 days, are similar to the curve of

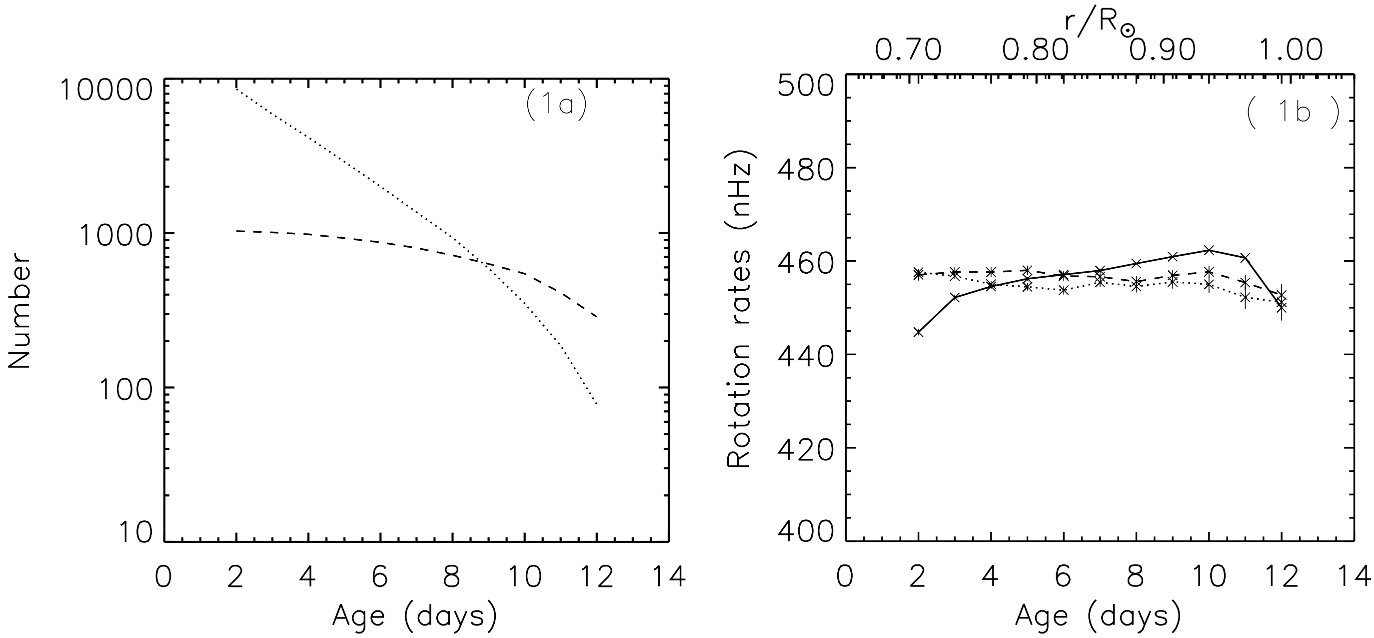

Fig. 1. a) Number of spot groups with respect to their age. The dotted line represents the area <100 mh and dashed line represents area >100 mh. **b)** Rotation rates ω of the sunspot groups with respect to their age. Continuous curve is helioseismologically inferred radial variation of rotation. Dotted curve represents the rotation rates of spot groups having areas <100 mh and dashed curve represents the rotation rates of spot groups having areas >100 mh. In the same plot, radius values are plotted along the top x axis.

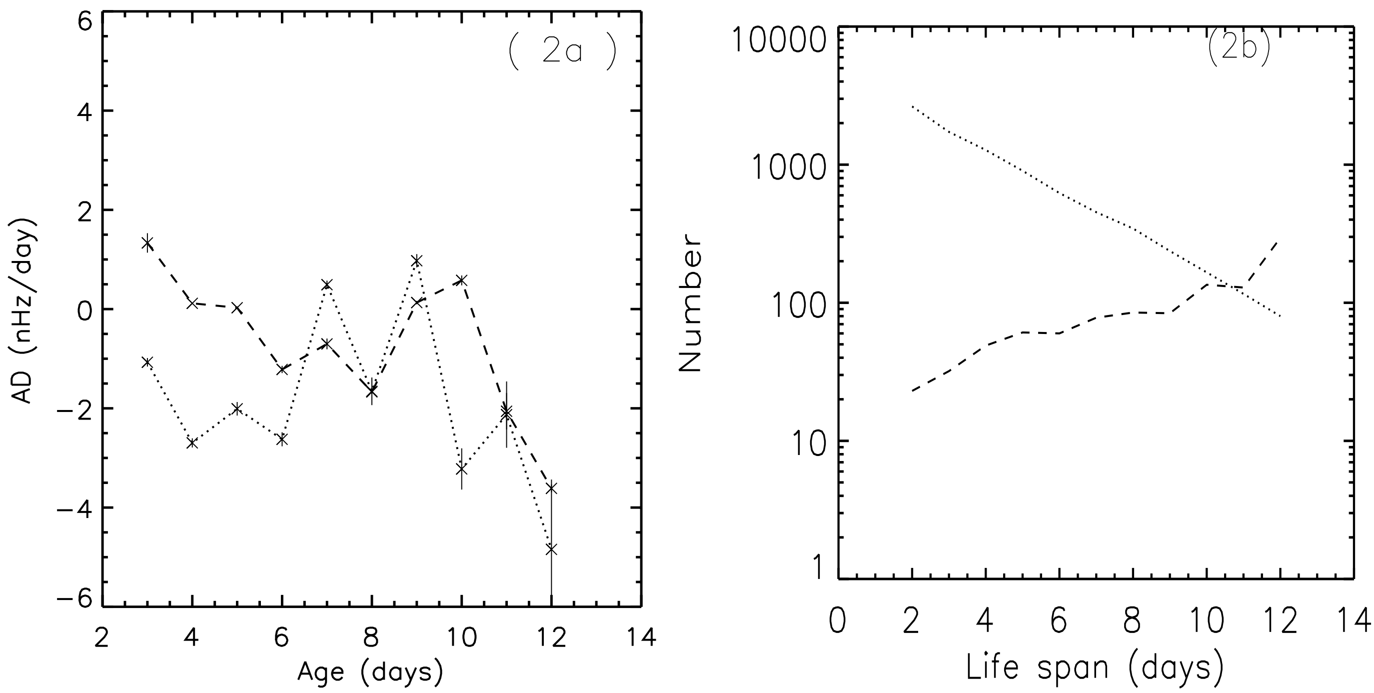

Fig. 2. a) Rate of change of rotation rates of sunspot groups with respect to their age. Dotted line represents the areas having <100 mh and dashed line represents the areas having >100 mh. **b)** Number of spot groups with respect to their life span. Dotted line represents the area <100 mh and dashed line represents area >100 mh.

radial variation of the internal rotation as inferred by helioseismology. The disagreement of rotation rate of spot groups below $\leq$4 days with the helioseismologically inferred rotation is due to mixture of life spans of all the spot groups. The large contribution of spot groups which have very small ($\leq$3 days) life spans and which may be rotating faster than the very low contribution slow rotating spot groups of long lifetime ($\geq$4 days) may be the reason for the aforementioned discrepancy. This hypothesis is justified by the following analysis wherein we compute initial rotation rates with respect to their different life spans. The aforementioned discrepancy will disappear in the following analysis.

3.2. Determination of ω_1 and AD_1 with respect to sunspot groups life span

After classifying the data into two groups of areas (<100 mh and >100 mh) and using Eqs. (1) and (2), we compute initial rotation rates ω_1 and rate of change of initial rotation rates AD_1 of sunspot groups with respect to their life spans. By computing these parameters we may get an idea at what depths sunspots may be originating and in turn we may get information on radial variation of rotation of the solar plasma beneath the surface. The number of spot groups with different life spans is presented in Fig. 2b. In Fig. 3a, we present ω_1 with respect to life span of sunspot groups for the two sets of areas. On the same curves, we plot radial variation of rotation inferred by helioseismology. Except in the case of large spot groups which are rotating slightly faster than the small spot groups, we get the same results as those obtained by JG97. Although large spot groups rotate faster than the solar plasma, the nature of curves of rotation rates of sunspot groups and rotation of the sun's internal plasma as inferred from helioseismology are similar. Now we justify our hypothesis as proposed in the previous section. Irrespective of their sizes, from Figs. 2b and 3a, it is clear that the spot groups having small ($\leq$4 days) life spans (in large numbers) rotate faster than the spot groups with long life spans. Thus this important fact may be the reason for the results presented in the previous section that the profile of rotation rates (with respect to their age) of spot groups whose lifetime is $\leq$4 days is different than the rotation inferred from helioseismology. The large error bars, for the spot groups having small ($\leq$4 days) life spans and areas <100 mh, may be due to greater dispersion in the rotation rates.

As in the analysis of JG97, we find a strong correlation between the two curves of rotation rates of sunspot groups and the solar internal rotation. The correlation coefficient for the area <100 mh is 0.8668 and that for the area >100 mh is found to be 0.7999. The high correlation between the curves of initial rotation rates of different sunspot groups and the curve of solar internal rotation inferred by helioseismology appears to indicate that rotation rates determined by sunspot groups really represent the solar internal plasma rotation. On the other hand, a very high correlation may sometimes be misleading in interpreting the results and initial rotation rates of sunspot groups need not represent actual plasma rotation. Thus after finding a correlation, one has to apply statistical as well as physical tests (see the following subsections).

For further statistical tests, in Fig. 3b, we plot the rotation inferred by helioseismology versus the initial rotation rates obtained from the analysis of sunspot groups. These results satisfy almost all the statistical criteria (Elmore & Woehlke 1996) including the criterion of homogeneity of the data which is clear from Fig. 3b. Moreover, the probability of correlation coefficients are found to be significant below less than 1% level (Fisher 1930). Thus, determined high correlation coefficients may not be due to a *casual* effect, it must be due to some *causal* effect. Applying a physical test in the following section, we delineate the *causal* effect.

3.3. Clues to the sites of origin of different sunspot groups

For the physical test, let us assume that sunspots of different sizes and of different life spans may originate near the base of the convection zone and rise towards the surface. We also assume that while the rise of the sunspots is balanced by the Coriolis force, buoyancy force, drag force, etc., the sunspots are mainly influenced by the ambient plasma rotation. Hence a naive conclusion is that the rising path of the flux tubes and thus rotation rates of sunspot groups represent the radial variation of solar internal plasma rotation. That means if we compute the rate of change of initial rotation rates ω_1, the spot groups that may originate in the belt of sunspot latitude zones and near the region of the base of convection zone up to $0.935\,R_\odot$ (see Figs. 1b and 3a, where we present radial variation of rotation curve inferred by helioseismology), we should get a positive value of AD_1 and for the spot groups that originate in the region between $0.935\,R_\odot$ to $1.0\,R_\odot$ we should get a negative value of AD_1. This is due to the fact that, in the radial variation of rotation profile inferred by helioseismology, we get a positive gradient of rotation from the base of the convection zone up to $0.935\,R_\odot$ and a negative gradient of rotation from $0.935\,R_\odot$ towards the surface. Thus the initial rotation rates of sunspot groups for different life spans may indeed represent the radial variation of the rotation of the solar plasma. In Fig. 4a, we present the results of rate of change of initial rotation rates AD_1 of sunspot groups which are similar to our expectation.

Once we establish that variation of the initial rotation rates of sunspot groups with respect to their life spans indeed represent the radial variation of solar internal plasma rotation, the question that arises then is do all the spot groups of different sizes originate near the base of the convection zone or in different places of the convective envelope or do different sizes of sunspot groups originate at different regions of the convective envelope. We therefore fit a straight line of the form $AD_1 = A + B\tau$, (where A and B are coefficients to be determined and τ is the life span of the spot group) to the results presented in Fig. 4a. By fitting a straight line to these AD_1 values, for two different sets of areas, we present the results in Figs. 4b and 5a. Note that in Fig. 5a, we have not included the point for the life span equal to 3 days; this is due to the fact that we get large uncertainties in the coefficients (A and B) of the least square fit compared to the coefficients of the least

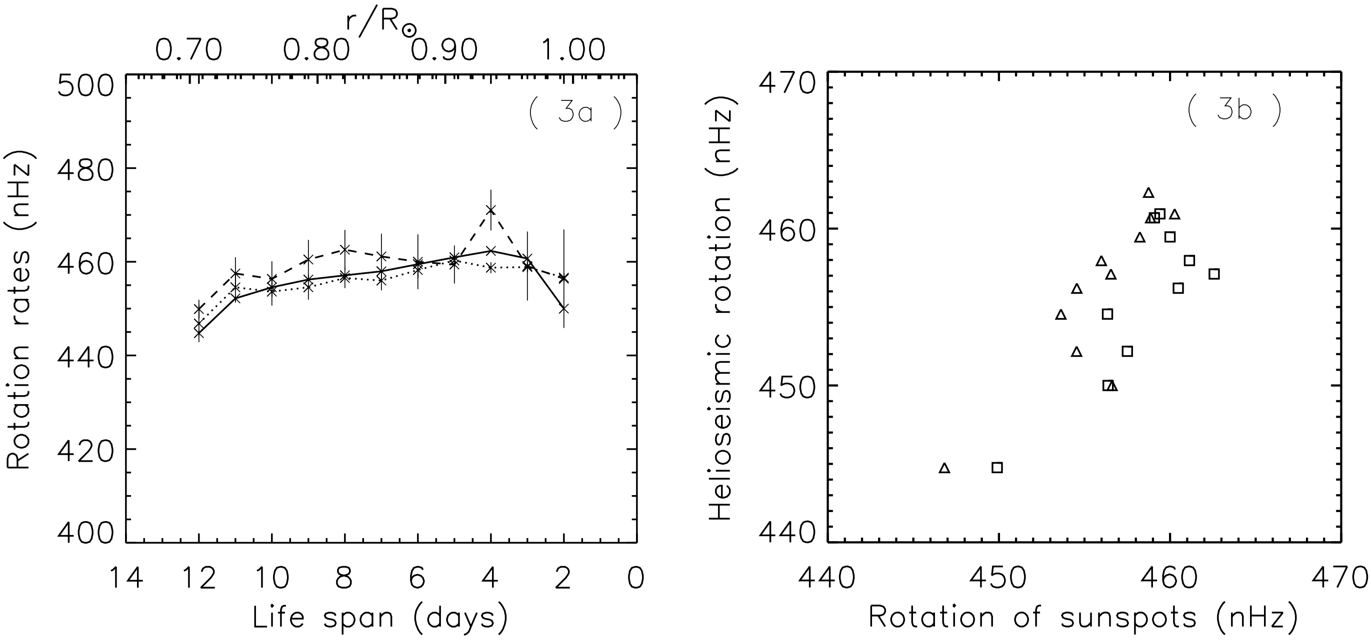

Fig. 3. a) Initial rotation rate ω_1 of the sunspot groups, with respect to their life span. Continuous curve is helioseismologically inferred radial variation of rotation. Dotted curve represents the rotation rates of spot groups having areas <100 mh and dashed curve represents the rotation rates of spot groups having areas >100 mh. In the same plot, radius values are plotted along the top x axis. **b)** Rotation inferred by helioseismology versus initial rotation rates of the sunspot groups. Signs of square values represent the areas having >100 mh and triangles represent the areas having <100 mh.

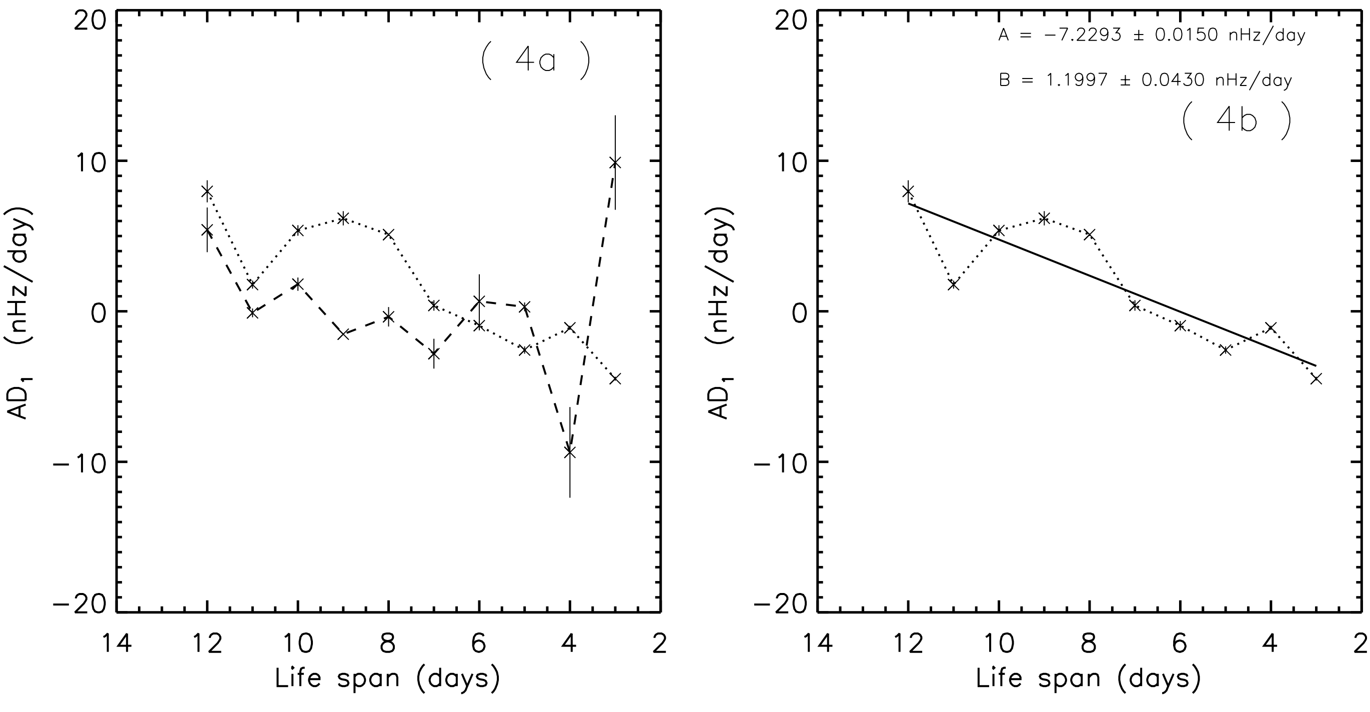

Fig. 4. a) Rate of change of initial rotation rates AD_1 of the sunspot groups for different life spans. The dotted line shows data on sunspots having areas <100 mh and the dashed line represents having areas >100 mh. **b)** Rate of change of initial rotation rates AD_1 of the sunspot groups for different life spans. The dotted line shows data on sunspots having areas <100 mh. Continuous line is a straight line fit to the AD_1 values.

square fit obtained by the data with life spans ≥4 days. From the straight line fit and, using determined coefficients A ($= -7.2293 \pm 0.0150$ nHz/day for the small spot groups and -8.8676 ± 0.9454 nHz/day for the large spot groups) and B ($= 1.1997 \pm 0.0430$ nHz/day for the small spot groups and 1.0252 ± 0.0433 nHz/day for the large spot groups), we can know the life span of spot groups of different sizes whose AD_1 values remain zero. For example, by taking a hint from the helioseismic rotation curve, one would expect that near $0.935\,R_\odot$ where the rotation

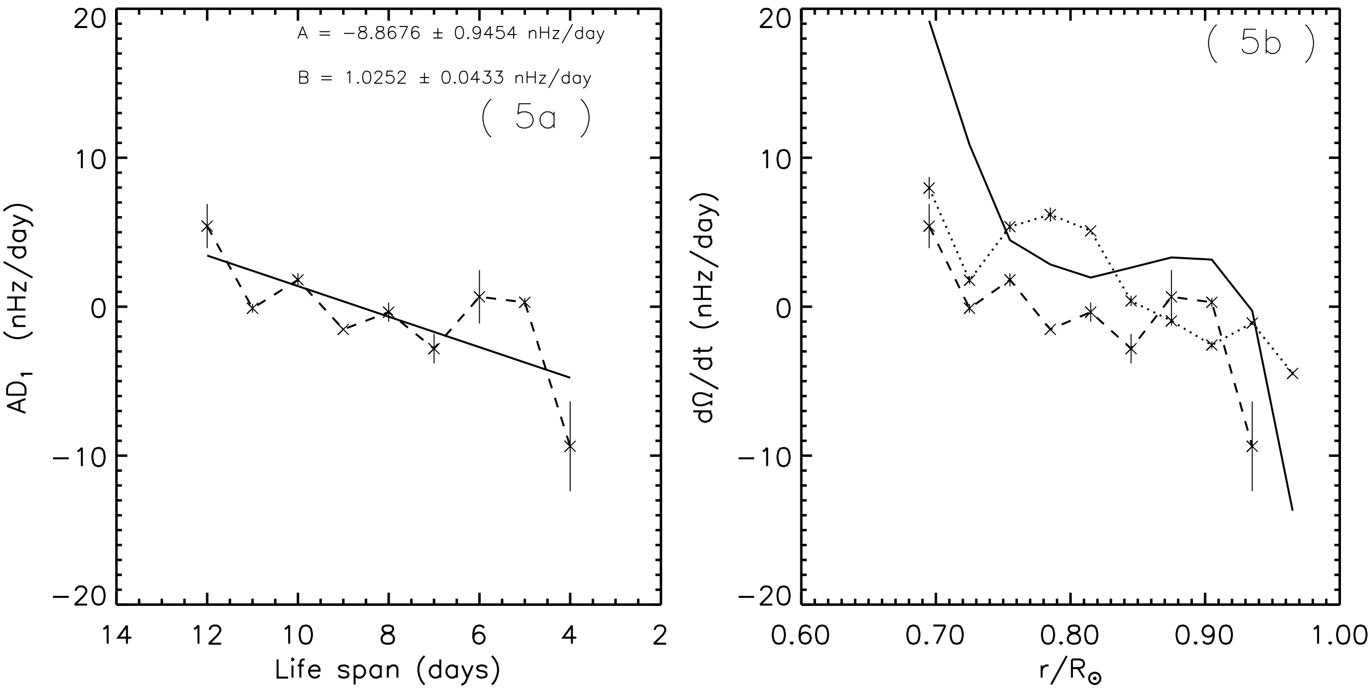

Fig. 5. a) Rate of change of initial rotation rates AD_1 of the sunspot groups for different life spans. The dashed line shows data on sunspots having areas >100 mh. Continuous line is a straight line fit to the AD_1 values. **b)** Rate of change of solar internal plasma rotation which is depicted as a continuous line. Where as AD_1 values presented in Fig. 4a are superposed on this figure.

curve is almost constant along the radius and the spot groups neither accelerate nor decelerate, the value of AD_1 must be zero. A least square fit to the data yields that for the small spot groups of areas <100 mh and for the life span of 6.03 ± 0.23 day, we get that AD_1 is zero. On the other hand the spot groups whose area is >100 mh have a zero value of AD_1 for the life span of 8.65 ± 1.3 day. This indicates that spot groups of area <100 mh whose life span is ≤6 days may originate in the region of the convective envelope from $0.935\,R_\odot$ to $1.0\,R_\odot$ and life spans greater than 6 days may originate below the region of $0.935\,R_\odot$. As for the areas >100 mh, spot groups which have a life span ≤9 days may originate in the region of $0.935\,R_\odot$ to $1.0\,R_\odot$ and life span greater than 9 days may originate below the region of $0.935\,R_\odot$.

4. Conclusions and discussion

Using the Greenwich Photoheliographic Results of non-recurrent sunspot groups for the data set of 103 years and irrespective of their life spans, we compute the rotation rate ω and rate of change of rotation rate AD of the spot groups. Our conclusions are as follows:

1. It is confirmed that young spot groups rotate faster than old spot groups and there appears to be a net deceleration as spot groups evolve to a later phase of their lifetime.
2. Except near early phases of the lifetime of sunspot groups, in later phases, rotation rates are approximately similar to the internal plasma rotation as inferred by helioseismology. This discrepancy is due to the large contribution of spot groups which have very small (≤4 days) life spans and which may be rotating faster than the very minor contributions of slow rotating spot groups with a large span of lifetimes (>4 days).

For the same set of data, we compute initial rotation rate ω_1 and rate of change of initial rotation rate AD_1 of sunspot groups for different life spans and conclude that:

1. In accordance with the previous study (JG97), we confirm that variation of initial rotation rates of sunspot groups with respect to their life spans is similar to the radial variation of internal rotation of the solar plasma as inferred by helioseismology. For two different sets of areas and with a high significance (significance level <1%), we find very high correlation between the variation of the initial rotation rates of sunspot groups and radial variation of internal rotation as inferred by helioseismology.
2. For the spot groups whose area is <100 mh, we find an acceleration during a life span of 6–12 days and deceleration for a life span which is less than 6 days. That is spot groups whose life span is 6–12 days may originate in between the region of the base of the convection zone and 0.935 $R_\odot$ and spot groups which have a life span less than 6 days may originate in between the region of 0.935 $R_\odot$ and 1.0 $R_\odot$.
3. For large spot groups (>100 mh), there is an acceleration for the life span of 9–12 days and a deceleration for the life span below 9 days. This indicates that spot groups whose life span between 9–12 days may originate below the region of 0.935 $R_\odot$ and the spot groups

whose life span is less than 9 days may originate in between the region of 0.935 $R_\odot$ and 1.0 $R_\odot$.

Presently we considered non-recurrent spot groups for our study. It would be interesting to know the results using the recurrent spot groups that are supposed to be anchored below the base of the convection zone. It is not surprising that variation of initial rotation rates of sunspot groups is similar to the radial variation of solar internal rotation as inferred by helioseismology. This is because in the limit of infinite conductivity, flux tubes are isorotating with solar plasma. That means that, while rising towards the surface, dynamics of the flux tubes is governed by the dominant ambient rotational plasma dynamics. This idea can be further supported by the following argument. Assuming that forces due to the Coriolis force, buoyancy, pressure gradient, drag force, etc., are balanced during rising of the flux tube, then to a crude approximation, dynamics of the flux tube is governed by the momentum equation $\frac{\mathrm{d}\Omega}{\mathrm{d}t} \sim \nu \frac{1}{\delta r}\frac{\mathrm{d}\Omega}{\mathrm{d}r}$, where Ω is the angular velocity and ν is the eddy diffusivity of the solar plasma. From this equation one can get an idea of which region of the convection zone the flux tube is accelerated or decelerated while rising towards the surface. By taking $\mathrm{d}r = \delta r = 0.03\ R_\odot$, the same equation can be simplified as $\frac{\mathrm{d}\Omega}{\mathrm{d}t} \sim \frac{\nu}{R_\odot^2}\frac{1}{\delta x}\frac{\mathrm{d}\Omega}{\mathrm{d}x}\,\mathrm{rad/sec}^2 \sim 2.94 \times 10^{-3}\frac{\mathrm{d}\Omega}{\mathrm{d}x}$ nHz/day, where $\mathrm{d}\Omega$ is the difference between the angular velocity from the upper region to the lower region of the solar plasma as the flux tube rises towards the surface and, ν is assumed to be $\sim 10^{13}$ cm^2/sec. By using helioseismic $\frac{\mathrm{d}\Omega}{\mathrm{d}x}$, the computed $\frac{\mathrm{d}\Omega}{\mathrm{d}t}$ values are presented in Fig. 5b. In the same figure, we plot the values of AD_1 for the sake of comparison. Except for a small difference in magnitudes of $\frac{\mathrm{d}\Omega}{\mathrm{d}t}$ and AD_1 values, the nature of the curves are similar. From the similarity of these curves, we can guess that a 12 day spot group may originate near base of the convection zone. On the other hand a spot group with 3 day lifetime has a deceleration of $\sim$10 nHz/day and may originate closer to the surface. Thus it is clear from this study that, irrespective of their size, spot groups which have a lifetime of $\geq$12 days may originate near the base of the convection zone and spot groups which have a lifetime $\leq$3 days may originate near the surface. However realistic MHD calculations and complementary studies from local helioseismology are necessary in order to understand these observed results.

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