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STUDY OF POSSIBLE SUBSURFACE INFLUENCES ON THE EMERGING ACTIVE REGIONS

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Abstract. The large-scale distribution of the orientations of emerging sunspot groups has been studied for the year 1977. It is probable that the declinations from the azimuthal directions are not entirely randomly scattered, but they can be governed also by subsurface velocity fields. If this assumption is correct, the most probable internal velocity distribution is a non-axisymmetric (columnar) giant convection pattern with a longitudinal wave number $l = 11$ rotating slightly slower than the Carrington system, on the basis of the given material.

1. Introduction

Hale's law describes the most important features of the orientations of the sunspot groups adequately apart from the few apparent exceptions certainly caused by the confusion of nearby groups. So, it is plausible to suppose that the internal magnetic fields producing the active regions are basically azimuthal toroidal fields. However, the sunspot groups emerge with a tilt, i.e., the straight line connecting the leading and following parts declines from the E–W direction, and later, primarily under the influence of the dynamics of the solar surface, the angle of this tilt changes. It diminishes in many cases, mainly at higher latitudes (Gilman and Howard, 1986). We suppose, however, that in the moment of the birth, this tilt may yield information about the subsurface influences on the rising flux tubes. If so, two mechanisms seem to be possible: (1) the local distortion of unknown origin of the azimuthal flux rope causes an instability of the flux at the bottom of the convection zone, and the rising material can drag the flux; in this case the distortion itself would be the cause of the appearance of the active region, (2) the (no matter why) rising flux tube can be rotated throughout the bulk of the convective layer by unspecified velocity fields. The two mechanisms perhaps do not exclude each other, but the latter type is more probable as we shall see later.

The data of the *Debrecen Photoheliograph Results 1977* (Dezsö, Kovács, and Gerlei, 1987) were used; this is the only material containing the positions of the preceding and following parts of the active regions. We considered only those sunspot groups, for which the catalog recorded both the appearance and the formation of the bipolar character within three days (except the groups belonging to the previous cycle), this means 76 sunspot groups in 1977.

2. Search for the Distribution of the Sunspot Group Tilts

The first important property of the orientations is that the angles of the tilts have different signs in either hemisphere. Therefore, a positive sign was attributed to the angle of the

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active region's axis, if the preceding part was nearer to the equator than the following one. That means $|B_f| - |B_p| > 0$, and the angle is negative if $|B_f| - |B_p| < 0$ in both hemispheres. B denotes the heliographic latitude. Fifty-two cases were positive and 24 negative in the given material. Their rate was 30 : 20 in the northern hemisphere and 22 : 4 in the south. So, if indeed an internal flux-twisting mechanism exists (which will be supposed henceforth), it cannot be a globally homogeneous feature, but it must be structured.

Two types of geometries can be hypothesized for the supposed internal structure: axially-symmetric and non-symmetric cases. In the former case we should have latitudinal bands in either hemisphere having alternative twisting influences on the flux ropes. This would be a similar geometry to that of the giant rolls described by Ribes, Mein, and Mangeney (1985). However, no latitudinal distribution can be pointed out.

The study of the non-axisymmetric cases is much more complicated. Many attempts have been made to recognize any longitudinal pattern in the distribution of the angles. There is no sensible structure in the Carrington coordinate system, therefore we supposed that the angular distribution is related to a certain subsurface formation of unknown angular velocity. At first we changed the angular velocity of this hypothetical internal formation by small steps, and searched for any distinguishable longitudinal domains containing sunspot groups of identical signs of tilt. Nothing could be recognized for domains of size between 90° and 30°.

After several trials it became obvious that just the signs of the angles do not show any simple distribution. We also realized that the emerging sunspot groups cannot have equal importances and appropriate weights had to be attributed to them depending on their sizes and tilt angles. Among several possibilities the following definition proved to be the most plausible: if the sunspot group has an angle α_i (in degrees) and area A_i (in millionths of the area of the solar hemisphere) on the ith day of its existence, then let its weight

$$W = \frac{\sum \alpha_i (A_i)^{1/2}}{10}, \quad i = 1, 2, 3\,.$$

We have more reasons for this choice. The square root assures that the parameters α and A are always commensurable and the spread of the parameter W is not too great (from 0.3 to 141.8), so it does not give a falsifying preponderance in α and A to any sunspot group, which could be able to dominate over the statistical material. Besides, the sum of the first three days gives greater weights to the unambiguous cases, because the tilts may change their signs in some cases, therefore the angle of the first day is eventually not completely reliable. We return to this definition at the end of this section.

So far the only published internal longitudinal structural pattern is the so-called 'banana-roll' system. These hypothetical cells would be the manifestations of a global convection and, although observationally not yet confirmed, they have resulted in independent theoretical calculations (Glatzmaier, 1984; Gilman and Miller, 1986). They are long meridional features and take the shape of a bunch of bananas, so that the

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material ascends in the border of two given ‘bananas’ and it descends in the next border. The longitudinal wave number of this pattern can be as high as 36, but according to the calculations, the most probable wave numbers are 10–12 (Glatzmaier, 1984; Gilman and Miller, 1986).

The following procedure has been performed: a hypothetical internal sector structure was considered with a given l wave number, say $l = 11$ (this means 22 banana rolls with alternating directions of velocity field, their longitudinal size equal to $16\overset{\circ}{.}36$) and alternating positive and negative signs were attributed to them. If the position of a sunspot group of positive (negative) weight coincided with a positive (negative) sector, respectively, then the absolute value of its weight was added to a sum of weights (ΣW). If not, then it was not added, so this sum of weights characterizes the coincidence of the given sunspot tilts with the supposed sector structure. Considering the finite distance of the preceding and following parts (2.5 deg on average in the present material) we allowed for a strip of tolerance of 2.5 deg on either side of a sector beyond the sector border. Four parameters were changed:

(a) The longitudinal wave number l from 9 to 15.

(b) If the angular velocity of this hypothetical sector structure differs from that of the surface, then it should be taken into account in calculating the coincidence of the position of an emerging flux with a sector. The $\Delta\omega$ differences (internal ω minus Carrington ω) were computed in the range of $-3.2 \Leftarrow \Delta\omega \Leftarrow 4.1$ deg day^{-1} by steps of 0. 01 deg day^{-1}. These limits were taken from Figure 1 of Hill’s (1987) review.

(c) The position of the sector structure in the Carrington system has to be shifted through the range of two sectors (one wave) by 2° steps in order to find the best coincidence.

(d) The sectors may have a curvature (Glatzmaier, 1984; Gilman and Miller, 1986), which was computed by the formula: $Z \times 4 \sin^2 B$, where Z has been varied from 0 to 36 by steps of 2.

The above (a)–(d) parameter variations yield a huge amount of ΣW-values (almost 1.3 million configurations) and the question is, whether or not a given parameter configuration results a convincingly high ΣW-value. The highest values of ΣW have been chosen for all l and $\Delta\omega$ values, they have been averaged (ΣW) over the $\Delta\omega$-parameters for all wave numbers and also the σ standard deviations have been computed. We present in Figure 1 only the ΣW-values greater than $\overline{\Sigma W} + 2\sigma$, for all wave numbers with the indication of the $\overline{\Sigma W} + 3\sigma$ and $\overline{\Sigma W} + 4\sigma$ levels. The highest achievable ΣW value would be 1399.3, if each tilt belonged to a proper sector.

The most remarkable feature of Figure 1 is the band of high maxima at $l = 11$ and $\Delta\omega = -(0.38\text{–}0.33)$ deg day^{-1}. The curvature of the sectors, the Z-parameter mentioned under (d) is very small ($Z = 0\text{–}6$) for all seven peaks constituting the band, the distribution of the peaks is nearly gaussian. Only two apparently concurrent bands approach the $4s$ level, but the ΣW-values are much lower than the major maximum mentioned.

The result is not an artifact resulting from the definition of the weight of orientations. As a check, the same calculations have been carried out for $l = 10, 11, 12$ by using

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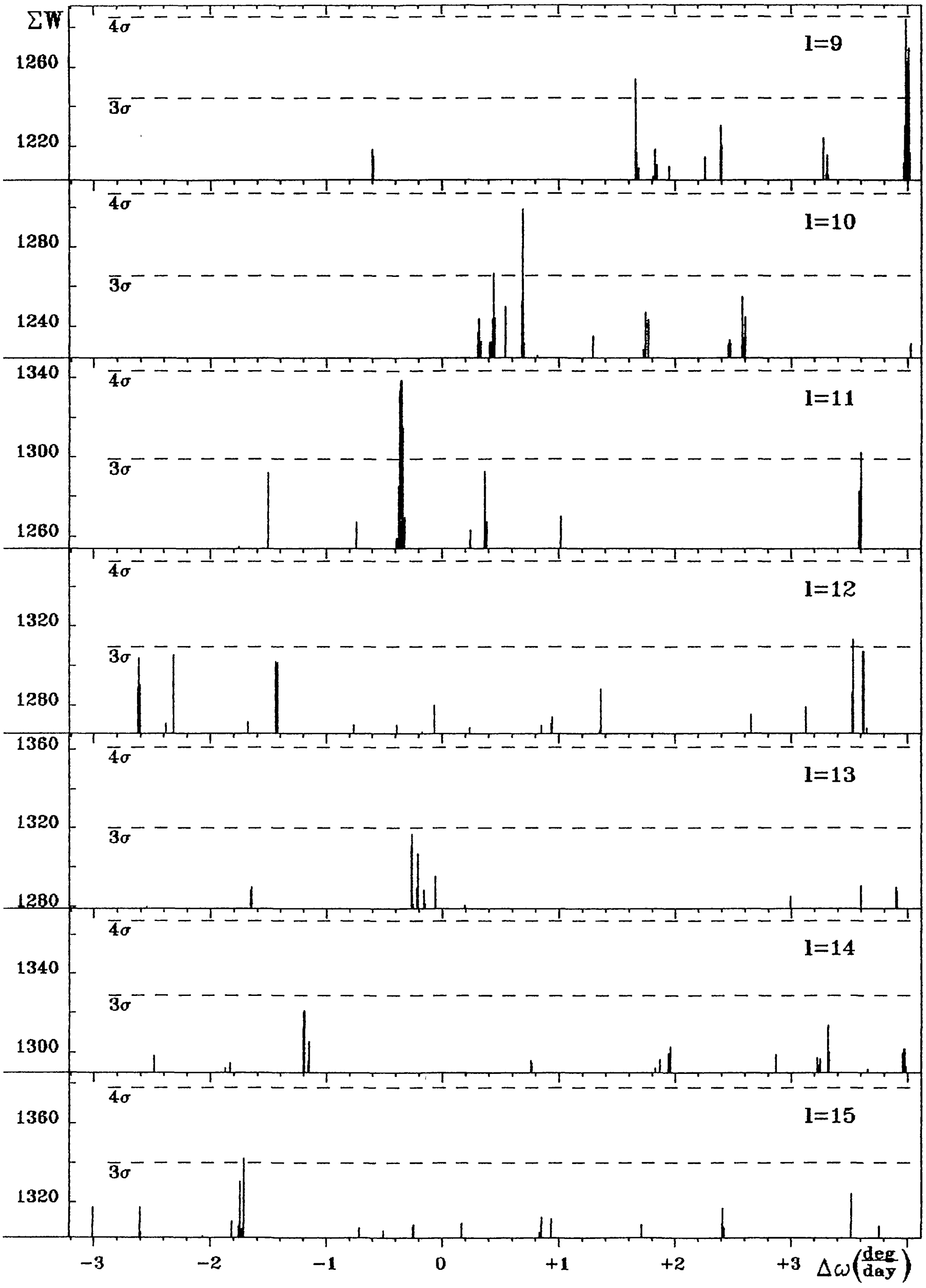

Fig. 1. Sums of orientation weights (Σ *W*) characterizing the coincidence of the sunspot group tilts with different supposed internal sector structures as a function of the longitudinal wave number (*l*) and the difference of the internal-outer rotation rates ($\Delta\omega$).

different definitions: namely, $W_B = \Sigma_i (|B_f| - |B_p|)_i$ (three days' sum of the latitude differences) and $W_\alpha = \Sigma_i \alpha_i$ (three days' sum of the angles with the above convention of signs). No substantial differences have been obtained. The main band of $l = 11$ is

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always present, although less remarkably, especially in the case of W_B as is expected. Moreover, the W_α can be problematic because there are many cases with small W_α, while in other cases small groups have large ($|\alpha| > 90°$) angles in the course of three days, so the spread of W_α is large. As a further check, a calculation has been carried out for $l = 11$ by using a fourth definition when the weight was simply the angle of the first day and the resulting major band is as remarkable and unambiguous as in Figure 1, so its reality is very likely. The other peaks, if present at all, are rather variable. We prefer, nevertheless, the original definition of W on account of the arguments mentioned.

3. Summary of Results

(i) The tilts of axes of new active regions are not unidirectional; in two-thirds of the examined cases the preceding part declines to the equator (positive tilt); in the rest of the cases the tilts are opposite.

(ii) If we suppose that there is a non-axisymmetric global convection system predicted theoretically ('banana rolls'), then it is possible that the magnetic features are turned clockwise at the places of rising and expanding material, and anti-clockwise in the sinking, contracting material in the northern hemisphere and in the opposite direction in the south on account of the Coriolis-force, see Figure 2. This interpretation is not impossible because the rise of magnetic flux is more favourable and probable in the domain of rising (and consequently positively turning) material than in the region of sinking, in accordance with point (i).

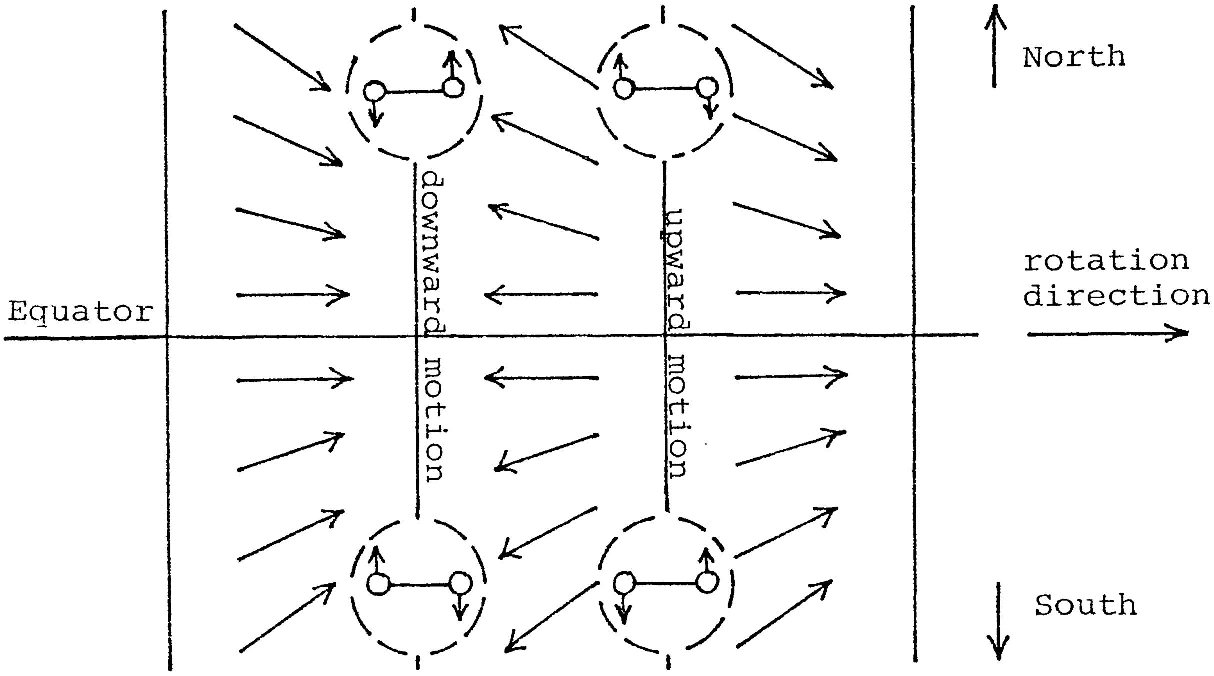

Fig. 2. Schematic view of three adjacent sectors close to the equator expected by theory. The rising-spreading as well as the contracting-sinking areas cause the plotted distortions of the azimuthal velocities on account of the Coriolis-force. The turning influence acting on the emerging fluxes are inserted in the dashed circles, the turn is positive in the rising regions in both hemispheres.

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(iii) We defined a sum of weights (ΣW) to describe the coincidence of the given tilts with the corresponding sectors and this ΣW has been computed for several internal rotation rates and curvatures and for seven longitudinal wave numbers: $l = 9 \ldots 15$. If we assume that the 'banana rolls' structure really exists and acts on the tilts of the emerging flux ropes, then the best fit (largest ΣW) can be achieved with the following parameters: wave number $l = 11$, difference of its angular velocity from that of the Carrington system, $\Delta\omega = -0.35$ deg day^{-1} (in other units $\nu = 444.6$ nHz or $\Omega = 2.79$ μrad s^{-1}), and the curvature of the rolls negligible.

4. Some Additional Remarks

It is worth comparing the above results with some recent observational and theoretical findings.

(a) The inwards increasing *angular velocity* reported by many authors and based mainly on tracer measurements is certainly localized to the vicinity of the surface (see the review article of Hill, 1987) and it is possible that the layer of the mentioned global convection as a whole rotates somewhat slower than the surface, as is indicated, e.g., by oscillation measurements (Duvall and Harvey, 1984; Brown, 1985, 1986; Libbrecht, 1986; Rhodes *et al.*, 1987; Rhodes, Cacciani, and Korzennik, 1991) and by theoretical considerations (Glatzmaier, 1985; Gilman and Foukal, 1979). It is noteworthy that Gilman and Howard (1984) measured the variations in the solar rotation rate; they subtracted the average rotation rate of the period 1967–1982 from the annual rates and the residual of the year 1977 is -0.32 deg day^{-1} (see their Figure 1), almost the value found above, indicating perhaps that there was no substantial difference between the internal and surface rotation rates in this year as was also the case eleven years later in the regions above $0.75\,R_\odot$ according to Goode and Dziembowski (1991), but this problem cannot be discussed without further data. In any case the same procedure can result in different rotation rates with different periods. Furthermore, this angular velocity is smaller than those reported by Stenflo (1989) or Bai and Sturrock (1991), indicating that these data do not refer to the regions studied by these authors.

(b) As for the *wave number*, the theoretical arguments are based on computations indicating maxima around $l = 10$–12 in both of the thermal and kinetic energy spectra and also in the rates of maintenance of differential rotation and angular momentum transport (Glatzmaier, 1984; Gilman and Miller, 1986). So it can be assumed that the most probable number of waves is about 11 (22 sectors or 'bananas') and their most probable characteristic size is $\pi/11$ at any given moment, and although many other sizes can appear temporarily, they cannot be distinguished with the present method as yet. This sector width is perhaps related to the size of the convective layer. These large N–S rolls stir up the whole convective region, and they extend over almost the whole convective layer, so the thickness of this layer probably determines the possible number of rolls necessary for optimal mixing. The wave number $l = 11$ (22 sectors) means an angular extension of 16.36 deg and an equatorial spatial extension of $0.286\,R_\odot$ on the surface. This is not necessarily the size of the rolls but with such dimensions they could

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extend to the whole convective layer, which has been measured recently to be as deep as 0.287 $R_\odot$ (Christensen-Dalsgaard *et al.*, 1991).

(c) Parameters other than the angular velocity can also be *variable in time* such as the wave number and the curvature of rolls. Computations indicate (Glatzmaier, 1984; Gilman and Miller, 1986) that these formations, if they exist, are not very stable. Therefore, an investigation of the present type cannot be performed on a much longer period because of the evolution of the given formation. Temporally separate structures could be confused (which can take place in our case as well in spite of the clear predominance of the $l = 11$ main band). Furthermore, the sizes of the sectors obviously cannot be precisely equal, which results probably in further false peaks.

(d) We cannot study the N–S symmetry of the rolls as suggested by Brown and Gilman (1984) because the division of the limited material leads to restricted reliability, so at the moment we have simply to exploit the theoretical assumption of the symmetry and the whole unified material should be considered by using appropriate sign conventions in both hemispheres.

(e) As far as the *meridional rolls* (Ribes, Mein, and Mangeney, 1985) are concerned, Glatzmaier (1987) notes that they are observed but they cannot be theoretically explained as yet, and at the same time the banana rolls seem to be well-established by theory, but they are not yet detected directly. He refers to a Spacelab experiment imitating similar geometry (Toomre, Hart, and Glatzmaier, 1987). He attempts to resolve the apparent controversy by supposing the coexistence of the two types of motions; the meridional rolls are restricted to a shallow layer below the surface (so they do not have an appreciable twisting effect) and the more extended banana-roll structure acts in the deeper regions. If this is the case, then these latter columnar giant convection cells constitute the deepest suspected structural pattern in the Sun. Therefore, they are scarcely detectable by spectroscopy, but perhaps the above method offers a chance.

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