GIANT CONVECTIVE ROLLS AND SUNSPOT GROUP TILTS

T. BARANYI and A. LUDMÁNY
Heliophysical Observatory of the Hungarian Academy of Sciences, H-4010 Debrecen, P.O.Box 30., Hungary
E-mail baranyi@tigris.klte.hu

Abstract. The theoretically predicted non-axisymmetric giant convection pattern has been studied by using its probable twisting influence on the emerging magnetic fields. The studies resulted in an evidence for a giant cell pattern with longitudinal wave number $l=11$ which has a rotation rate differing by $\Delta\omega = -0.35$ degrees/day from that of the Carrington system.

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 may suppose, however that at 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 (Dezső et al.,1987) were used, this is the only material containing the positions of the preceding and following parts of the active regions. Only those sunspot groups were considered in a previous work (Baranyi and Ludmány, 1992, referred to as Paper I henceforth), for which the catalog recorded both the appearance and the forming of the bipolar character within three days (except the groups belonging to the previous cycle), this means 76 sunspot groups in 1977. Later on (Baranyi and Ludmány, 1993, Paper II) the material has been completed to 88 sunspot groups considering only the firs days of the bipolar character.

2. DISTRIBUTION OF TILTS OF EMERGING SUNSPOT GROUPS

The first important property of the orientations is that the angles of the tilts have different signs on either hemispheres. Therefore positive sign was attributed to the angle of the active region's axis, if the preceding part was nearer to the equator than the following one, that means $\mid B_f \mid - \mid B_p \mid > 0$, and the angle is negative if $\mid B_f \mid - \mid B_p \mid < 0$ on both hemispheres, B_f and B_p denote the heliographic latitudes of the following and preceding parts respectively. 58 cases were positive and 30 negative in the given material, this is a rate similar to that found by Howard (1991, 1993). So, if indeed an internal flux-twisting mechanism exists (which will be supposed henceforth) then 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 on either hemispheres having alternative twisting influences on the flux ropes. This would be a similar geometry to that of the giant rolls described by Ribes et al. (1985). However, no latitudinal distribution can be pointed out on the basis of the present material and approach.

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 varied the angular velocity of this hypothetical internal formation by small steps, and searched for any distinguishable longitudinal domains containing sunspot groups of identical sings of tilt. Nothing could have been recognized for domains of size between 90° and 30°.

The only published internal longitudinal structural pattern sc far 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 been 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 material ascends in the border of two given "bananas" and it descends in the consecutive 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).

After several trials it became obvious, that purely 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. 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 equals to 16.36°) 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, than 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 group tilts with the supposed sector structure. Considering the finite distance of the preceding and following parts (2.5 degrees on average in the present material) we allowed for a strip of tolerance of either 2.5 degrees or 1/6 sector widths on both sides of a sector beyond the sector border. Thus the following three definitions were used :

Definition 1 (Paper I) : if the sunspot group has an angle α_i (in degrees) and area A_i (in millionths of the solar hemisphere) on the i-th day of its existence (i=1,2,3), then let its weight :

$$W = \Sigma \alpha_i \sqrt{A_i}$$

Definition 2 (Paper II) : the same as in definition 1 but using only the first day's angle and area allowing more (88) sunspot groups :

$$W = \alpha \sqrt{A}$$

Definition 3 (Paper II) corresponds to definition 2 but the strip of tolerance is equal to one sixth of the sector width.

Four further parameters were varied :

(a) The longitudinal wave number l from 2 until 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 $-3.2 \leq \Delta\omega \leq 4.1$ (degrees/day) by steps of 0.01 (degrees/day). These limits were taken from the Figure 1 of Hill's (1987) review.

(c) The position (phase) 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)), it was computed by the formula : $4Z \sin B$, 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 in a convincingly high ΣW -value. The highest values of ΣW have been chosen for all l and $\Delta\omega$ values ((a) and (b) parameters) from the possible phases and curvatures ((c) and (d) parameters). If we plot the $(\Sigma W - \Delta\omega)$ histograms for all wave numbers then the peaks characterize the coincidence of the observed tilts with the considered sector structure. There is a remarkable peak at l=11 and about $\Delta\omega = -0.37$ degrees/day for all the three definitions but its predominance is much more convincing if the ΣW - values are normalized to the highest achievable ΣW (complete coincidence) and averaged for the three definitions at all l and $\Delta\omega$ -values ($\overline{\Sigma W}$). Figure 1 shows the result. Only $\overline{\Sigma W}$ -values higher than 3s level are indicated.

The most remarkable feature of Figure 1 is the band of high maxima exceeding the 5s level at l=11 and about $\Delta\omega = -0.37$ deg/day. The curvature of the sectors, the Z-parameter mentioned under (d) is very small (Z=0-4) for all the peaks constituting

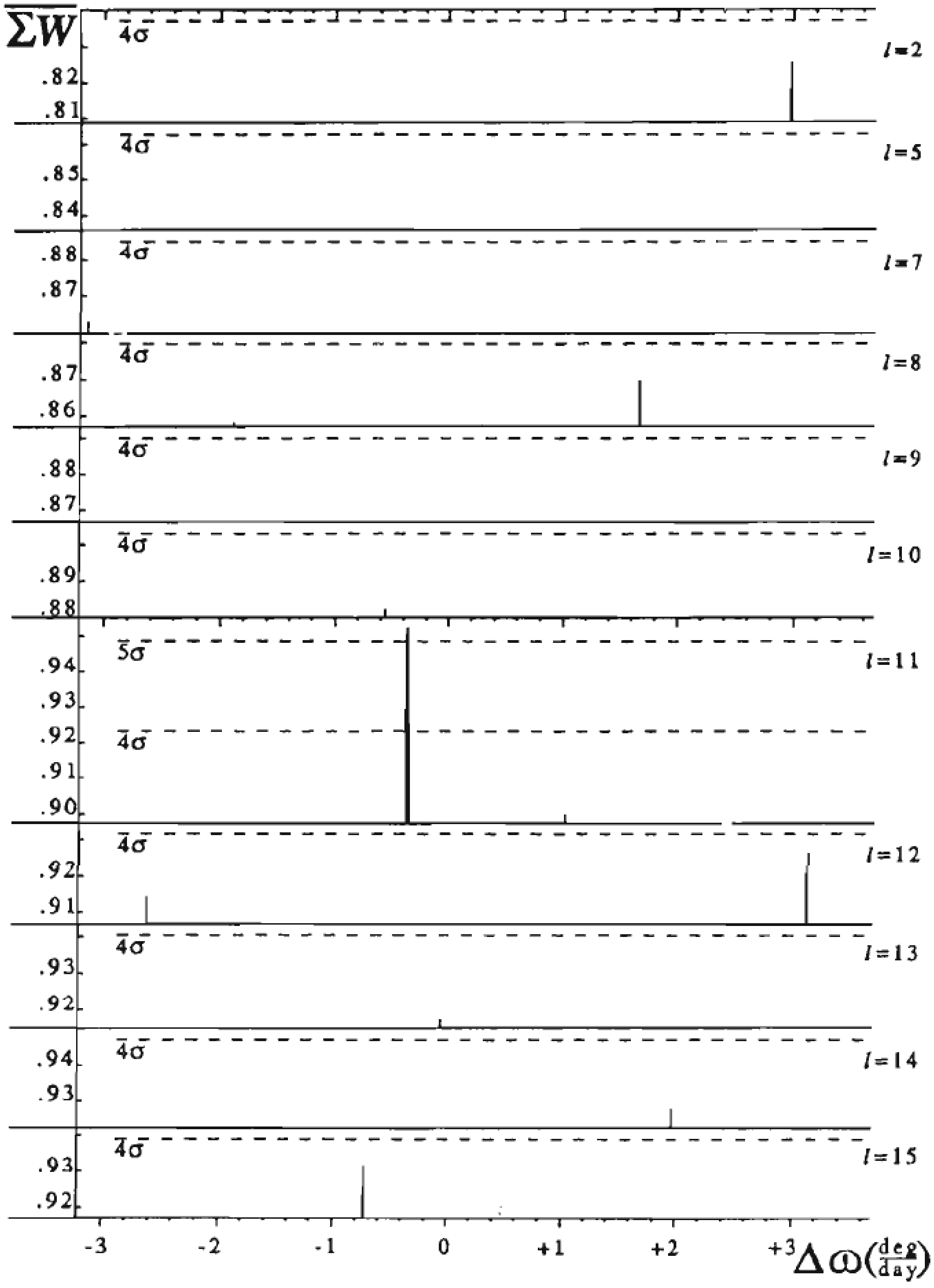

Fig. 1. Normalized sums of orientation weights ($\overline{\Sigma W}$) characterizing the coincidence of the tilts of emerging sunspot groups with various supposed internal sector structures as functions of longitudinal wave number (l) and difference of the internal-outer rotation rates ($\Delta\omega$). Only values above 3s level are displayed. The band of high values at l=11 and $\Delta\omega = 0.37$ deg/day indicate a probable internal structure.

the band, the distribution of the peaks is nearly gaussian. All possible concurrent peaks prove to be spurious and disappear in the averaging.

3. SUMMARY OF RESULTS

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.

If we suppose that there is a non-axisymmetric global convection system predicted by theory ("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 forces, see Figure 2. This interpretation is not impossible because the rise of a 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 the point (1).

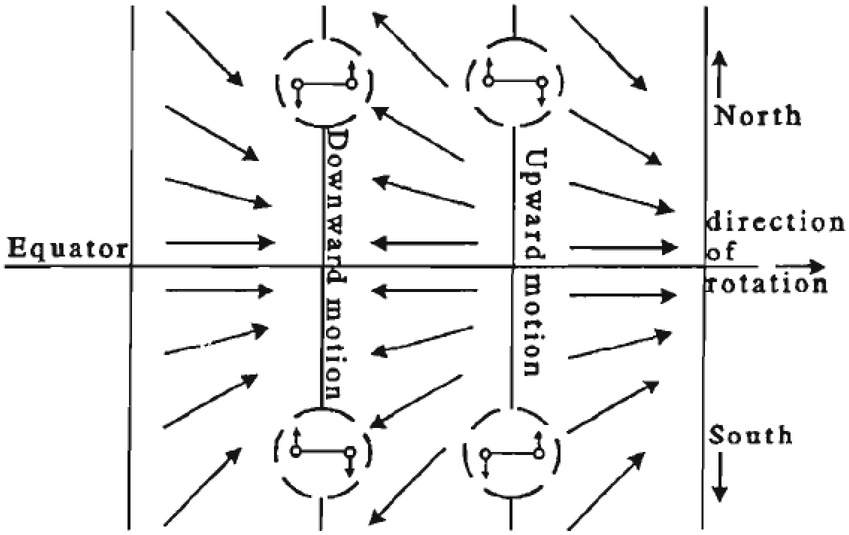

Fig. 2. Schematic view of three adjacent sectors close to the equator expected by theory. The rising-spreading as well as the contracting-sinking areas cause the plotted distortions of the azimuthal velocities on account of the Coriolis-force. The turning influence acting on the emerging fluxes are inserted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

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 fourteen longitudinal wave numbers : l=2,..,15. If we assume that the "banana rolls" structure really exists and acts on the tilts of the emerging flux ropes, than 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 : $\Delta\omega = -0.35$ degrees/day (in other units $\nu = 444.6nHz$ or $\Omega = 2.79\mu rad/sec$), and the curvature of the rolls is negligible.

4. SOME ADDITIONAL REMARKS

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

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 and 1986; Libbrecht 1986; Rhodes et al., 1987 and 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 degrees/day (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 $0.75R\odot$ 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 on 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.

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 by 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, they extend over almost the whole convective layer, so the thickness of this layer probably determines the possible number of the rolls being capable to optimal mixing. The wave number l=11 (22 sectors) means an angular extension of 16.36 degrees and an equatorial spatial extension of $0.286R\odot$ on the surface. This is not necessarily the size of the rolls but with such dimensions they could extend to the whole convective layer which has been measured to be as deep as $0.287R\odot$ (Christensen-Dalsgaard et al. 1991).

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.

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 conventions of signs in both hemispheres.

As far as the axisymmetric or "doughnuts" rolls (Ribes et al., 1985) are concerned, we suggested that the two types of rolls could be reconciliated in time because 1977 is a minimum year with poloidal magnetic field and perhaps the toroidal field would enhance the axisymmetric geometry, but Gilman (1993) argued that this alternation should also cause variations in the differential rotation profile which is not yet observed. Glatzmaier (1987) notes that the "doughnut" rolls 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 et al., 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 appreciable twisting effect) and the more extended banana-roll structure acts in the deeper regions, this idea was later discussed and supported also by Roberts (1991). If this is the case than these latter columnar giant convection cells constitute the deepest suspected structural pattern in the Sun. Therefore they are hardly detectable by spectroscopy, but perhaps the above method offers a chance.

It should be admitted that the present material does not allow to get a final proof of the existence of the columnar giant cells, it yields just a remarkable signal which might be the signature of them in the given year. Further studies should cover a longer period but this will be more complicated on account of the probable variability of the pattern. A further parameter : the length of the studied interval should also be varied and these variable intervals should be shifted along the whole interval in order to find the most persistent patterns. This needs a much longer material than used here so we should concentrate our efforts to the compilation of the Debrecen Photoheliographic Results which is a very long-term project.

Acknowledgements

We express our gratitude to dr. P. Gilman for a helpful discussion and for his advices and kind encouragements. The work was supported by grants OTKA F4142/1993 and T014036/1994.

References

Bai, T. and Sturrock, P. A. : 1991, *Nature*, **350**, 141.
Baranyi, T. and Ludmány, A. : 1992, *Solar Phys.* **139**, 247. (Paper I).
Baranyi, T. and Ludmány, A. : 1993, in *Inside the Stars,* IAU Colloquium 137., Weiss W. W. and Baglin A. eds., ASP Conf. Ser. **40**, pp. 81. (Paper II).

Brown, T. M. : 1985, *Nature*, **317**, 591.

Brown, T. M. : 1986, in *Seismology of the Sun and the Distant Stars, NATO ASI Series C169.*, Gough D. O. ed. D. Reidel, Dordrecht, p.199.

Christensen-Dalsgaard, J., Gough, D. O. and Thompson, M. J. : 1991, *Astrophys. J.* **378**, 413.

Dezső, L., Kovács and Gerlei, O. : 1987, *Debrecen Photoheliographic Results 1977, Publ. Debrecen Obs., Heliographic Series* No. 1.

Duvall, T. L. Jr. and Harvey, J. W. : 1984, *Nature*, **310**, 19.

Gilman, P. A. and Foukal, P. V. : 1979, *Astrophys. J.* **229**, 1179.

Gilman, P. A. and Howard, R. : 1984, *Astrophys. J.* **283**, 385.

Gilman, P. A. and Howard, R. : 1986, *Astrophys. J.* **303**, 480.

Gilman, P. A. and Miller, J. : 1986, *Astrophys. J. Suppl.* **61**, 585.

Gilman P. A. 1993, *personal communication.*

Glatzmaier, G. : 1984, *J. Comp. Phys.* **55**, 461.

Glatzmaier, G. : 1985, *Astrophys. J.* **291**, 300.

Glatzmaier, G. : 1987, in *The Internal Solar Angular Velocity* , Durney B. R. and Sofia S. eds., ASSL Vol. 137., D. Reidel, Dordrecht, p. 263.

Goode, P.R. and Dziembowski, W.A. : 1991, *Nature*, **349**, 223.

Hill, F. : 1987, in *The Internal Solar Angular Velocity*, Durney B. R. and Sofia S. eds., ASSL Vol. **137**, D. Reidel, Dordrecht, p. 45.

Howard, R. : 1991, *Solar Phys.* **136**, p.251.

Howard, R. : 1993, *Solar Phys.* **145**, p.95.

Libbrecht, K. G. : 1986, *Nature*, **319**, 753.

Rhodes, E. J. Jr., Cacciani, A., Korzennik, S., Tomczyk, S., Ulrich, R. K. and Woodard, M. : 1990, *Astrophys. J.* **351**, 687.

Rhodes, E. J., Cacciani, A. and Korzennik, S. : 1991, *Advances in Space Research*, **11** No. 4. 17.

Ribes, E., Mein, P. and Mangeney, A. : 1985, *Nature*, **318**, 170.

Roberts, P. H., 1991, in *The Cool Stars : activity, magnetism and dynamos*, Proc. of IAU Coll. 130. Tuominen I. et al. eds., Springer-Verlag, p.37.

Stenflo, J. O. : 1989, *Astron. Astrophys.* **210**, 403.

Toomre, J., Hart, J. E. and Glatzmaier G. A. : 1987, in *The Internal Solar Angular Velocity*, Durney B. R. and Sofia S. eds., ASSL Vol. **137**, D. Reidel, Dordrecht, p. 27.