On the Orientational Relaxation of Bipolar Active Regions

L. Tóth[1] **and O. Gerlei**[2]
Heliophysical Observatory of the Hungarian Academy of Sciences
H-4010 Debrecen, P.O.Box 30., Hungary
E-mail: [1]`tothla@tigris.klte.hu`, [2]`gerlei@fenyi.sci.klte.hu`

Abstract

Our work on the basis of selected regular bipolar magnetic regions (BMRs) strengthens the assumption that the scatter of tilt angles of BMRs around Joy's law is determined by the convective turbulence. Furthermore, regular BMRs grouped by age do not show the phenomenon of toroidal relaxation, which may probably mean the disconnection of Ω-loops from the bottom of the convection zone.
KEYWORDS: *Sun, Ω-loop, convective turbulence, dinamic disconnection, tilt angle*

1. Introduction

It is assumed that the solar magnetic field originates in the dynamo operating in a stable layer at the base of the convection zone. According to dynamo models (Parker, 1955; Babcock, 1961; Leighton, 1964; Leighton, 1969) the initial poloidal field turns into toroidal because of differential rotation. The toroidal strands of this subjacent magnetic flux locally may come out of this stable layer and would rise through the convection zone as an Ω-loop. It is one of the possible phenomena that is responsible for the formation of BMRs.

The emerged flux tubes show Joy's law that means, in general, that the preceding (p) spots of BMRs are closer to the equator than the following ones (f). Thus the BMRs are inclined to the local latitudinal line by an angle, which increases with latitude (Hale et al., 1919) and is called tilt. One of the explanations for this phenomenon is to take the Coriolis force into account (Schmidt, 1968) that can twist the ascending flux loops so that it finally emerges at the surface with a tilt to the local latitudinal line (Wang & Sheely, 1989; Wang & Sheely, 1991; Howard, 1991; Howard, 1996a; Howard, 1996b; Sivaraman et al., 1999).

Later on, in the theoretical descriptions (D'Silva & Choudhuri, 1993; Longcope & Choudhuri, 2002) further effects, namely the role of convective turbulence and dynamic disconnection have been taken into account, which influence the rising flux loop. In the present article we investigate observational signatures of these processes.

2. Method of investigations

In our investigations we applied the data of Greenwich Photo-Heliographic Results (GPHR) concerning the 14^{th} solar cycle from 1901 to 1913 from which only those clearly aligned active regions (ARs) were taken into account of which longitudinal co-ordinates were not farther from the central meridian than 60 degree. The selection of the regular ARs was made on the basis of photospheric observations of the Haynald Observatory (Tóth et al., 2002) and it resulted in 3754 BMRs.

The tilt angle (γ) is, by convention, positive for BMRs where p-spots are equatorward and negative if they are poleward of f-spots. Furthermore, this angle was calculated as the bend of a straight line to the local latitudinal line from which the first one was fitted by area weighted least-squares method to the spots of the given BMR. In accordance with Howard (1991) we applied latitudinal correction as well.

3. The distribution of tilt angle and its rotation

The distribution of tilt angles (γ) of BMRs over 5 degree increments is shown and compared with other results (Howard, 1996b; Sivaraman et al., 1999) in Figure 1 where the Kodaikanal and the Mount-Wilson data are basically the same but differ from our result. Due to the above-mentioned selection of regular BMRs our peak is more narrow than the others and apart from the small differences at it's wings follow the Gaussian distribution well.

Further information is obtainable from the distribution of the daily tilt angle changes of BMRs, which according to Howard (1994) were determined as simple day to day differences ($\omega = \Delta\gamma/\Delta\text{day}$). The distribution of them over 2 degree increments is shown in Figure 1, which is for the same reason as mentioned before narrower than that of the others'. Of special interest is the fact that it follows the Lorentzian distribution well.

The peak positions and the half-widths of our fitted Gaussian (γ_0, σ) and Lorentzian (ω_0, Γ) curves for the whole and the different age BMRs are compared with the theoretical results of Longcope & Choudhuri (2002) in Table 1. Our results show that the average tilt (γ_0) of BMRs is close to the mean angle determined by Joy's law and it slightly decreases as the BMRs are growing old.

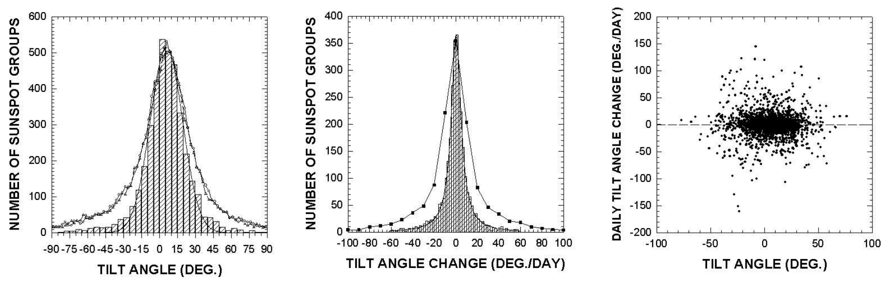

Figure 1: *Left:* The distribution of tilt angles (γ). The striped columns show our results that are based on the selected regular BMRs of the 14^{th} solar cycle (1901-1913). The solid line is a Gaussian curve fitted by the least-squares method applied to our data. The open circles represent the Kodaikanal (1906-1987) while triangles the Mount Wilson data (1917-1985) (Sivaraman et al., 1999) normalised to our results. *Center:* The distribution of the daily tilt angle changes (ω). The striped columns show our result and the solid line is a Lorentzian curve fitted by the least-squares method applied to our data. The black squares with solid line represent the Mount Wilson data (Howard, 1994) normalised to our result. *Right:* The plot ω versus γ of our selected regular BMRs and the straight line fitted by the least-squares method to its points (dashed line)

Moreover, the average rotational velocity (ω_0), though to a less degree, but is larger than zero, but tends to disappear as BMRs are growing old.

4. The role of dynamic disconnection

Howard (1996a) made first a plot of ω against γ that shows a relation between the tilt angle and its change, and fitted them with a straight line as ω = a+b$*\gamma$. This fitting (Howard, 1996a) resulted in the slope as b = -0.229±0.004 and the location of the intersection of the γ axis at $\gamma_{(\omega=0)}$ = 5.65±0.32 degree that is close to the angle γ_0 determined by Howard (1996b) (γ_0= 4.28±0.19), Sivaraman et al. (1999) (γ_0= 4.2) and this article (γ_0= 5.8±0.3, Table 1). This lead to the conclusion that the bipoles relax from their orientation toward the angle γ_0 specified by Joy's law. This phenomenon is called orientational relaxation.
On the bases of Howard (1996a) work Longcope & Choudhuri (2002) gives an overall theoretical description of this phenomenon. In their theories they took into account the effect of the Coriolis force on the rising flux tube as the origin of Joy's law, and the effect of the convective turbulence as being responsible for the random scatter of tilts around the systemic ones determined by Joy's law. This assumption is proved by our results since the measured tilt angles follow

Table 1: Our γ_0 [deg], σ [deg], ω_0 [deg/day], Γ [deg/day], $\gamma_{(\omega=0)}$ [deg] and b [day^{-1}] parameters compared with Longcope & Choudhuri (2002) theoretical results. The explanations of these parameters are in chapters 3 and 4.

	Our work:			Longcope & Choudhuri (2002)		
				anchored life time:		dis-conn-ected
	all group	life time: 2≤day≤7	7<day	2≤day<7	7≤day	
γ_0	5.8±0.3	5.5±0.3	4.8±0.4	3.71	2.43	4.05
σ	13.5±0.3	13.0±0.3	12.2±0.4	-	-	-
ω_0	0.32±0.06	0.35±0.06	0.12±0.09	-	-	-
Γ	11.0±0.2	11.4±0.2	8.3±0.3	-	-	-
$\gamma_{(\omega=0)}$	21±30	18±18	9±16	3.3	-0.03	2.12
b	-0.02±0.02	-0.03±0.02	0.07±0.07	-0.302	-0.097	-0.024

Gaussian distribution (Figure 1), which seems to describe the distribution of random observations. Consequently, we assume that there must be a connection between the half-with of the tilt angle distribution (σ in Table 1) and the scale of convective turbulence as well.

Furthermore, there is a question, which gains importance, whether the rising Ω-loop is connected to the bottom of the convection zone or not. The last case is called dynamic disconnection. Namely, if the flux tube is connected to the strong toroidal magnetic field at the bottom of the convection zone then following the emergence, the magnetic tension with the progress of time may force to align the bipolar magnetic region toward the east-west direction. That is, the above-mentioned slope (b) and the intersection ($\gamma_{(\omega=0)}$) with the progress of time may keep to 0, that kind of behavior is called toroidal relaxation. But if the flux tube were dynamically disconnected, this relaxation to zero tilt would stop. Considering this Longcope & Choudhuri (2002) calculated artificial ω-γ plots for the younger and the older than 7-day-old Ω-loops, in cases when they are connected to or disconnected at 75 Mm below the solar surface from the bottom of the convection zone. The parameters of the straight lines fitted to these artificial plots are visible in Table 1.

Based on our selected, clearly aligned BMRs, we have investigated the distributions of the related ω and γ pairs for all and for BMRs of different age-groups as well. The plot of all selected BMRs with the fitted straight line to its points is in Figure 1. The parameters of the fitted straight lines, namely the slope (b), and the intersection ($\gamma_{(\omega=0)}$) of all the BMRs and of the different age-groups are in Table 1. The difference is striking between the work of Howard (1996a) (see above) and our's (Figure 1, Table 1), since our results do not show the phenomena of orientational and toroidal relaxations. But practically neither the younger than 8-day-old BMRs show these relaxations nor the olders (Table 1). What on the base of Longcope & Choudhuri (2002) may mean, that the Ω-loops of the regular BMRs are possibly disconnected from the bottom of the convection zone.

5. Conclusions

First of all, we can claim that the selection of the clearly aligned BMRs lead to the reduction of several error sources and gave new results.
The distributions of the tilt angles of BMRs and their rotations agree with other results well, and show that the average alignment (γ_0) determined by Joy's law just as its near zero average rotational velocity (ω_0) slightly decreasing as the active regions are growing old.
The Gaussian shape of the tilt angle distribution is in agreement with the assumption that the scattering of the tilt around the Joy's law determined systemic ones is caused by random-like convective turbulence.
Furthermore, the regular, clearly aligned active regions do not show the phenomenon of toroidal relaxation, which may mean that the Ω-loops are presumably disconnected from the bottom of the convection zone.

Acknowledgments

We would like to say thank to Pascal Demoulin and Lidia van Driel-Gesztelyi for their creative remarks and for the encouragement coming from Arnab Rai Chudhuri and Valentine I. Makarov. This work was supported by the Hungarian National Science Foundation (OTKA: F030957).

References

Babcock, H. W. 1961, *Astrophys. J.* , 133, 572

D'Silva, S., Choudhuri, A. R. 1993, A&A, 272, 621

Hale, G. E., Ellerman, F., Nicolson, S. B., Joy, A. H. 1919, *Astrophys. J.* , 49, 153

Howard, R. F. 1991, Solar Phys., 132, 49

Howard, R. F. 1994, Solar Phys., 149, 23

Howard, R. F. 1996a, Solar Phys., 167, 95

Howard, R. F. 1996b, Solar Phys., 169, 213

Leighton, R. B. 1964, *Astrophys. J.* , 140, 1547

Leighton, R. B. 1969, *Astrophys. J.* , 156, 1

Longcope, D., Choudhuri, A. R. 2002, Solar Phys., 205, 63

Parker, E. N. 1955, *Astrophys. J.* , 122, 293

Schmidt, H. U. 1968, in K. O. Kiepenheuer (ed.), Sructure and Development of Solar Active Regions, D. Reider Publ. Comp., p. 95

Sivaraman, K. R., Gupta, S. S., Howard, R. F. 1999, Solar Phys., 189, 69

Tóth, L., Mező, G., Gerlei, O. 2002, J. Hist. Astr., 33, 278

Wang, Y. M., Sheely, N. R. 1989, Solar Phys., 124, 81

Wang, Y. M., Sheely, N. R. 1991, *Astrophys. J.* , 375, 761