MAGNETIC FIELD AND DIFFERENTIAL ROTATION OF THE SUN

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Abstract. The solar magnetized surface reveals a stable spin period - the Carrington period - and a stable oscillation period - the Hale period. The latter is traced by each of the low-order multipole moments, whereby the total magnetic energy (near the surface) is more or less constant. This highly non-stochastic structure is reminiscent of a permanent magnetic flux frozen into the Sun's radiative core, and dragged out into the heliosphere by the solar wind. The radius-dependent torque exerted by this magnetic flux can restore the observed system of torsional oscillations of the convection zone.

1. The Carrington Cycle

It is well known that the solar surface rotates at various angular velocities, depending on heliospheric latitude, altitude (above the photosphere), and on the tracer (e.g. Schröter, 1985). The observed range of angular velocities amounts to $(\Omega_{max} - \Omega_{min})/\Omega_{max} \lesssim 0.3$. Remarkable is the fact that despite this non-uniformity of surface rotation, there exist so-called 'active longitudes', i.e. there exists a periodically recurring surface structure which can be traced through as many as 16 successive cycles (Sawyer 1968, Bogart 1982, Stenflo 1989). Figure 1 shows two of Stenflo's autocorrelation functions, at latitudes $-39°$ and $-2°$, which reveal both the long-time period $P_{Carrington} = (27.3 \pm 0.5)\ d$ and the period of short-lived features ($\lesssim$ 10 days: broken). Short-time motions are overtaken by the recurring structure. Apparently, magnetic flux is dragged through the plasma at significant velocities.

The Carrington period has also been found in the cosmic-ray intensity reaching Earth (Parker 1992).

2. The Hale Cycle

Another well-known phenomenon are the quasi-periodic sunspots, and sunspot groups, which trace the solar magnetic oscillation cycle, of period $P_{Hale} = (22 \pm 2)$ yr. Bracewell (1953, 1985) has pointed out that the two-thirds power of the sunspot number $R := \pm(f + 10g)$, when equipped with a sign, varies almost sinusoidally. (The power 2/3 was stated wrongly in eq. (1) of (Kundt 1992). The Hale period has been observed since about 1700. It has been likewise found in the drought record for the High Plains, and in the D/H ratio from two bristle cone pines (Dicke 1978). Schröder (1992) traces the solar cycle via the aurora borealis recorded from Central Europe, back to the year 1550; and Bracewell (1985) believes it to show up in the 0.68 Gyr-old Elatina formation in South Australia, a controversial interpretation. But already the well-observed last 16 cycles of the Hale oscillator show that it does not perform the random walk in phase expected from a relaxation oscillator, i.e. from an oscillator without a resonator. Both Bracewell (1953), Dicke (1978) and Layzer et al. (1979) conclude at a 'flywheel', or 'chronometer' in the core of the

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Sun; and Layzer et al. (1979) specify this chronometer as the primordial magnetic flux of the Sun's radiative core coupled magnetically to the convection zone.

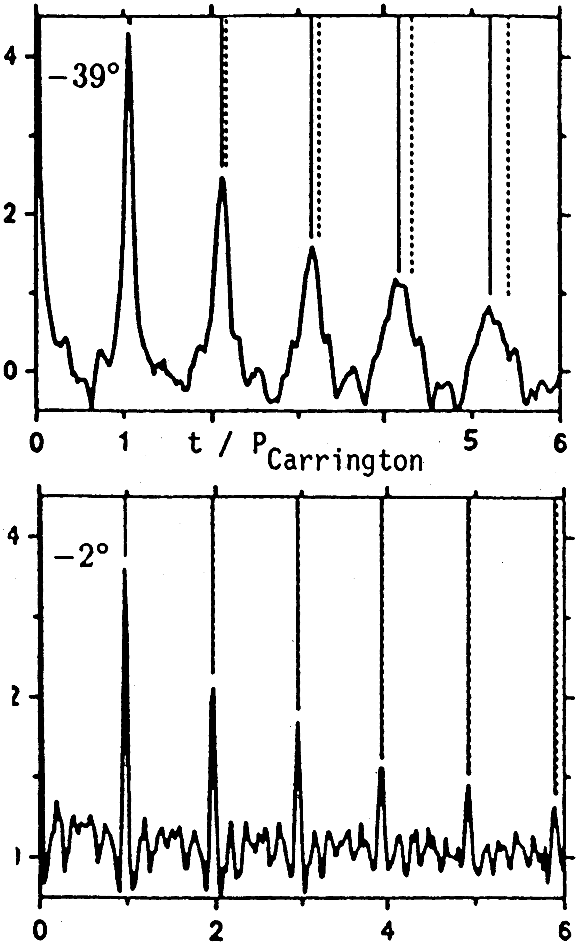

Figure 1: Autocorrelation function of the solar sub-Earth-meridional radial magnetic-field strength at −39° and −2° heliographic latitude, from Stenflo (1989). Note how distinctly the Carrington period can be recognized (solid vertical lines), as opposed to Snodgrass's period defined by the short-time motions (broken).

Note that (i) full magnetic cycles can be read off throughout the Sun's surface (Wilson et al. 1988), that (ii) the amplitude of a cycle correlates with the length of the preceding one (length + log (amplitude) = constant (Waldmeier 1955, Simon 1992, Hoyng 1992), and that (iii) flux concentration into isolated tubes is reminiscent of fast two-fluid motion in which an anchored flux, being dragged through a fluid conductor, splits into discrete tubes in order to reduce its resistance. (Detached) flux-rope motion has been considered by Moreno-Insertis (1986) and by Schüssler (1992).

3. Multipole Structure

The solar surface field is routinely monitored, and expanded in terms of multipole moments up to $l \lesssim 90$, depending on the angular resolution (Altschuler et al. 1977, Hoeksema 1990). Such multipole moments S_l are strongly cycle-dependent, see figure 2. In general, the dipole S_1 dominates, odd-order moments dominate over even-order ones, and energy densities $S_l = \sum_m ({g_{lm}}^2 + {h_{lm}}^2)$ decrease with l (for $l \lesssim 50$)

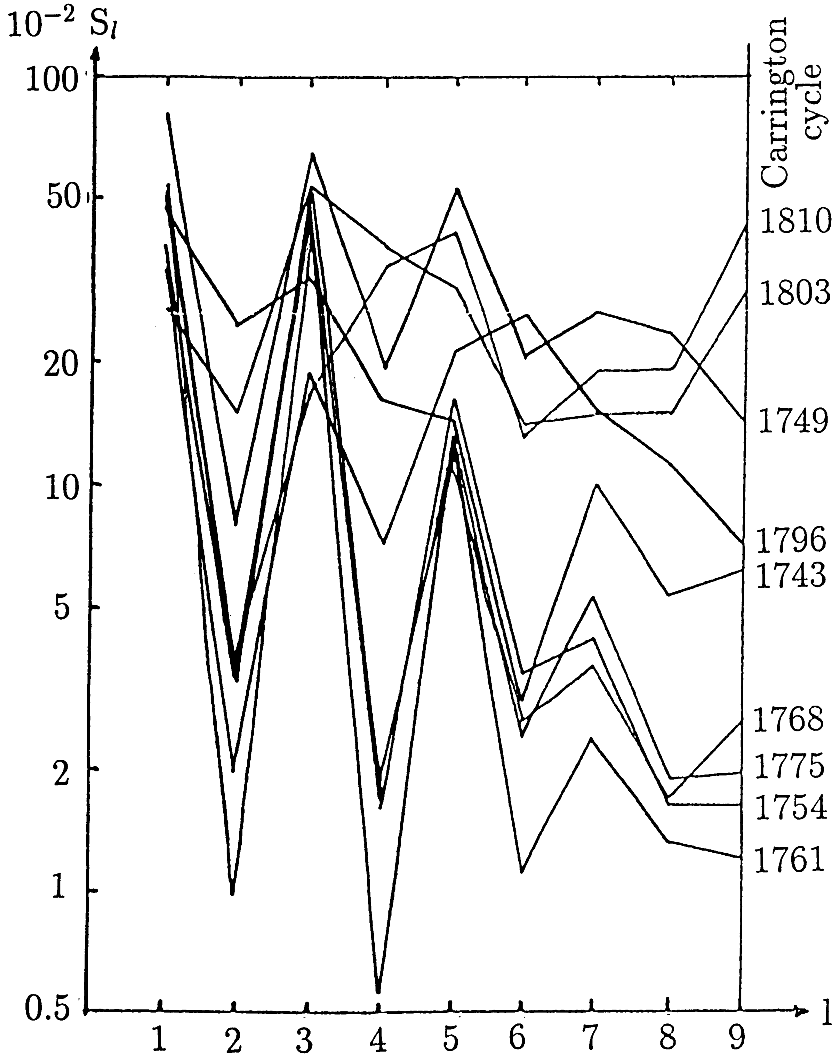

Figure 2: A few solar magnetic multipole spectra at various epochs, measured at the indicated Carrington cycles, from Hoeksema (1990). S_l is proportional to the energy in the l^{th} multipole. Note that the dipole is not always leading in energy: temporally leading can be the third, fifth, or even ninth multipole moment.

roughly as $l^{-1/2}$, reminiscent of Kraichnan's energy distribution of magnetohydrodynamic turbulence. Remarkable are the relative constancy of the total energy $S = \sum_l S_l$ throughout a cycle, varying some ten times less than S_1, and the existence of a small secondary maximum (of both S_1 and S) near solar minimum (figure 3; cf. Howard and La Bonte 1981). It would be of interest to know how accurately this structure repeats from cycle to cycle.

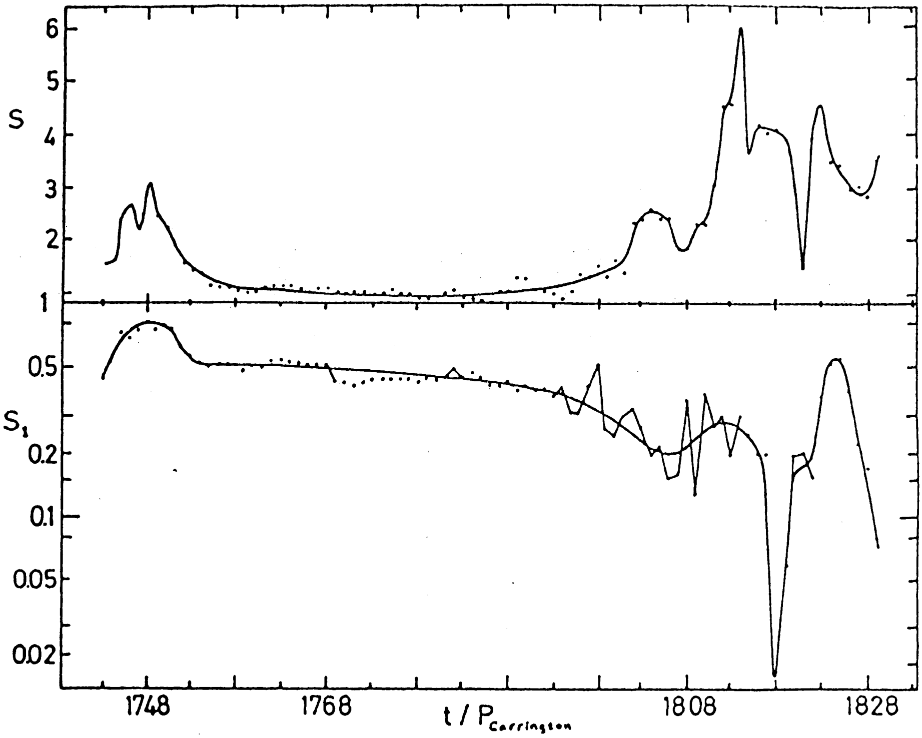

Figure 3: Magnetic dipole energy S_1 and total energy $S := \sum_l S_l$ during one quarter of a Hale period, plotted as functions of the Carrington cycle; based on Hoeksema (1990). Note that the dipole energy is plotted logarithmically.

4. Torsional Oscillations

The Sun does not only rotate differentially; its surface also oscillates horizontally, at half the Hale period (Howard 1984). More precisely, the torsional oscillations of the solar surface are decomposable into both rigid and twisting ones. These oscillatory motions can be understood as the result of a periodically varying magnetic torque, i.e. as caused by the magnetic cycle (Kundt 1992). Volland (1992) has expanded them in terms of Rossby-Haurwitz waves, an approach which trades closed-form solvability with a realistic radial dependence of the magnetic field. Even so, his model confirms the interpretation that the solar surface motions are driven by magnetic (Maxwell) stresses.

5. Equatorial Superrotation

The most puzzling property of the Sun's kinematics is its equatorial superrotation, expressed by figure 4 (from Schröter 1985). Stationary, axisymmetric MHD stellar models do show equatorial superrotation (Mestel 1961), but their applicability to the Sun is far from obvious: they ignore its (flux-dragging) wind, poor (turbulent) conductivity, and unexpected meridional circulation (at the required speed). Bisnovatyi-Kogan's (1990) buoyant prograde flux tubes have the correct tendency but may have been overestimated. My preferred explanation uses the magnetic torque exerted by the locally trailing flux ropes dragged out by the solar wind, as in Volland's (1992) model. It treats all differential motions on equal footing.

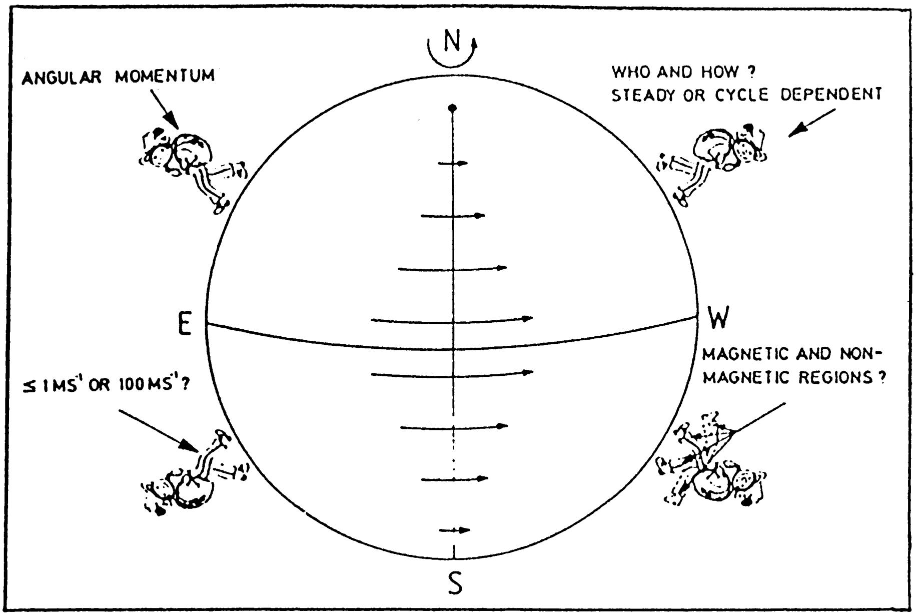

Figure 4: The problem of equatorial superrotation of the Sun, from Schröter (1985).

6. The Solar Dynamo

At this conference, Van Geffen (1992) has presented calculations which rule out the $\alpha\Omega$-dynamo both for the solar convection zone, and for its (lower) boundary layer: the locally-generated stochastic fields do not reproduce the observed large-scale order at sufficient strength.

Independently of the correctness of his conclusions (which I have no reason to doubt), I cannot see how a stochastic dynamo could strictly couple to the spin motion of the solar core - which, moreover, differs from that of the convection zone - and how it could show an oscillation period without random-walk behaviour. Why does the Hale cycle produce secondary maxima? Why does the magnetic field nucleate in flux tubes, leaving large parts of the surface field-free? And why does the field-free plasma flow around magnetic-flux tubes?

Each of these worries leads me to follow Layzer et al. (1979) in their conclusion that the solar radiative core anchors a non-zero magnetic flux whose buoyant rise through the - differentially rotating - convection zone causes the Hale cycle, and all the other mentioned properties. The solar convection zone thus loses its active role in the flux generation, in favour of a passive one.

References

Altschuler, M.D., Levine, R.H., Stix, M., Harvey, J.: 1977, *Solar Physics* **51**, 345.
Bisnovatyi-Kogan, G.S.: 1990, *Solar Physics* **128**, 299.
Bogart, R.S.: 1982, *Solar Physics* **76**, 155.
Bracewell, R.N.: 1953, *Nature* **171**, 649.
Bracewell, R.N.: 1985, *Australian J. Phys.* **38**, 1009.
Dicke, R.H.: 1978, *Nature* **276**, 676.
Dicke, R.H.: 1988, *Solar Physics* **115**, 171.
Hoeksema, J.T.: 1990, private communication.
Howard, R.: 1984, *Ann. Rev. Astron. Astrophys.* **22**, 131.
Howard, R., La Bonte, B.J.: 1981, *Solar Physics* **74**, 131.
Hoyng, P.: 1992, contribution to this Conference.
Kundt, W.: 1992, *Astrophys. Space Science* **187**, 75.
Layzer, D., Rosner, R., Doyle, H.T.: 1979, *Astrophys. J.* **229**, 1126.
Mestel, L.: 1961, *Mon. Not. Roy. Astron. Soc.* **122**, 473.
Moreno-Insertis, F.: 1986, *Astron. Astrophys.* **166**, 291.
Parker, G.D.: 1992, in Solar Wind Seven, eds. E. Marsch and R. Schwenn, Pergamon, p. 233.
Sawyer, C.: 1968, *Ann. Rev. Astron. Astrophys.* **6**, 115.
Schröder, W.: 1992, *J. Geomagn. Geoelectr.* **44**, 119.
Schröter, E.H.: 1985, *Solar Physics* **100**, 141.
Schüssler, M.: 1992, contribution to this Conference.
Simon, P.A.: 1992, contribution to this Conference.
Stenflo, J.O.: 1989, *Astron. Astrophys.* **210**, 403.
Van Geffen, J.H.G.M.: 1992, forthcoming thesis, and contribution to this Conference.
Volland, H.: 1992, *Astron. Astrophys.* **259**, 663.
Waldmeier, M.: 1955, Ergebnisse und Probleme der Sonnenforschung, Leipzig.
Wilson, P.R., Altrock, R.C., Harvey, K.L., Martin, S.F., Snodgrass, H.B.: 1988, *Nature* **333**, 748.