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SOLAR MAGNETIC FIELD AND ROTATION

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Abstract

Sun's highly inhomogeneous asymmetrical, and time-dependent magnetic field plays a vital role in the non radiative energy transport that maintains the inhomogeneous asymmetrical and time dependent atmosphere of the sun so much hotter than the surface Along with convection, sun's rotation plays an important role in maintaining the highly inhomogeneous and time dependent magnetic field of the sun Here I briefly review our knowledge of magnetic field and rotation the two interrelated attributes of the sun on various scales

1 Introduction

From the beginning of this workshop we have been hearing about a diverse variety of symmetry breaking and time varying phenomena that heat the sun's atmosphere in various way Most of these have rightly been blamed on the sun's magnetic field I shall now briefly review what we know, or do not know, about the magnetic field of the sun The field itself is believed to be maintained by dynamo processes run by sun's convection and rotation We have heard about convection from Dr Narasimha I shall review briefly what we know about the sun's rotation before proceeding to review the magnetic field

2 Sun's Rotation

Sun's rotation was discovered by Galileo in the beginning of 17th Century when he studied sunspots through his telescope He found that the daily positions of individual sunspots shifted systematically towards the western limb of the sun's disc It soon became obvious that this was not possible unless the sunspots were indeed features on the sun's surface and the surface rotated about an axis whose direction does not differ much from the terrestrial north south direction Soon the sunspot occurrence became rather scarce for a period of about 75 years which we know as the 'Maunder minimum' It was Carrington who later established the well known law of the differential rotation with a mean sidereal period of 25 38 days which has been used to define the heliographic coordinate system known by his name Since then the rotation of the sun has been studied by many authors using different tracers' and different methods

Since 1969 there have also been direct studies of the rotation of the photospheric plasma by measuring the Doppler shifts of spectral lines A third method is based on the autocorrelation of fourier analysis of the intensity distribution of various emissions on the sun's disc This method gives some idea of the rotation of sufficiently long lived features in the intensity distribution However, uncertainties in the heights of the line formation and in the distributions of sizes and lifetimes makes physical interpretations rather complicated

2.1 Surface Differential Rotation

In tables I, II and III are given the values of the coefficients in the differential rotation formula

$$\omega = A + B \sin^2\theta + C \sin^4\theta$$

between the angular velocity ω and the heliographic latitude θ as determined by various authors using various methods (Schrotter, 1985 and references therein)

Table I

Differential rotation from tracings of sunspots

Reference	A	B	Period
Single long lived and recurrent sunspots			
Newton and Nunn (1951)	14 368 ±0 034	2 69 ±0 04	1878 1944
Ward (1966)	14 378 ±0 003	2 69 ±0 08	1878 1944
Balthasar et al (1982)	14 34 ±0 08		1940 1967
Lustig (1983)	14 38 ±0 01	2 57 ±0 07	1947 1981
Howard et al (1984)	14 393 ±0 010	2 95 ±0 09	1921 1982
Lustig and Dvorak (1984)	14 23	2 36	1948 1976
Balthasar et al (1985)	14 37 ±0 01	2 86 ±0 12	1948 1976
All Sunspots			
Ward (1966)	14 523 ±0 006	2 69 ±0 06	1905 1954
Godoli and Mazzucconi (1979)	14 58	2 84	1944 1954
Balthasar and Wohl (1980)	14 525 ±0 009	2 83 ±0 08	1940 1968
Arevalo et al (1982)	14 626 ±0 014	2 70 ±0 16	1872 1902
Howard et al (1984)	14 552 ±0 004	2 84 ±0 04	1921 1982
Balthasar et al (1985)	14 551 ±0 006	2 87 ±0 06	1874 1976

It is now well accepted that sunspots rotate faster than the photospheric plasma and that the smaller or shortlived spotgroups rotate faster than the larger or long lived ones (Fig 1) Rotations of chromospheric and coronal features are similar to those of the photospheric plama or of sunspots depending on the features and their sizes (Table III)

2.2 Time Dependence and Differential Rotation

From the study of the time dependence of the differential rotation of the photospheric plasma Howard and Labonte discovered torsional oscillations of the sun, in

Table II

Differential rotation of the photospheric plasma

References	A	B	C	Period
Livingston	13 74			1966 1968
Howard and Harvey (1970)	13 76	1 74	2 19	1966 1968
Snider et al (1979)	13 5			1977
Howard et al (1980)	13 95	1 61	2 63	1973 1977
Scherrer et al (1980)	14 44	1 98	1 98	1976 1979
Perez Garde et al (1981)	14 32			1978
Duvall (1982)	14 14			1978 1980
LaBonte and Howard (1982)	14 23	1 54	2 80	1967 1980
Howard et al (1983)	14 192	1 70	2 36	1967 1982
Snider (1983)	13 8			1979 1982
	14 15			1981
	13 90			1982
Snodgrass et al (1984)	14 112	1 69	2 35	1967 1982
Snodgrass (1984)	14 049	1 492	2 605	1967 1984
Koch (1984)	14 20			1980 1981
Pierce and Lopresto (1984)	14 07	1 78	2 68	1979 1983

Table III

Differential rotation from chromospheric and coronal structures

Reference	A	B	Type of structure
Short lived features			
Milosevic (1955)	§ 14 14	3 18	Ca K_3 faculae
Shorter & Wohl (1975,1976)	§ 13 93 ± 0 08	2 9 ± 0 73	Ca bright mottles
Dupree & Henze (1972,1973)	¥ 14 7 ± 0 2	1 5	Lyman continuum emission
Simon and Noyes (1972)	¥ 14 7 ± 0 2	7 1 ± 1 1	Lyman continuum bright points in active regions
Golub and Vaiana (1978)	as photospheric plasma as sunspots		X ray emission features small, short lived, larger and longer lived
Liu and Kundu (1976)	¥ 14 5 ± 0 27	4 19 ± 3 0	Radio mm emissive regions
Long lived features and Doppler shifts			
Livingston (1969)	¥ 14 90		H Doppler shifts
Antonucci & Dodero (1977)	§ 14 33	0 34	Green corona line
Antonucci et al (1977)	§ 14 09	0 37	Long lived Ca K regions
d'Azambuna^2 (1948)	¥ 14 48	2 16	H filaments
Liu and Kundu (1976)	¥ 14 73 ± 0 28	1 05 ± 1 6	Radio mm absorption regions
Wagner (1975)	§ 14 33	0 39	EUV coronal holes magnetic fields surrounding coronal holes
Adams (1976)	¥ 14 48	0 29	
Timothy et al (1975)	§ 14 23 ± 0 03	0 4 ± 0 1	Coronal holes

¥ More like sunspots § More like photospheric plasma

[For references see: Schroter, 1985]

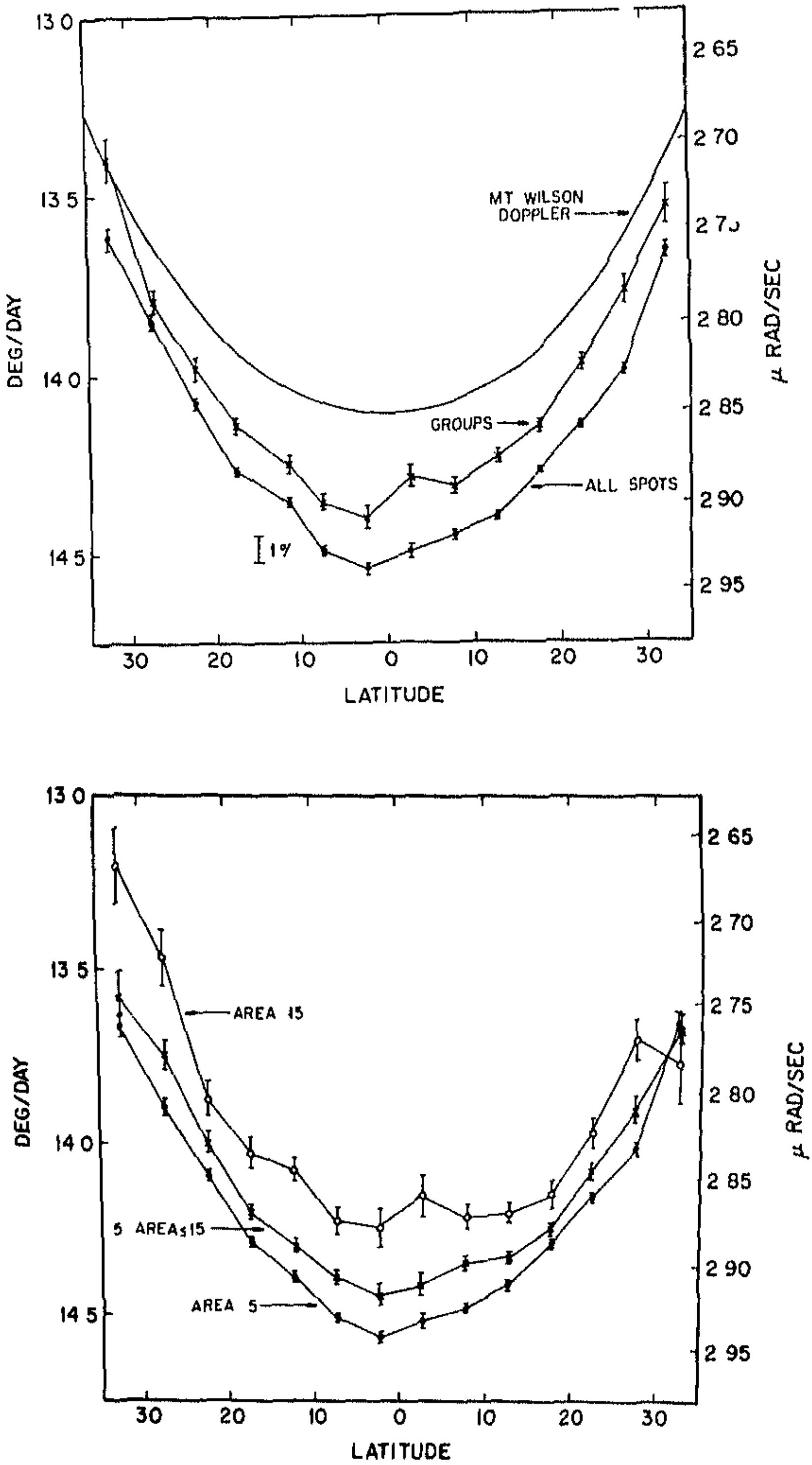

Fig. 1(a) Rotation rates of all sunspots and sunspot group in 5° latitude zones and of photospheric plasma (from Mt Wilson Doppler measurements) as functions of solar latitude (b) Rotation rates of spots of various sizes which two latitude belts in each hemisphere rotate faster than the average local rate, and each belt shifts from the pole to equator in 22 years, over a period of two peak to peak sunspot cycle. Strong magnetic fields are associated with the latitudes of excess rotational shear created by the faster rotating belts (Figure 2).

Recently Gilman and Howard (1984) have found that the rotation rates of even the sunspot groups in various latitude zones vary systematically with the phase of the solar cycle (Figure 3).

2.2 Depth Dependence of Rotation

From the helioseismological measurements (of the average rotational splitting of the frequencies of global acoustic modes) it has been shown that the equatorial rotational rate is independent of depth at least upto the base of the convection zone (Brown, 1985, Libbrecht, 1986, Duvall et al 1986). However regarding the depth dependence of the differential rotation, there is a controvesy. Brown (1985) has concluded that the rotation is *much less* differential near and below the base of the convection zone than at the surface. Duvall et al (1986) on the other hand find that the differential rotation is independent of depth at least upto the base of the convection zone.

3 Sun's Magnetic Field

That the sunspots have magnetic field as strong as several kilogauss was discovered by G Hale in 1908 by observing Zeeman splitting of spectral lines. This was the first observation of a magnetic field outside the earth. The measurement of the quiet region field eluded observers till Babcock in 1955 developed his method based on the large gradients in the line profile. Since then daily magnetic maps of the sun have been recorded by Mount Wilson and Kitt Peak observers.

In the early decades of this century Hale and Nicholson showed that (i) majority of the spotgroups are magnetically bipolar, (ii) the polarity orientations in the two hemispheres are opposite and (iii) the orientations in both hemispheres reverse from one sunspot cycle to the next. In 1959 Babcock found that even the polarities of the field near the poles reverse but within a year or two after a sunspot maximum, before reversal, the polarity near each pole is same as that of the leading spots in the corresponding hemisphere. This has been confirmed directly for subsequent cycles, and indirectly during the earlier sunspot cycles (Makrov et al, 1984). Thus the sun has a 'magnetic cycle' of approximately 22 years periodicity (see Fig 5 in "Solar Activity', this volume).

3.1 Magnetic Field in Active Region

The magnetic field in an active region, outside the sunspots, is in the form of 'clumps' or 'knots' of sizes of a few arc seconds and of field intensity 1-2 kilogauss. An active region starts by concentration of such knots near corners of supergranules. Sunspots are seen to grow and decay by converging or diverging movements of such "Magnetic Knots". During the decay of active regions the 'climps' or 'knots' spread out forming large scale monopolar regions in which knots of one or the other polarity are numerically more abundant. Howard (1974) found that streams of "following polarity" rush from the active region latitudes to the poles within an year or two and seem to be responsible for the reversal of the polar field. This is confirmed by corresponding motions of the H alpha filament channels that mark the average positions of neutral lines in the large scale field (Makarov et al 1983).

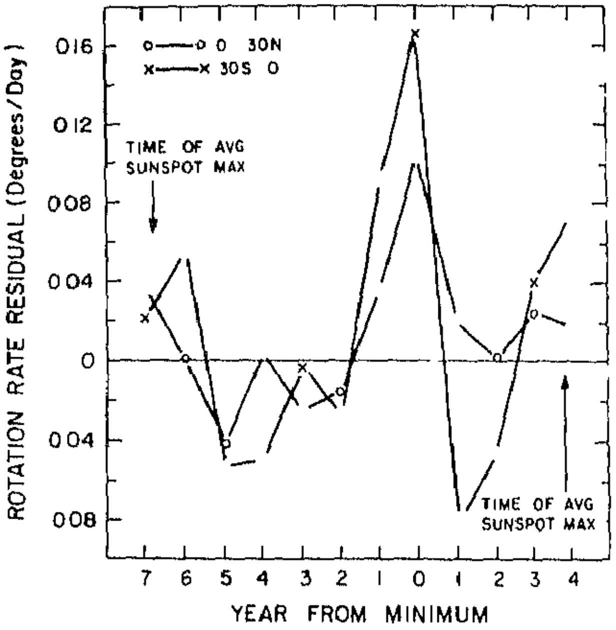

Fig 2 Solar cycle dependence of the residual rotation rates of sunspots in the northern and southern belts

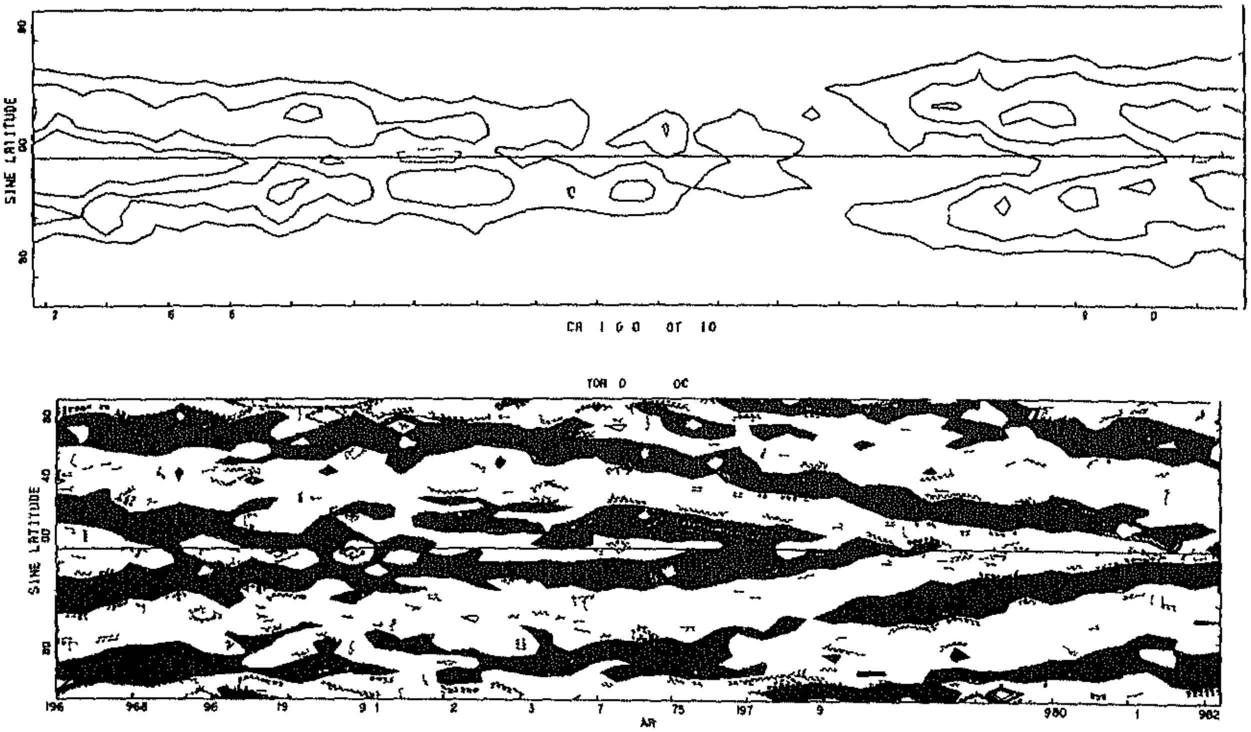

Fig. 3 Lower pand shows the 22 y period torsional oscillations of the Sun in the velocity signal observed at Mount Wilson The contours are 1 5, 3 and 6 m s^{1} of excess (solid contours) or 'deficit (dashed contours) in rotational velocity compared to that given by the smooth averaged rotation latitde curve The upper panel shows magnetic flux in four rotation averages The contour levels are 1 5, 3 6 and 6 x 10^{21} MX Both panels represent data averaged in 34 equal intervals in sine latitude

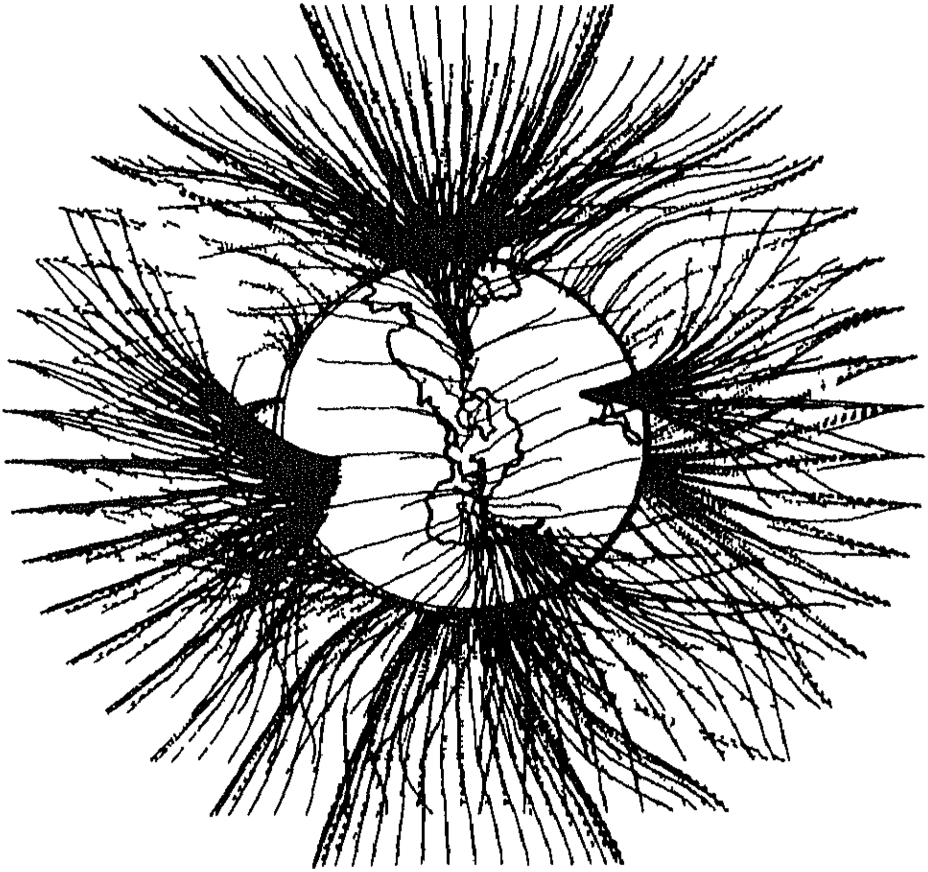

Fig. 4. Magnetic field structure calculated from the photospheric data agreeing with the large scale structure of the corona seen on the limb with a coronal hole' observed on the disc

3 2 Fields in the Quiet Region

The field in the quiet regions is also in the form of clumps or knots of 1 2 kilogauss field (Stenflo 1984) these are normally concentrated along the boundaries of supergranulation cells which in turn coincide with the chromospheric emission network Besides these there are knots of weaker field and magnetic flux ~ 10^{15} Mx, inside the network

Recently Stenflo and Vogel (1986) have subjected the 25 years magnetogram data to spherical harmonic fourier analysis and shown that the distribution of poloidal magnetic field on the sun and its variation in time can be described as a superposition of odd modes of global, axisymmetric and oscillation modes of odd parity having periods of ~22 y

Myself and Javaraiah have shown from analysis of sunspot data over five cycles (1902 1954) that if we define a 'synoptic toroidal field' from the distribution of sunspots (eg by attaching opposite signs to sunspot data in the two hemispheres and altering the signs), then the synoptic toroidal field can also be represented by a superposition of axisymmetric modes of odd parity and 22 year periodicity The power spectrum of amplitudes is qualitatively similar to that obtained by Stenflo, from the observed poloidal field

3 3 Coronal and Interplanetary Magnetic Field

Coronal magnetic field is not directly observable except in prominence and during radio bursts It can however be computed making suitable assumptions using the observed photospheric field as a boundary condition Assumption of a current free or force free nature for coronal field reproduces the large scale structures in the corona (eg 'arches', helmets, Streamers and "holes) reasonably well (eg Altschuler et al, 1977) (see Figure 4) However considerable differences occur in respect of details on smaller scales The electromagnetic current and forces are important in determining coronal equilibria Interplanetary field can similarly be computed assuming a source surface near the sun or using photospheric data and the values measured by space crafts near the earth A dominating feature of the interplanetary field is its sectorial structure which itself changes from time to time during the sunspot cycle

4. Conclusion

Sun s magnetic field is extremely complex, inhomogeneous and time dependent The description varies with the scale However descriptions on different scales are needed to solve the magnetohydrodynamical problems associated with solar activity and with the non radiative, non convective heat transport that plays dominant role in the equilibrium and energetics of the sun s atmosphere Most models ultimately depend upon the boundary conditions at the maximum depths and the maximum heights reached by the field lines Hence most studies ultimately depend upon the theories of thin fulx tubes and of the solar magnetic cycle Solar physicists in Indian Institute of Astrophysics have therefore concentrated efforts of studying these two areas

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