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SEARCH FOR MECHANISMS OF SOLAR MAGNETISM

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Abstract

Study of 'Solar magnetism' (totality of solar magnetic phenomena on different scales) and its 'mechanisms' (physical processes responsible for the phenomena) is obviously essential for the advancement of solar and solar-planetary physics. Apart from that, it has presently acquired immense importance in stellar physics as a part of the study of non-radiative modes of energy storage and transport.

Mechanisms of most of the solar magnetic phenomena are not yet fully understood owing to the uncertainties regarding the following three factors: (i) the depths at which the observed flux tubes originate, (ii) the inter-relation between the flux tubes and the large-scale field and (iii) the processes responsible for production, maintenance and periodic reversal of the large scale field.

A latest study of the preferred longitudes of sunspot activity reveals the presence of non-axisymmetric oscillations inside the sun. Such oscillations were postulated in a model providing common phenomenology for three crucial factors mentioned above but were not detected so far.

1. Introduction

By 'solar magnetism' I mean the totality of solar magnetic phenomena on various scales from ~1" to interplanetary distances and from a few seconds to millienia. The term 'mechanisms' is used for the physical processes responsible for and participating in these phenomena. The 'search' for these mechanisms is essential for: (i) understanding physics of the sun, (ii) understanding effects of solar magnetism on the interplanetary space and solar system bodies and (iii) advancement of stellar physics beyond the spherically symmetric, non-rotating, non-magnetic and non-oscillating (except radially), models. The first two applications being obvious and well known, I shall review the third application in a little more detail. I shall describe the three questions which are crucial for the study of various phenomena in solar magnetism and briefly describe a phenomenological model which provides plausible answers to these questions. Finally I shall report on a new evidence which indicates that the basic postulates in the phenomenology may be essentially valid.

2. Importance of Solar Physics for Stellar Physics

2.1 Conventional Model of a Star

The conventional model of a star has been a spherically symmetric, non-rotating, non-oscillating (except radially) and non-magnetic body in which the energy is generated near the centre and transported outwards by radiation, convection and acoustic shocks which are distributed symmetrically in all directions.

2.2 Sun as We Know

The sun, as we now know, has been spherically asymmetric and magnetic at least in its outer atmosphere, and rotating as well as non-radially oscillating even in its interior. It is now well recognized that non-radiative, non-convective, non-acoustic processes associated with magnetic fields (viz. magnetohydrodynamical and plasma processes) play a vital role in the physics of the outer atmosphere of the sun. Inside the sun the thermal energy and gravitational energy density is several orders of magnitude higher than the density of convective and rotational energy which are again several orders of magnitude higher than the average magnetic energy density. However the magnetic energy is adequate to heat the sun's atmosphere to $\sim 10^6$ K if it can somehow be transported to, and deposited into, the atmosphere.

2.3 Evidence that Similar Processes may be Operating in the Outer Atmospheres of Other Late Type Stars

During the last decade the space observations have revealed the presence of chromospheric ($\sim 10^4$ K), transition region ($\sim 10^5$ K) and coronal ($\sim 10^6$ K) emissions from stars of all spectral types. However the following characteristics strongly indicate that processes in the outer atmospheres of late type stars are similar to those in the sun's outer atmosphere:

1. It has been known (Skumanich, 1974) that in case of late type stars the chromospheric (Ca II K) emission and surface rotation both decrease with increasing age.
2. Light curves of RSCVn binaries indicate the presence of large 'groups' of dark spots clearly breaking the spherical symmetry. The asymmetry is associated with the faster rotating component (Hall, 1981).
3. Magnetic fields of $\sim 10^3$ G have been inferred to be occupying only a fraction of the area on some stars where Robinson's method of field measurement has been successfully applied (Robinson et al, 1980).
4. Rotation modulated (i.e. patchy) x-ray emission has been observed in the case of a partially eclipsing binary (Gibson et al, 1983).
5. Ratios of fluxes in chromospheric, transition region and coronal emissions from late type stars indicate dependence on a single 'activity' parameter (Schrijver, 1983).
6. In the case of early type stars the ratio of the x-ray luminosity L_X is proportional to the bolometric luminosity L_*; but in late type stars the two are uncorrelated. On the other hand the ratio $L_X : L_*$ is well correlated to angular and surface velocities of rotation. Moreover, even the scatter from the mean relation is not related to the global parameters like either effective temperature or the surface gravity (Pallavicini et al. 1981; Walter & Bower, 1981; Schrijver, 1985).
7. The general association of hot ($\sim 10^6$ K) coronae with low mass loss rates ($\sim 10^{-14}$ M y^{-1}) and of cool ($\sim 10^4$-10^5 K) coronae with high mass loss rates ($\sim 10^{-8}$-10^{-6} y^{-1}) show a striking similarity with magnetically closed 'active regions' and magnetically open 'coronal holes' in the sun's atmosphere (Stencel and Mullan, 1980).
8. Hartmann's (1983) model based on heating by alfven waves has successfully predicted the above two types of atmospheres.

2.4 Strides in Solar Research During Last Fifteen Years

Several major discoveries were made in solar physics during the last fifteen years or so, some of which made it possible to realize the significance of the above stellar observations and the others are expected to throw more light on the basic processes in the envelopes and atmospheres of late type stars in general. Here I list those which are most significant in my opinion. (I have not included in this the discovery of the unexpectedly low flux of solar nutrinos since I am concerned mainly with processes in the envelopes and atmospheres).

1. Most of the solar magnetic field is concentrated in strong thin, flux tubes with intensities $\sim 10^3$ G and cross-sections $\sim 1''$ at the photosphere, occupying only a few percent of the surface area (Stenflo, 1976).

2. The solar corona consists of three types of regions: active regions, quiet regions, and coronal holes and the major contribution to the solar wind comes from the coronal holes which are magnetically open (Golub, 1983).

3. Besides the sunspot associated activity, there is another variety of activity seen only in magnetograms and x-ray emission (appearing as x-ray bright points) which consists of a large number of 'tiny' active regions spread in all latitudes upto poles. The amount of magnetic flux associated with this activity is as much as that associated with the sunspot associated activity but the two varieties are out of phase in the solar cycle (Golub, 1980).

4. The magnetic structure of corona frequently (~ once a day) undergoes large-scale topological changes leading to observable effects at large distances (coronal transients in the interplanetary space) (MacQueen et al. 1974).

5. The so called 5-min oscillations observed on the surface are in fact global, non-radial, modes of large orders and a host of new global modes are being discovered yielding unambiguous information on the internal structure of sun almost up to the energy generating core (Deubner, 1975; Toomre, 1984).

6. Torsiorial oscillations have been discovered on timescales ~ 22 y at least in the photospheric layers (Howard & Labonte, 1980).

These major discoveries during a span of only 15 years or so show that:

SOLAR PHYSICS IS NOT A DEAD HORSE (AS SCIENCE MANAGERS ARE SOMETIMES LED TO BELIEVE), BUT IT IS A MARCHING MAMMOTH READY TO GIVE SPACE PHYSICS AND STELLAR PHYSICS - (PERHAPS EVEN RELATIVELY AS PROF. CHITRE POINTED OUT IN HIS TALK) - LONG RIDES IN THE FORWARD DIRECTION.

3. Examples of Phenomena in 'Solar Magnetism', the 'Mechanisms' to be Understood, and the Crucial Questions Common to all

3.1 The Phenomena

Here I list some phenomena in solar magnetism on various scales and the mechanisms still not understood:

1. The smalle-scale flux tubes in photosphere and chromosphere: formation, structure, dynamics.

2. Sunspots: Formation, structure in large depths (e.g. energy balance, inhomogeneities), internal dynamics (Evershed flow, waves and oscillations), decay.

3. Quiescent Prominences: Formation, structure (mass momentum and energy balance), disappearance.

4. Flares and Transient Events: Energy storage, instabilities for release, release of energy in different forms.

5. Chromospheric and Coronal Structures: Energy balance in chromospheric network elements in quiet regions, energy transport, dissipation and disposal in active regions, (e.g. coronal loops), mass, momentum and energy balance in coronal holes.

6. Solar wind: Mass, momentum, angular momentum and energy transport above quiet regions, active regions, and in coronal holes.

7. Solar Cycle and Solar Dynamo: Processes responsible for production, maintenance and periodic reversal of the large-scale field.

8. Modulation of Solar Cycle on Large-Time Scales: Maunder type minima and revival therefrom; long term stability in spite of such modulations.

4. The Crucial Questions in the Study of the 'Mechanisms'

4.1 The Questions

The progress in the study of the 'mechanisms', of solar magnetism depends crucially on the answers to the following three questions:

1. the depths at which the observed flux tubes originate,
2. the inter-relation between the flux tubes and the large-scale field, and
3. the processes responsible for the production, maintenance and periodic reversal of the 'large scale' field.

The first question concerns the boundary conditions at large depths, the second relates to the contribution of new modes of energy transport provided by the tubes and the lateral boundary conditions, and the third question is important for answering the first two questions.

4.2 The Answers According to the Two Kinds of Models

According to the turbulent dynamo theory, the large-scale field is homogeneous, it is maintained and reversed by differential rotation and convective turbulence, and flux tubes are formed from the large-scale field by local processes like instabilities.

However, turbulent dynamo theory is not a single model, it is only kinematical and its basic postulates contradict solar observations.

According to an alternative phenomenological flux tube dynamo model (Gokhale 1977, 1984) the aforementioned crucial questions have the following answers.

(i) Strong, thin, topologically closed magnetic flux tubes are produced in 'clusters' by locally non-linear interactions of oppositely propagating azimuthal MHD waves, near the base of the convection zone, in the presence of a homogeneous field which is essentially a remnant of the previous cycle.

(ii) The background field and the similarly oriented parts of the newly produced tubes emerge above the surface providing the two varieties of solar activity. The 'reversely' oriented parts of the newly produced tubes stay behind, and slowly diffuse inside the sun, thereby providing the rervesed 'homogeneous' background field for the next cycle (and the process repeats).

The advantages of the latter model are already discussed earlier (Gokhale, 1984). Here I may only repeat that it 'provides for' consistency with all the twelve observational constraints that a solar cycle model should eventually satisfy.

I shall now present a latest result of an analysis of the longitudinal distribution of sunspot activity which provides evidence for the existence of non-axisymmetric aximuthal MHD oscillations as postulated in the above model.

5. Azimuthal MHD Oscillations on Time Scales Comparable to that of the Solar Cycle and their Role in the Production of Sunspot Activity

5.1 Peaks in the Monthly Distributions of Sunspots Activity with Respect to Heliographic Longitudes

From Greenwich phtoheliographic results we have determined the monthly sums ΣA_M of the observed maximum areas of sunspot groups which appeared in each 10° interval of the heliographic longitude L, for each month from January 1933 to December 1954. Each monthly distribution of ΣA_M with respect to L shows one or two outstanding peaks of widths ~30°, with or without a low random component. By taking running averages over three consecutive intervals at a time, we determine the locations of the centres of these peaks within an accuracy ~15°. In figures 1a-1d we illustrate such smoothened distributions of ΣA_M for four months in different phases of the solar cycle 1933-1943.

5.2 Distribution of Peaks in Longitude-Time Diagrams

In figures 2(a) we show by marked and unmarked bars the highest and the second highest peaks, respectively, in the monthly distributions from January 1933 to December 1943 excepting seven months in which no spot groups appeared. In Figure 2b is shown, without distinction, the distribution of both 'first' and 'second' peaks during the cycle 1944-1954. Both diagrams reveal large 'voids' in the distribution of peaks suggesting that the peaks may be located along some curves in the longitude-time plane.

In fig.2(a) we have shown five sinusoidal (four parameter) curves fitting the 'first' peaks. Only two more sinusoidal curves are needed to fit all the 181 first and second peaks. In Fig.2(b), all the 170 first and second peaks can be fitted by four curves (each with seven parameters representing sinusoidal curves with time dependent amplitude period and phase). The goodness of these fits are given in Table I.

Table I

Statistical properties of curve-fittings for the distributions of 'first' and 'second' peaks

Cycle	Curve No.	No. of points	rms deviation	χ^2-Probability
1933-1943	1	22	15°.3	0.99999
	2	30	22°.7	0.99999
	3	42	27°.0	0.99673
	4	22	21°.2	0.99788
	5	24	14°.3	0.99999
	6	18	23°.3	0.99560
	7	23	19°.3	0.98609
	All	191	25°.3	$(1-10^{-15})$
1944-1954	1	40	24°.3	
	2	41	32°.0	
	3	39	24°.6	
	4	50	21°.5	0.99999
	All	170	29°.3	$(1-10^{-23})$

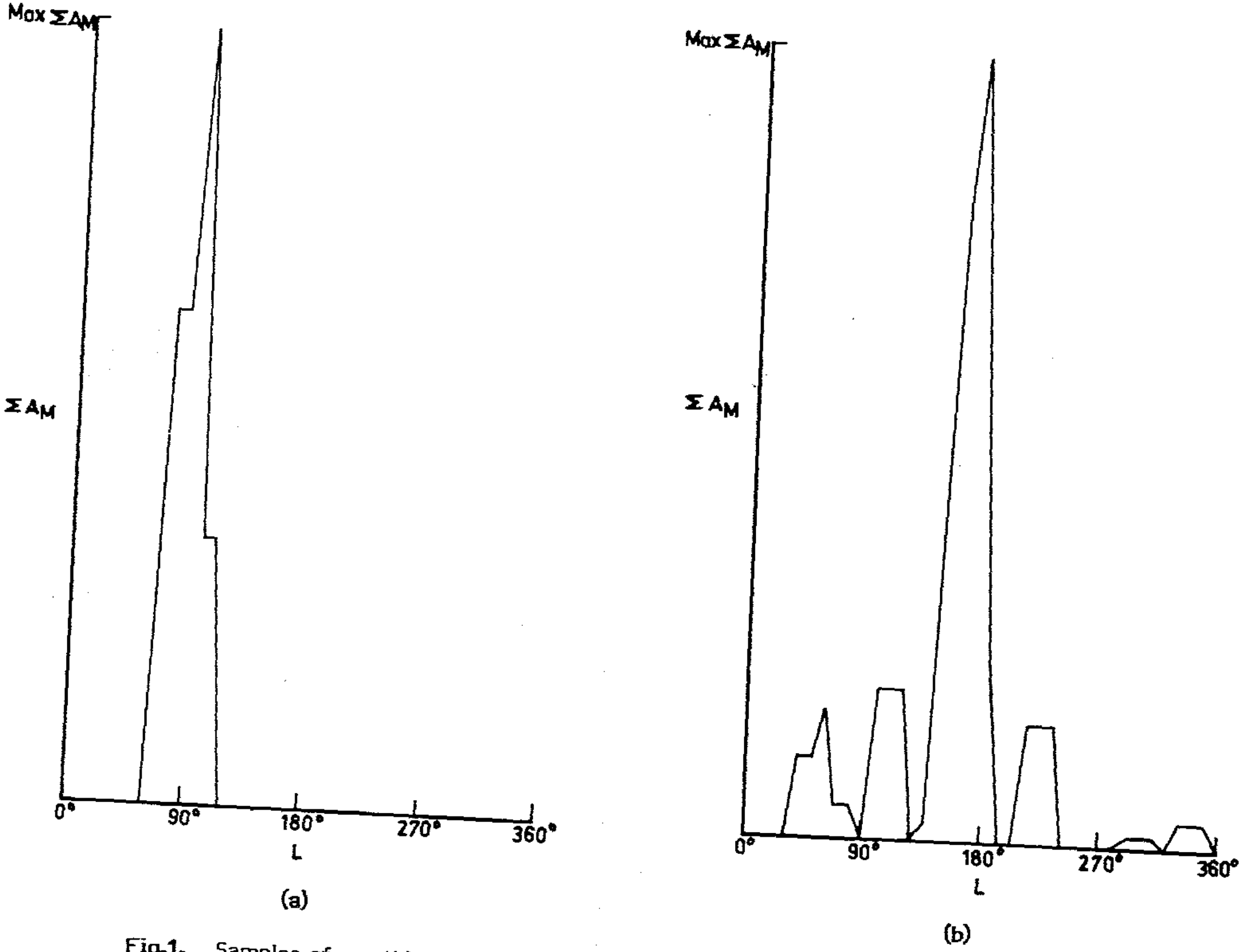


Fig.1. Samples of monthly distributions of ΣA_M with respect to heliographic longitudes for (a) January 1934, (b) May 1936.

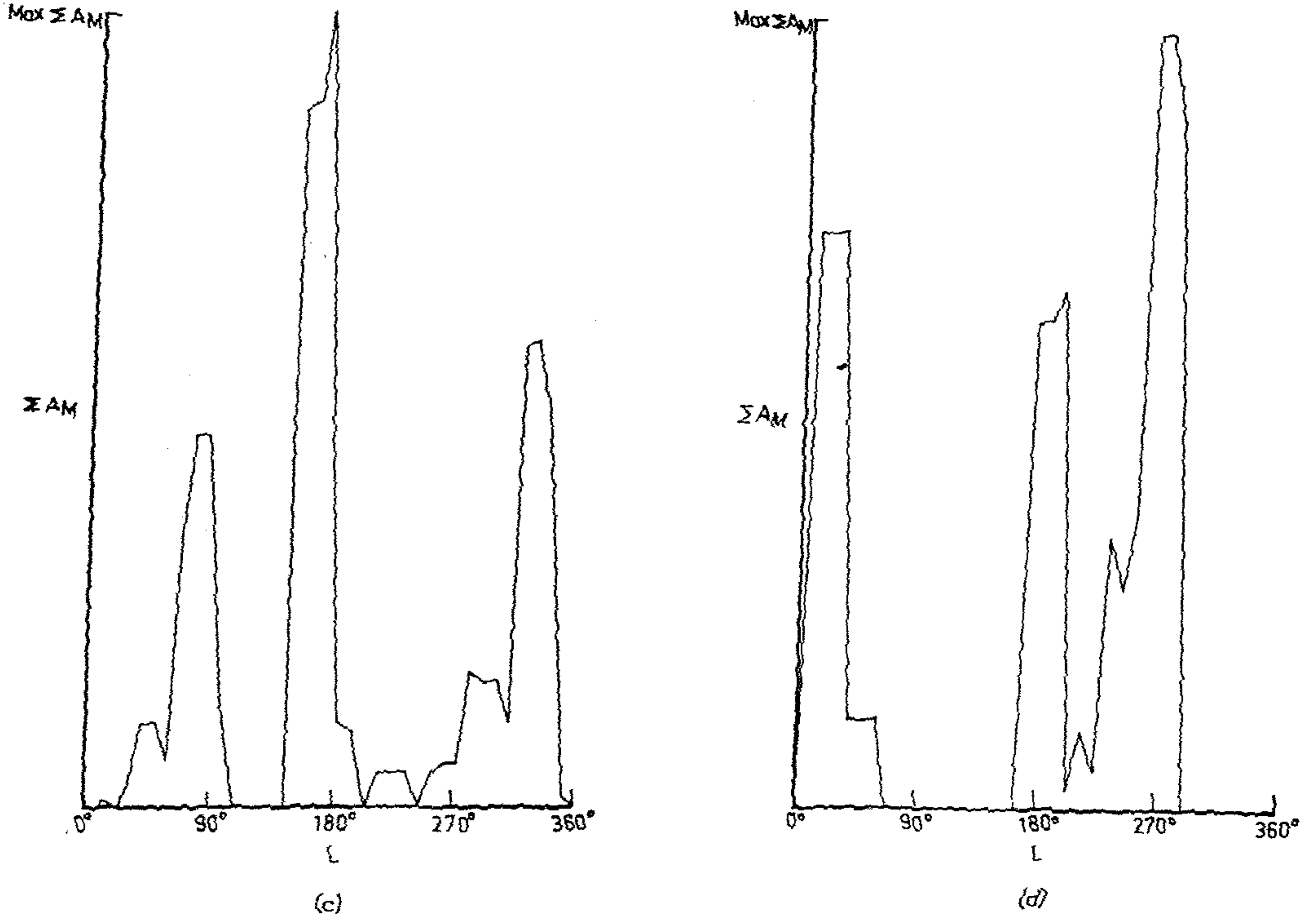
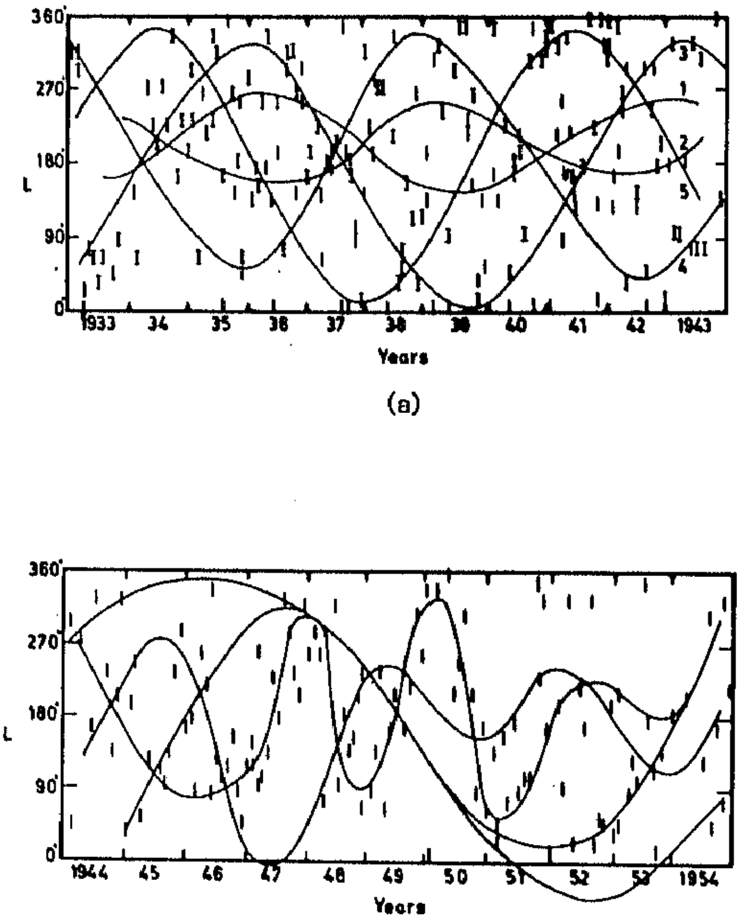


Fig.1. Samples of monthly *distributions of* ΣA_M with respect to *heliographic longitudes* for (c) July 1938, *and* (d) July 1941.



(a)

(b)

Fig.2. Locations of the centres of 'first' and 'second' highest peaks in the monthly distribution of ΣA_M, and curves along which these are located. Bars represent 15° intervals containing the centres of the peaks. **(a)** Solar cycle 1933-1943: Bars representing the 125 'first' peaks are marked at the ends, and only the 5 sinusoidal curves fitting these peaks are shown. Two more sinusoidal curves are required to fit all the 181 peaks. (b) Solar cycle 1944-1954: The four approximately sinusoidal curves (each involving seven parameters) fitting the 170 'first' and 'second' peaks.

It is clear that most of the sunspot activity in each cycle can be considered to have originated in the azimuthal oscillations represented by the curves. The periods of these oscillations corresponds to a slow MHD mode in a field $\sim 10^3$ G near the base of the convection zone.

There remains a reasonable doubt about the uniqueness of the set of curves fitting the peak in either cycle. However if it turns out that the peaks can be fitted to another set of curves representing an alternative set of oscillations it would mean that the sunspot magnetic flux tubes are produced by interaction of various modes of azimuthal MHD oscillations as suggested earlier (Gokhale, 1984).

If these results are confirmed by further detailed analysis, it would mean another important advancement in the understanding of solar magnetism particularly in reference to the crucial questions mentioned in sec.4.1.

References

Deubner, F.L. 1975. Astron. & Astrophys. **44**, 371.

Gibson, D.M., Walter, F.M. and Basri, G.S. 1983, in Stenflo, J.O. (ed) 'Solar and Stellar Magnetic Fields: Origin and Coronal Effects', (IAU Symp. **102**), 369.

Gokhale, M. 1977. Kodaikanal Obs. Bull. Ser. A. 2, 19.

Gokhale, M.H. 1984. Kodaikanal Obs. Bull. 4, 25.

Golub, L. 1983, in Stenflo J.O. (ed) 'Solar and Stellar Magnetic Fields: Origin and Coronal Effects', (IAU, Symp. **102**), 345.

Hall, D.S. 1981, in Bennet, R.M. and Dupree, A.K. (eds) 'Solar Phenomena in Stars and Stellar Systems', D. Reidel, Dordrecht, 269.

Hartmann, L. 1983, in Stenflo, J.O. (ed) 'Solar and Stellar Magnetic Fields: Origin and Coronal Effects' (IAU Symp. **102**) 419.

Howard, R. and Labonte, B.J. 1980. Astrophys. J. **239**, L33.

MacQueen, R.M., Eddy, J.A., Gosling, J.T., Hildner, E., Munno, R.H., Newkirk, G.A. Jr., Poland, A.I. and Cross, C.L. 1974. Astrophys. J. **187**, L85.

Pallavicini, R. 1984, in Pallavicini, R. (ed) 'Frontiers of Astronomy and Astrophysics', Italian Astron. Soc. Florence, 83.

Robinson, R.D., Worden, S.P. and Harvey, J. 1980. Astrophys. J. Lett. **236**, L155.

Schrijver, C.J. 1983. Astron. Astrophys. **127**, 289.

Schrijver, C.J. 1985. Space Science Rev. **40**, 24.

Skumanich, A. 1972. Astrophys J. **171**, 565.

Stencel, R.E. and Mullan, D.J. 1980. Astrophys J. **238**, 221.

Stenflow, J.O. 1976, in Bumba, V. and Kleezek, J. (eds). 'Basic Mechanisms of Solar Activity', IAU Symp. **71**, 69.

Toomre, J. 1984, in Ulrich, R.K. (ed) 'Solar Seismology from Space', JPL Publication, Pasadena, 7.

Walter, F.M. and Bowyer, S. 1981. Astrophy. J. **245**, 671.