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DIFFERENTIAL ROTATION OF SOLAR FEATURES AND ITS VARIATION AS DEDUCED FROM THE 'SHOCK-TRANSITION MODEL' OF THE SOLAR CYCLE

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ABSTRACT

From the topology of the two families of flux tubes in the shock-transition model of the solar cycle we predict the general nature of the differential rotation of: (i) sunspots and the small scale emission features in active regions and (ii) the large scale magnetic and emission features which have major contributions from the quiet regions. From the expected variation of the proportion in which the two flux tube families would contribute to the relevant data we also predict the manner in which the differential rotation of features in these categories will vary with the solar cycle. These predictions are found to be in good agreement with the so far observed rotation characteristics of various features in each category. The significance of this agreement is discussed. Directions for further theoretical and observational studies are suggested.

Key words: solar cycle—solar magnetic fields—solar rotation

1. Introduction

It is well known that all solar magnetic features, except some of those in high latitudes, rotate faster than the photospheric plasma (*e.g* summary of observed rotation rates in Van Tend and Zwaan, 1976). Such a faster rotation must be imposed on them by the rotation of plasma in the large depths. Therefore, the magnetic field lines must be concentrated in strong structures like flux tubes and/or their clusters, and the magnetic rigidity of these structures must be increasing with depth. This will enable their deeper portions to drag the upper portions ahead of the surrounding plasma (*e.g.* Stenflo, 1974). If these basic conditions are satisfied then the rotation of a photospheric intersection of a given flux tube will depend upon the "maximum depth" reached along that flux tube *before reaching the next intersection.* Owing to the inertial and magnetic forces in the flux tube and the frictional forces at all the penetrated depths, the photospheric intersection may *not* necessarily rotate at the *same* rate as the plasma at the 'maximum depth'. However, since the mass density inside as well as outside the flux tube will generally increase with depth, the rotation of the photospheric intersection will be ultimately *controlled* by the rotation of the plasma at the "maximum depth".

The 'shock-transition model' of the solar magnetic cycle is consistent with the aforementioned basic conditions in that for each 11-year cycle of activity it provides magnetic fields in the form of flux tubes and their clusters which are stronger at larger depths. For each activity cycle it provides *two topologically distinct* sets of flux tube clusters : the 'R' family and the 'S' family (Gokhale, 1979).

In the next section we summarize the model and from the topology of the two flux tube families we derive certain relations between the 'maximum depths' reached along flux tubes of either family starting from observable magnetic and emission features at different latitudes. From this we predict the nature of the "rotation curves" (curves representing the differential rotation) for features given by either family separately and also for those features to which both families contribute. From the solar cycle variations of the topologies of the two families and from the variation of their relative contribution to the relevant data, we predict the nature of variation of the rotation curves with the solar cycle.

In Section 3 we compare the predictions with the observed rotation curves for various types of magnetic and emission features and their variation with the solar cycle. We find in general a good agreement of the predicted and the observed nature of the rotation curves and their variations.

In Section 4 we discuss the significance of the agreement and point out the necessity of having 'simultaneous observations' during different phases in a whole solar cycle.

2. The Nature of the Rotation Curves and their Solar Cycle Variations as Predicted from the Model

2.1 *The 'Two Component Model' of the 'Activity Cycle' as a Consequence of the 'Shock-Transition Model' of the 'Magnetic Cycle'*

According to the shock-transition model of the solar magnetic cycle (Gokhale, 1977), two topologically distinct families of flux tubes are created before the beginning of each 'activity cycle'. As a corollary, we have the 'two-component model' of the 'activity cycle' (Gokhale 1979). According to this model, all observable magnetic features (and the associated emission features) are produced by the flux tubes of one or both families as they gradually rise across the

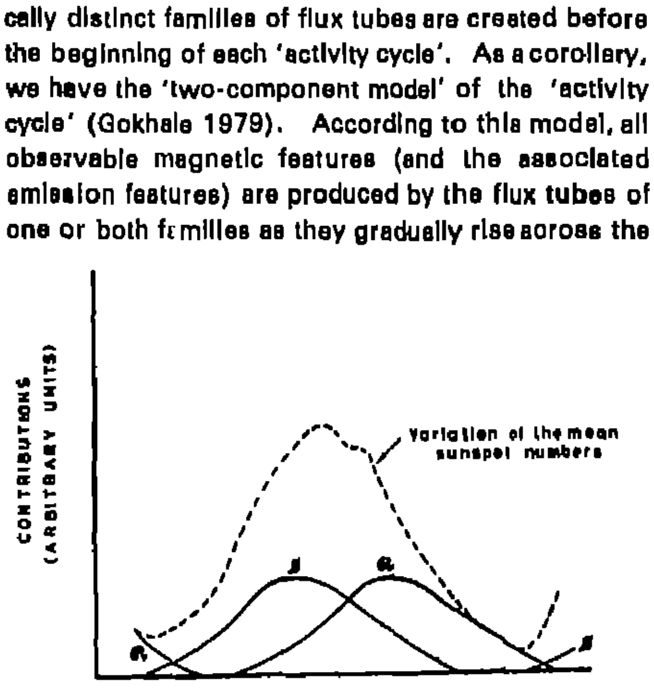

Fig. 1 The Curves '*S*' and '*R*' represent schematically the manner in which the contributions from the *S* and the *R* families of flux tubes (to most of the varieties of observable magnetic features and field-related emission features) are expected to vary in time. The resulting variation of the mean sunspot numbers will determine the phase of the solar cycle, and is represented by the dotted curve. (Since the '*S*' family flux tube clusters will be more fragmented, they will yield larger sunspot numbers than 'R' family flux tube clusters of same magnetic flux. Therefore for illustrating the variation of sunspot numbers we have arbitrarily assigned weightage ratio 2:1 to the *S* and the *R* family contributions).

photosphere and the outer layers of the solar atmosphere during the course of the whole activity cycle. For any variety of observable features to which both families contribute, the contribution from the '*S*' family peaks around the solar maximum (the main maximum of the yearly mean sunspot number), and the contribution from the '*R*' family peaks one or two years later (*cf* Fig. 1).

2.2 *The nature of the rotation curve for features with 'maximum depths' in the 'base layer'*

According to the 'two-component model' of the 'activity cycle', the 'R' family of flux tubes produces the following observable features :

(a) large, stable, spots formed from 'clusters' emerging in latitudes $\lesssim 20°$,

(b) the small scale emission features formed from loose flux tubes (which either emerge along with the clusters or get detached from the clusters during the decay of the spots), and

(c) the long-lived 'unipolar', open-field regions in the large scale magnetic fields ("M" regions) and the associated long-lived coronal holes which may be formed, *in any latitudes*, during the declining years of the solar cycle.

From the topology of the '*R*' family flux tubes it follows that for spots and the small scale features produced by these flux tubes in latitudes $\lesssim 20°$, and for the long-lived 'M' regions and the associated coronal holes in any latitudes, the 'maximum depths' as defined in Sec. 1 will be in the 'base layer'. (According to the model, this is a layer of thickness about one density-scale-height near the base of the convection zone). Hence the rotation of these features will be as imposed by the rotation of plasma in the 'base layer'.

Thus, (*e.g.* in the diagram of Van Tend and Zwaan, 1976) if we draw an 'enveloping curve' starting from the rotation of the fastest rotating spots in the low latitudes and going over to the 'rigid' rotation of the long-lived coronal holes in the high latitudes, it will represent the rotation as imposed by the rotation of plasma in the base layer. Such a curve is schematically represented by the curve 'R' in Fig. 2.

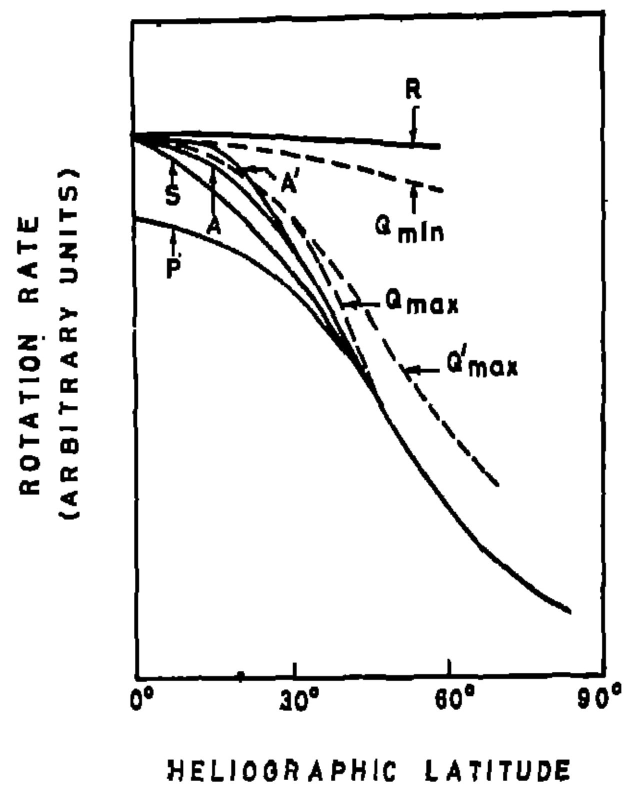

Fig. 2 A schematic diagram showing the *predicted* nature of the differential rotation curves for: (i) features produced by the *'S'* family of flux tubes only (curve *S*), (ii) active-region features produced by both the families of flux tubes (curve *A'* during solar maximum and curve *A* in other phases of the solar cycle), (iii) large scale features contributed by both families of flux tubes during solar maximum (curve Q_{max} or Q'_{max} depending on the method) and during solar minimum (curve Q_{min}). (*cf.* Sections 2.2-2.4). These curves lie in-between the curves *P* and *R* representing, respectively, the observed differential rotation of the photospheric plasma and the nearly rigid rotation of features whose 'maximum depths' are expected to be in the base-layer.

2.3 *Rotation curve for features produced by the 'S' family flux tubes*

According to the two-component model, the *S* family flux tubes produce the following features :

In latitudes $\lesssim 40°$ they yield sunspots of various sizes and the associated small scale features like faculae and network elements. *In all latitudes* they also yield only *small-scale activity* without spots (*e.g.* 'ephemeral active regions', 'XBP's etc.).

From the topology of the 'S' family flux tubes in the model it follows that : (a) near the equator the "maximum depths" reached along these flux tubes will be in the base layer, and (b) *at successively higher latitudes* the "maximum depths" reached will be *successively smaller.*

Therefore, near the equator the rotation of sunspots and small scale features produced by 'S' family flux tubes will be controlled by the rotation of plasma in the *'base layer'* while at *successively higher latitudes* their rotation will be determined by plasma rotation at successively smaller depths. Thus, the small scale features in the highest latitudes might almost co-rotate with the photospheric plasma.

Thus for the features given by the *'S'* family the rotation curve will be like the curve 'S' in Figure 2.

2.4 *Rotation curves for features contributed by both the familiys of flux tubes and the variation of such curves with solar cycle*

In case of most (but certainly not all) varieties of features the data used for determining the rotation rates will have contributions from *both* the *'R'* and the *'S'* families of flux tubes. For any such variety of features, the rotation curves can be predicted to have the following properties.

(i) The rotation curves will lie between the *'R'* and the *'S'* curves of Figure 2.

(ii) Around the solar maximum the contribution from the 'S' family will be dominant (*cf.* Fig. 1.) Hence, around that time, the rotation curves of such features will be nearer to the curve *'S'*, for example, as illustrated by the curve Q_{max} in Figure 2. However, if the *'observed rotation curve'* is derived by statistical methods (like autocorrelations and power spectra of time series which effectively filter out the contribntion from the shallow, short-lived features), then in the high latitudes it *will not descend so much* as to coincide with curve *'P'* for the photospheric plasma rotation. Instead, it will be like the curve Q'_{max}.

(iii) As the annual mean sunspot number decreases the relative contribution of the *'S'* family will decrease and that of the *'R'* family will increase (*cf.* Fig. 1). Therefore, the rotation curves will *vary with the solar cycle* in the following manner.

(A) Curves for active region features

With the decline of the activity cycle, the contributions to the active region features from both families of flux tubes drift towards the equator. This includes the *increasing contribution* from the faster rotating '*R*' family flux tubes. Consequently the rotation in the low latitudes will become somewhat faster with the decline of the solar activity (as in the curve A), but the general shape (A) of the rotation curve will not vary much with solar cycle.

(B) Curves for the large-scale features which have a major contribution from the quiet regions

In the case of large scale field and emission features which have a major contribution from the quiet regions, the contribution of the '*R*' family flux tubes goes on increasing at all latitudes as the yearly sunspot number goes on decreasing. Consequently the rotation profiles of such features will change from Q_{max}-type or Q'_{max}-type around the solar maximum to '*R*'-type just before the solar minimum. This trend will reverse when the features of the next cycle start contributing. Thus, around the solar minimum the rotation curves will look like Q_{min}.

3. Comparison with the Observed Rotation Curves for different varieties of Solar Magnetic and Emission Features.

3.1 *Sunspots and associated chromospheric emission features*

3.1.1 Sunspots

Sunspots have contributions from '*S*' family in latitudes $\lesssim 40°$ and from '*R*' family in latitudes $\lesssim 20°$.

The shapes of the rotation curves obtained by Newton and Nunn (1951) for recurrent spots and by Ward (1966) for recurrent as well as nonrecurrent *spotgroups* are similar to the curve 'A' in Fig. 2 as predicted in Sec. 2.4.

The nature of variation of the rotation curve for *all* spots with solar cycle is not known, but at lest for *recurrent* spots Newton and Nunn found practically no variation. This is as predicted in Sec. 2.4 (Prediction III-A).

3.1.2 A note on the relatively slow rotation of long-lived round spotgroups and the acceleration of the equatorial plasma.

Ward (1966) found that long lived and approximately round spotgroups rotate on the average slower than the short lived and elongated spotgroups. This seems to contradict the contention that the major contribution to the large spotgroups comes from the faster rotating '*R*' family flux tubes. However, the discrepancy would not arise if the long-lived round spotgroups given by the clusters of the '*R*' family flux tubes rapidly exchange rotational energy and momentum with the surrounding plasma in the first few days of their life and thereby contribute more to the slow rotation during the rest of the life (*cf.* Delury's remark quoted by Ward). Such a process (also suggested by Stenflo, 1977) would make the photospheric plasma rotate faster with the decline of the solar cycle. This effect will be predominant at small latitudes. Howard (1976) has, in fact, observed such an acceleration of the equatorial plasma from the solar maximum of 1968 to the solar minimum of 1976 (*cf.* also Livingston and Duvall, 1979).

3.1.3 Solar Cycle variation of the rotation period deduced from the peaks in the power spectra of Sunspot Numbers.

In the power spectra of year-long time of series of daily sunspot numbers, Rajaram and Singh (1979) found peaks at frequencies ν_{peak} in the vicinity of 1/27 day $^{-1}$. They found that during each of the last four solar cycles, the 'rotation period' T_{peak} (defined as $1/\nu_{peak}$) varies in the same manner as the yearly mean sunspot number. They also pointed out that the amplitude and the smoothness of this variation preclude its simple interpretation in terms of the drift of sunspot latitudes. The observed variation leads to the conclusion that the sub photospheric *sources* of sunspots must be, on the average, rotating faster during the sunspot minimum than during the maximum. In our model, such a variation in the average 'rotation rate' of the sources is provided by the presence of *two* kinds of 'sources' (viz. the *R* and the *S* families of flux tubes) along with the variation in their contributions and latitudinal distributions (*cf.* Prediction 'III-A' in Section 2.4).

3.1.4 Small scale features associated with active regions

Small scale features associated with active regions such as 'photospheric faculae', 'Ca K3 faculae', 'Ca^{+} bright mottles', 'EUV bright points', all have rotation curves similar to those of sunspots. (Schröter and Wöhl, 1976; Simon and Noyes, 1972; Van Tend and Zwaan, 1976). Moreover, as pointed out by Antonucci *et al* (1977), this similarity is there even though the observations of these features cover different phases of the solar cycle. Thus the rotation curves for the small scale active region features seem to agree with the prediction 'III-A' in Sec. 2 4.

3.2 *Large scale photospheric fields and large scale chromospheric and coronal emission features*

According to the model outlined in Sec. 2.1, the photospheric field at any stage is provided by the photospheric intersections of the flux tube stitches. The stitches themselves produce the chromospheric and the coronal inhomogeneities. Thus, the large scale photospheric fields and the large scale chromospheric and coronal inhomogeneities will have contributions from both the *'R'* and the *'S'* family flux tubes. Therefore, here we compare their rotational properties with the predictions of Sec. 2.4.

3.2.1 *Large scale photospheric fields*

We find that the nature of the rotation curve for large scale photospheric fields and its variations with the solar cycle as observed by Stenflo (1974, 1977) are in complete agreement with *all the three predictions* of Sec. 2.4. In fact the topology of the *'R'* and the *'S'* families of flux tubes in the present model is consistent with the requirements of Stenflo's (1977) own interpretation of his observations.

3.2.2 *Prominences*

The observed rotation curve for prominences follows that of the large scale fields (*cf.* Van Tend and Zwaan, 1976). This is to be expected since the prominences lie along the neutral lines in the large scale photospheric fields.

3.2.3 *Large scale chromospheric emission features*

(a) Ca^+-K_3 emission Features :

During the years 1972-1973 (which are intermediate between the solar maximum of 1969 and the minimum of 1976), the large scale Ca^+-K_3 emission features which survived longer than one rotation gave a rotation curve similar to the curve 'R' in Fig. 2 (Antonucci *et al.* 1977). However, when similar features with life times 1-27 days were included in the data, the rotation curve looked like the curve Q_{max} (Antonucci *et al.* 1979)*. This shows that the long-lived and the short-lived features are produced by topologically distinct sets of flux tubes ; and in the combined data the short-lived variety dominates completely. If the two varieties come from the *R* and the *S* families of flux tubes as suggested in the model, then the long-lived one must be produced by the *'R'* family and the short-lived one by the *'S'* family. If it is so, the shapes of the observed rotation curves are as expected from the model.

[* In a latest paper (*Solar Phys.* **63** (1979), 17), Anntonucci *et al* have filtered the 1972 data into 'small-scale' and 'large scale' groups corresponding to Fourier wavelength ranges ~ 24000-110000 km and ~ 120000-300000 km respectively. Both these scale-ranges come under the term 'large scale' used in the present paper. Each 'scale-group' includes features with life-times down to ~ 1 day. So, as expected, the rotation curves for both scale-groups resemble the curve Q_{max}. The slight difference between the rotation rates of the two groups, if real, could result from a small difference in the relative contributions from the *'R'* and the *'S'* flux tube families to the two scale-groups.]

(b) Ly-alpha Emission Features

Rotation curve for the large scale Ly-alpha continuum emission features seems to vary form the Q_{max}-type in 1967 to *R*-type in 1969. (Dupree and Henze, 1972; Henze and Dupree, 1973). According to Gnevyshev, 1977), the years 1967 and 1969 correspond to the peaks of the two components of the activity cycle 1966-1976. Therefore, the observed variation of the rotation curve is in accordance with the prediction 'III-B' of Sec. 2.4

3.2.4 *Coronal Inhomogeneities*

Fe 6303 Emission Features

Rotation curves for the coronal inhomogeneities as observed in the Fe6303 line by Antonucci and Svaalgard (1974) and by Antonucci and Dodero (1977) also show the solar cycle variation as per prediction 'III-B'.

The long lived Coronal Holes ;

The 'rigid' rotation of the long-lived coronal holes is already incorporated in the definition of the curve *'R'* (*cf.* Section 2.2).

4. Conclusions and Discussion

It is clear that the observed rotation curves and their solar cycle variations are like those predicted from the topology of the *'R'* and the *'S'* families of flux tubes and from the varying contributions of these two families to the relevant data.

This conclusion does not necessarily imply that the shock-transition model or its corollary (the 'two component model') are correct in *all details*. However, along with the agreement between the predicted and the observed properties of the two components of the activity cycle (Gokhale 1979), it strongly suggests that this model might represent essentially the true overall topology of the subphotospheric fields and its variation during the solar cycle.

The agreement regarding the rotation characteristics indicates that it may be correct to interpret the observed rotations of the various features as those *imposed* by the rotation of plasma at the "maximum depths" reached along the magnetic flux tubes. If this interpretation is correct, then a theoretical study of the motion of magnetic flux tubes in moving stratified media may enable one to use the rotation rates of magnetic features for determining the rates of plasma rotation at various depths and latitudes (Stenflo 1977). Conversely if the rotation rates of the plasma at various depths could be accurately determined by some independent method (like *e.g.* Deubner *et al.* 1979) then such a study will be of help to learn more about the depth-dependence of the structure of flux tubes below the photosphere. Such studies may be needed for *quantitative comparison* between theory and observations.

For understanding the exchange of rotational energy and momentum between the flux tubes and the solar plasma, it may be necessary to determine the rotation curves for the plasma and simultaneously for various kinds of magnetic (and emission) features during different phases of the solar cycle. A large cooperative effort will be necessary for acquiring such information.

References

Antonucci, E., Svaalgard, L., 1974, *Solar Phys*. 34, 3.

Antonucci, E., Dodero, M.A., 1977, *Solar Phys*. 53, 179.

Antonucci, E., Azzarelli, L., Casalini, P., Cerri, S., 1977, *Solar Phys*. 53, 519.

Antonucci, E., Azzarelli, L., Casalini, P., Cerri, S., 1979, *Solar Phys*. 61, 3.

Deubner, F.L., Ulrich, R.K., Rhodes, E J, 1979, *Astr. Astrophys* (in press)

Dupree, A K., Henze, W.Jr., 1972. *Solar Phys*. 27 271.

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

Gokhale, M.H., 1979, *Kodaikanal Obs Bull. A, Ser.*, 2, 217.

Gnevyshev, M.N., 1977, *Solar Phys*. 51, 175.

Henze, W. Jr., Dupree, A.K, 1973, *Solar Phys*. 33, 425.

Howard R., 1976, *Astrophys. J.* 210, L159.

Livingston, W.C., Duvall, Jr, 1979. *Solar Phys*. 61, 219.

Newkirk, G., 1967, *Ann Rev. Astr, Astrophys*. 5, 213

Newton, H. W., Nunn, M.L, 1951. *M. N. R. A. S.* 111, 413.

Rajaram, M., Singh, B P., 1979, presented in XXII COSPAR Meeting at Bangalore.

Stenflo, J.O., 1974, *Solar Phys*. 36, 495.

Stenflo, J.O., 1977, *Astr. Astrophys*. 61, 797.

Van Tend, W., Zwaan, C., 1976, in *'Basic mechanisms of solar activity,' IAU Symp.* 71, ed. *V. Bumba, and J. Kleczek*, P. 45.

Ward, F., 1965, *Astrophys. J*, 145, 416.