II . ROTATION – ACTIVITY – CYCLE – AGE CONNECTION: OBSERVATIONS

THE OBSERVED RELATIONSHIPS BETWEEN SOME SOLAR ROTATION PARAMETERS AND THE ACTIVITY CYCLE

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ABSTRACT

Several parameters of the solar rotation show variations which appear to relate to the phase of the solar activity cycle. The latitude gradient of the differential rotation, as seen in the coefficients of the $\sin^2$ and $\sin^4$ terms in the latitude expansion, shows marked variations with the cycle. One of these variations may be described as a one-cycle-per-hemisphere torsional oscillation with a period of 11 years, where the high latitudes rotate faster at solar activity maximum and slower at minimum, and the low latitudes rotate faster at solar activity minimum and slower at maximum. Another variation is a periodic oscillation of the fractional difference in the low-latitude rotation between north and south hemispheres. The possibility of a variation in the absolute rotational velocity of the sun in phase with the solar cycle remains an open question. The two-cycle-per-hemisphere torsional waves in the solar rotation also represent an aspect of the rotation which varies with the cycle. We show that the amplitude of the fast flowing zone rises a year before the rise to activity maximum. The fast zone seems to be physically the more significant of the two zones.

1. INTRODUCTION

Variations of solar rotation in phase with the 11-year spot cycle have been sought by several investigators (Howard, 1979; Livingston and Duvall, 1979; Belvedere *et al.*, 1979). The discovery of large-scale plasma flows in step with the cycle would provide important clues to the mechanism which generates the magnetic activity of the sun.

Measurements using sunspots as rotation tracers suffer from potential systematic effects, as the nature of the spots and their connection

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to the solar plasma may vary through the cycle. Spots are also limited in their latitude range, precluding studies of polar rotation. Doppler shift measures cover all latitudes, but may also have systematic errors in their absolute calibration (Scherrer et al., 1980). Because of such errors we expect that variations of the absolute rotation rate may be difficult to verify, but variations of the shape of the differential rotation, a relative measurement, may be easier to detect. A recent paper (Howard et al., 1983) describes and presents the Mount Wilson velocity data since 1967, and we use that data here to measure variations of solar rotation correlated with the activity cycle.

The torsional waves on the sun, discovered from the Mount Wilson velocity data (Howard and LaBonte, 1980; LaBonte and Howard, 1982a) are in a sense a parameter of the latitude distribution of the solar rotation. These 11-year oscillations are clearly associated with the solar cycle in both period and latitude motion, with the latitudes of sunspot appearance and torsional velocity shear coincident.

In this paper we will discuss correlation of the differential rotation and the torsional oscillations with the activity cycle. We will exclude from our study the global velocity fields that appear symmetric about the central meridian (e.g., limbshift and "ears"). Those velocity fields and their relation to magnetic activity are considered in detail elsewhere (LaBonte and Howard, 1982b). All the observations discussed here were made with the 5250.2 Å line of Fe I, with a square aperture of 17.5 arcseconds until 1975, and 12.5 thereafter. Details of the instrument, observation procedure, and reduction procedures are given in earlier papers.

The dataset of Howard et al. (1983) contains 3164 full-disk velocity maps in the interval January 1, 1967 to March 31, 1982. The data are fitted by least squares to determine the angular rotation coefficients $\underline{A}$, $\underline{B}$, $\underline{C}$, in the polynomial equation

$$\omega(\phi) = \underline{A} + \underline{B}\sin^2\phi + \underline{C}\sin^4\phi,$$

where ϕ is the solar latitude. Plots of the coefficients are given in that paper. In practice, the fit is done for the full disk and for the north and south hemispheres separately. In Section 2 we consider those variations of solar rotational velocities which are measured by the coefficients $\underline{A}$, $\underline{B}$, and $\underline{C}$ in this simple representation. In Section 3 we consider those velocity variations that are not measured by the coefficients, because of their higher latitudinal wavenumber.

2. DIFFERENTIAL ROTATION VARIATIONS

A. Absolute rotation rate

The absolute value of the equatorial rotation rate, $\underline{A}$, is most sensitive to systematic error. By examination of a plot of the time

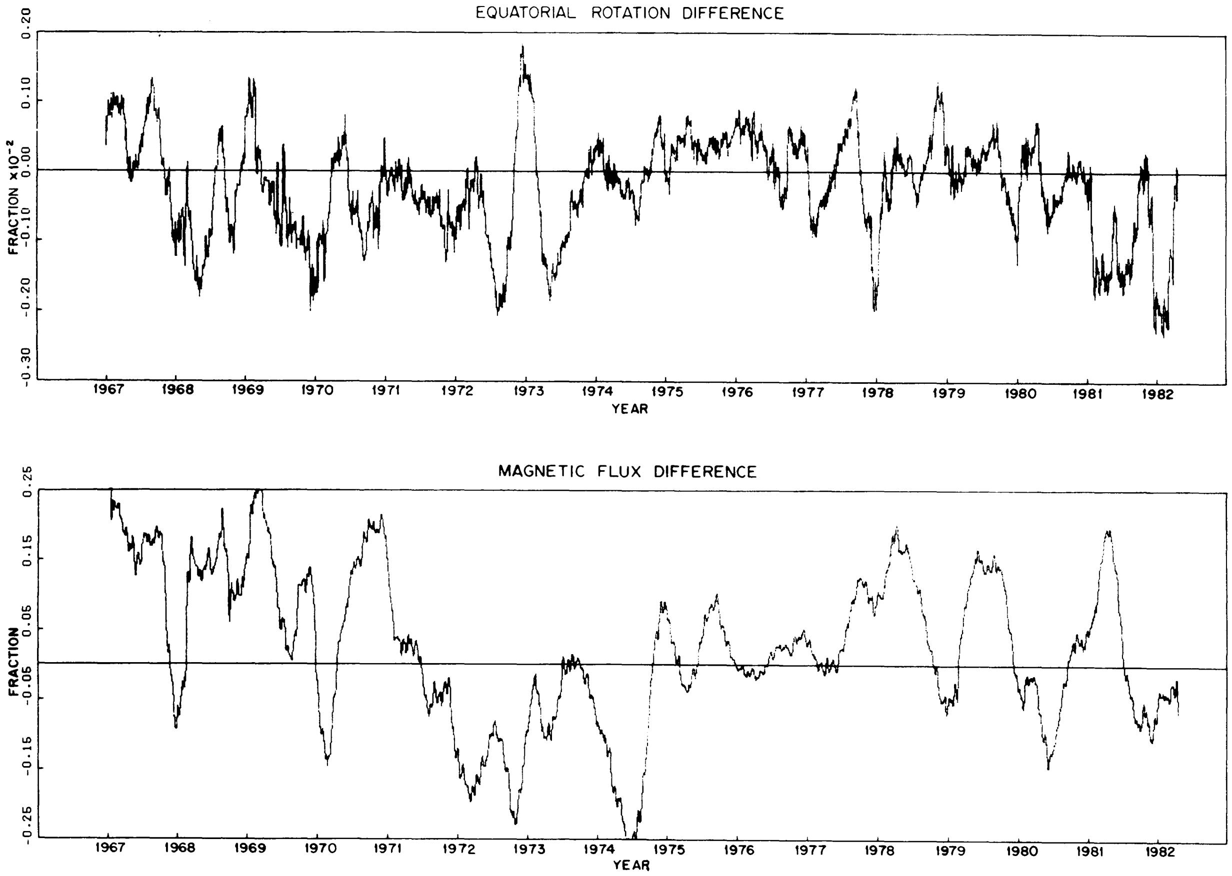


Fig. 1. (Top) Fractional difference of the rotation coefficients A determined from data in the north and south hemispheres separately (N-S/N+S). (Bottom) Fractional difference of the total magnetic flux in the two hemispheres (N-S/N+S). Daily values are averaged over intervals of 4 Carrington rotations (109.1012d). Although A is strictly the equatorial rotation rate, it is influenced by data over a range of low latitudes. The roughly sinusoidal variation of the rotation difference is not seen in the magnetic flux difference.

series of A, we can set a limit on the 11-year variation of ∿2% (0.06 μ rad s^{-1}) sinusoidal amplitude. Better limits from the Mount Wilson data will require an improved understanding of the remaining sources of systematic error. Livingston and Duvall (1979) reported an increase of the equatorial rotation rate of 3.7% over the interval 1966 to 1978, with no apparent 11-year periodic variation. Scherrer et al. (1980) found no variation >0.5% in the equatorial rotation rate over the interval 1975 to 1980, from activity minimum to maximum.

B. Hemispheric rotation difference

The coefficient A in the solution for the angular rotation is affected by the data over a range of latitudes near the equator, and in a sense, represents a mean rotation rate over that range. In Figure 1 is shown the fractional difference of the equatorial rotation rates derived from the data in the north and south hemispheres separately. There is a variation of this parameter, which may be periodic at a period of 11 ±3 years. The sense of the difference is that the north hemisphere rotated faster in the years 1974 to 1980. The peak-to-peak amplitude of the fractional difference is $1.5 \pm 0.3 \times 10^{-3}$ m sec^{-1}. This corresponds to a peak velocity difference between hemispheres of 1.5 m s^{-1}. Thus each hemisphere rotates faster and slower by ∿1 m s^{-1}, with roughly an 11-year period. This can be considered a torsional oscillation of wavenumber 0.5 $hemisphere^{-1}$.

This rotation difference between the hemispheres may be a deep-seated phenomenon, or it could be a simple response to the unequal distribution of magnetic flux in the two hemispheres. Figure 1 also shows the fractional difference of the total magnetic fluxes in the north and south hemispheres. There is no clear relation between the fractional flux difference and the fractional rotation difference on long time intervals. The relative motion of the north and south hemispheres is not simply related to the distribution of surface magnetic flux.

C. Latitude gradient of rotation

The coefficients B and C measure the latitude gradient of the angular rotation rate. The ratios B/A and C/A should be free of systematic error, and LaBonte and Howard (1982a) showed that those ratios vary in phase with the 11-year cycle. The behavior of C/A is shown in Figure 2; B/A is anticorrelated with C/A and is shown in Howard et al. (1983).

This variation of latitude gradient can be considered a torsional oscillation of wavenumber 1 $hemisphere^{-1}$. The ratio C/A varies about its average value (-0.171) by 0.020 ±0.003 sinusoidal amplitude; the ratio B/A varies about its average value (-0.122) by 0.009 ±0.002 sinusoidal amplitude. The velocity amplitude is ∿10 m s^{-1} peak to peak, and may be concentrated at high latitudes (Livingston and Duvall, 1979). Our measures of the true latitude distribution may be colored by the form of the differential rotation curve adopted.

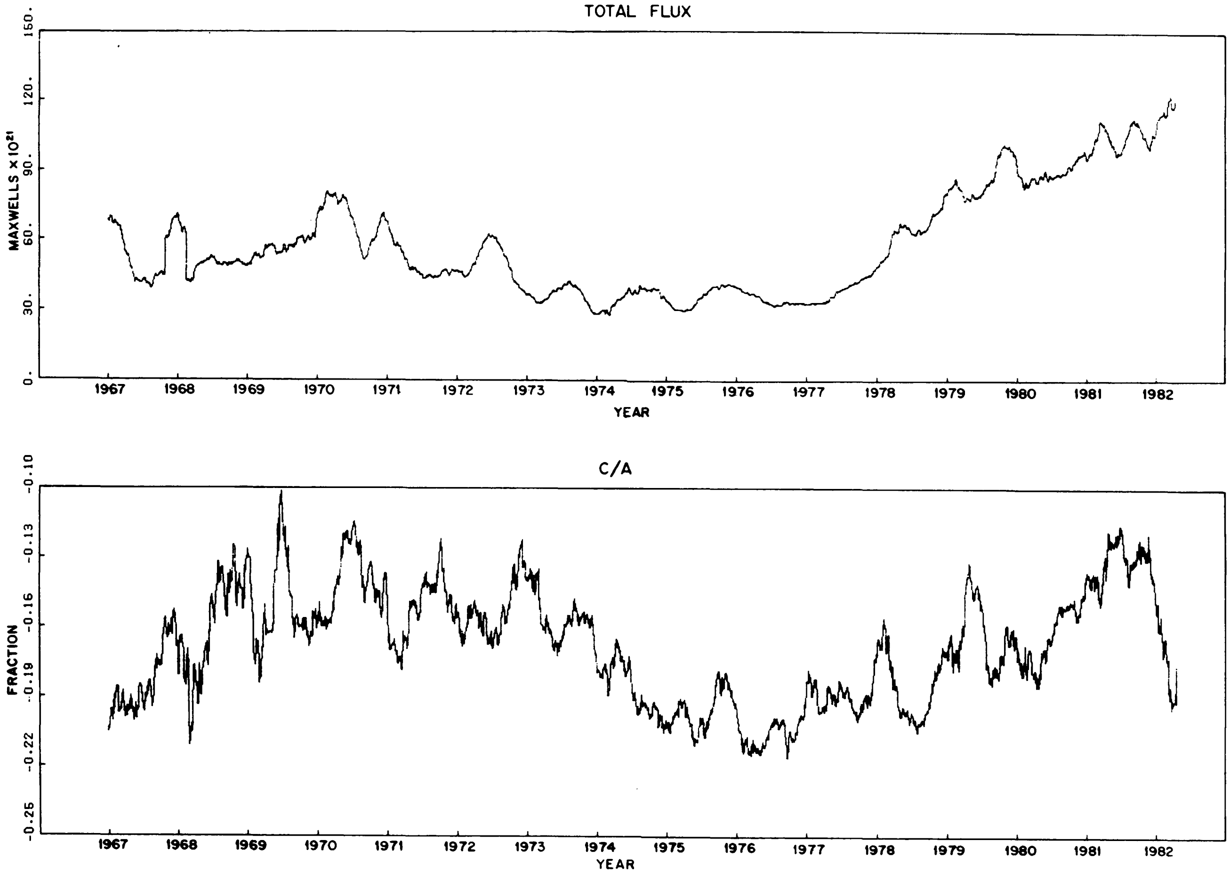


Fig. 2. (Top) Disk total magnetic flux. (Bottom) Ratio of the full-disk rotation coefficients C/A. Daily values are averaged over intervals of 4 Carrington rotations. The ratio C/A shows a clear cycle-related variation. Note that the total magnetic flux has continued to increase after the time of maximum sunspot number.

For comparison, the disk total magnetic flux is also shown in Figure 2. The sense of the variation of B/A and C/A is that high latitudes rotate faster at spot maximum and slower at spot minimum.

3. TORSIONAL OSCILLATIONS

The difference of the rotation rates measured independently in each of 34 zones of equal interval in sine latitude from the rotation rates given by the polynomial fit is a residual east-west velocity field. In previous papers we have shown that this residual velocity field takes the form of a travelling torsional wave of wavenumber 2 hemisphere^{-1}. The data representation used here is improved from that used in the earlier papers. The dataset now extends to April, 1982, well past the sunspot maximum of Cycle 21. In each time interval, the average of the residual velocities in the central 32 latitude zones was removed; this corrected the residuals for a slight bias ($\sim$1 m s^{-1}) that was a part of the average solar rotation rate. The time averaged values of the two equatormost latitude zones were also removed, because there is a constant rotation deficit $\sim$5 m s^{-1} at the equator which is too small in latitude extent for the polynomial representation of the differential rotation to remove. The resulting residual velocity map is shown in Figure 3. All systematic bias has been reduced to <1 m s^{-1}. For comparison with the magnetic activity, a map of the latitude distribution of magnetic flux (butterfly diagram) is also shown in Figure 3.

The improved representation of the torsional velocity more clearly shows the motion of the wave to the equator. The continuity of the waves as they travel from high to low latitudes is also more easily seen. The westward zones of the waves which will be cospatial with the Cycle 22 activity zones later in this decade are now distinctly seen to have moved from the poles to latitudes $\sim$45 degrees north and south.

We noted previously (LaBonte and Howard, 1982a) that the westward flowing zones of the waves appeared to have increased amplitude in the years before spot maximum. The velocity amplitude has now returned to its former value. In Figure 4, the average velocity amplitude of the Cycle 21 westward flowing zones is plotted, along with the total magnetic flux in the Cycle 21 activity zones. The velocity amplitude is seen to precede the magnetic activity, increasing $\sim$1 year before the total magnetic flux, as judged from the times of the steep increases in their relative amplitudes. An equal lead of the torsional velocity relative to the sunspot number has also been found, but is not plotted here. The data are not good enough at this time to measure the time difference between the torsional wave and magnetic flux in the north and south hemispheres separately. Only the westward flowing zone of the wave shows this amplitude increase; the eastward flowing zone has unchanged amplitude throughout this time interval.

Note also that although the maximum sunspot number (1 year smoothed value) was reached in 1980.0, the total magnetic flux in the activity

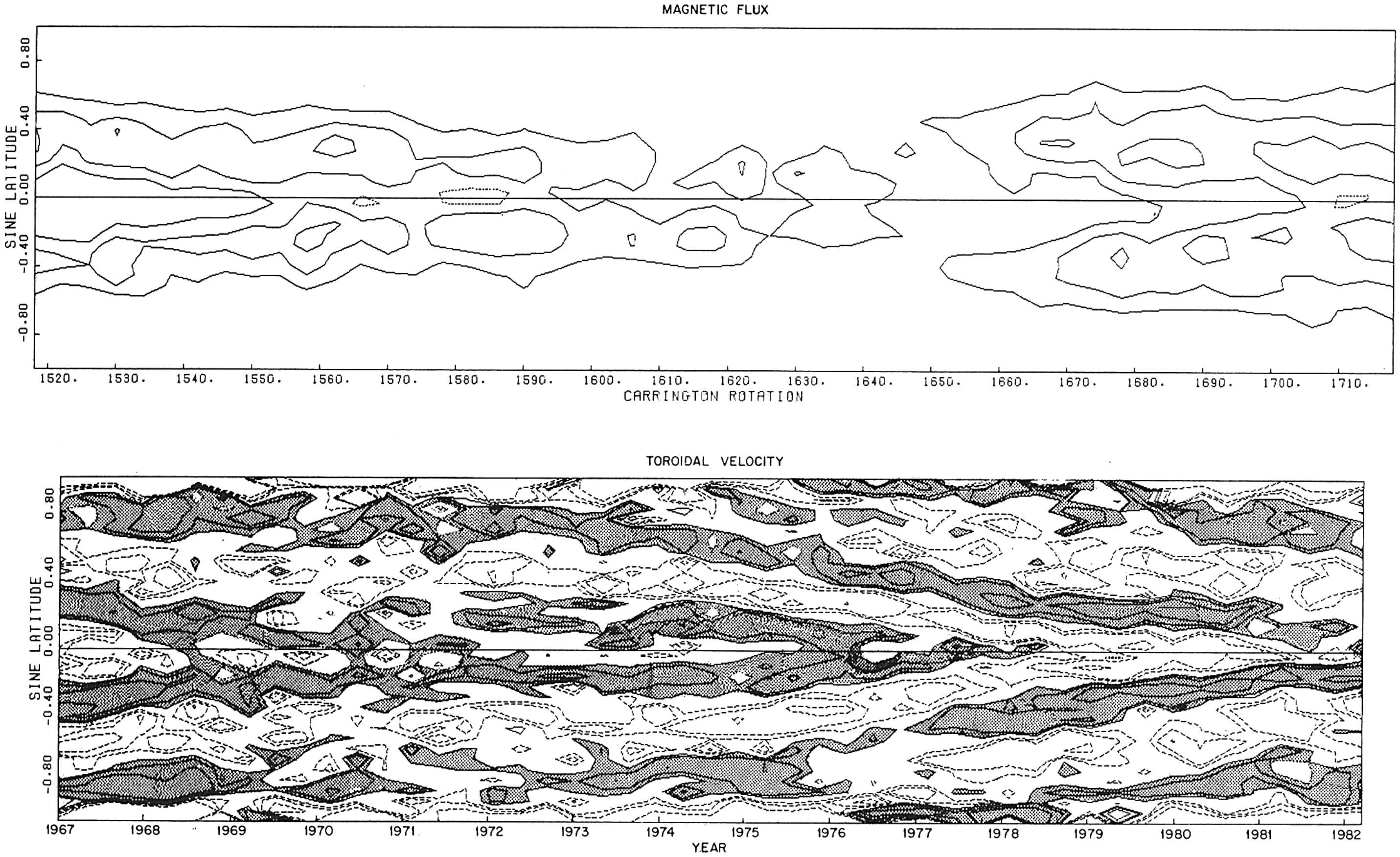
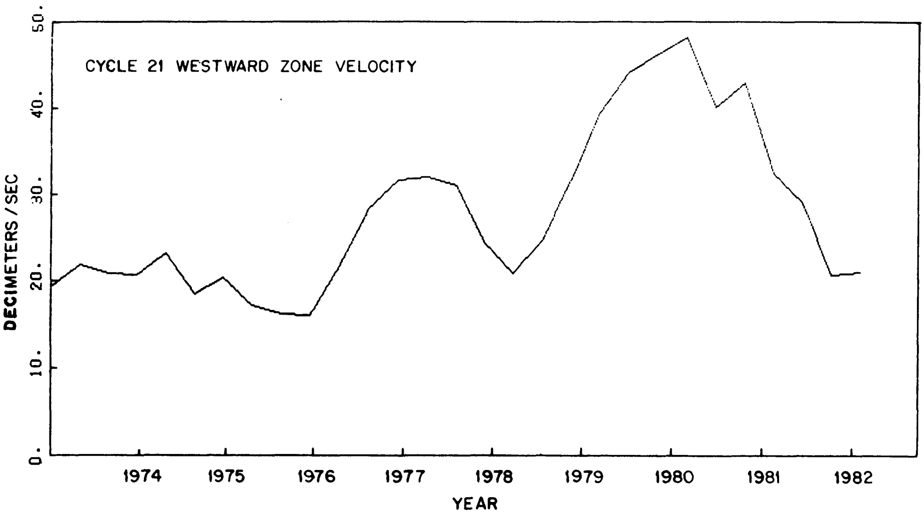


Fig. 3 (Top) Total magnetic flux. There are 34 zones of equal intervals in sine latitude. (Bottom) Zonal velocity plot from the Mount Wilson data since 1967. Daily values are averaged over intervals of 4 Carrington rotations. The zonal velocity is the residual from the smooth polynomial differential rotation curve. A constant rotation deficit at the equator has also been removed, which cannot be fit by the polynomial form. The average velocity in each time average has been set to zero. Velocity contours are ±1.5, 3, 6 m s^{-1}. Flux contours are 1.5, 3, 6 x 10^{21}Mx. Positive velocities (solid contours) are westward flows.



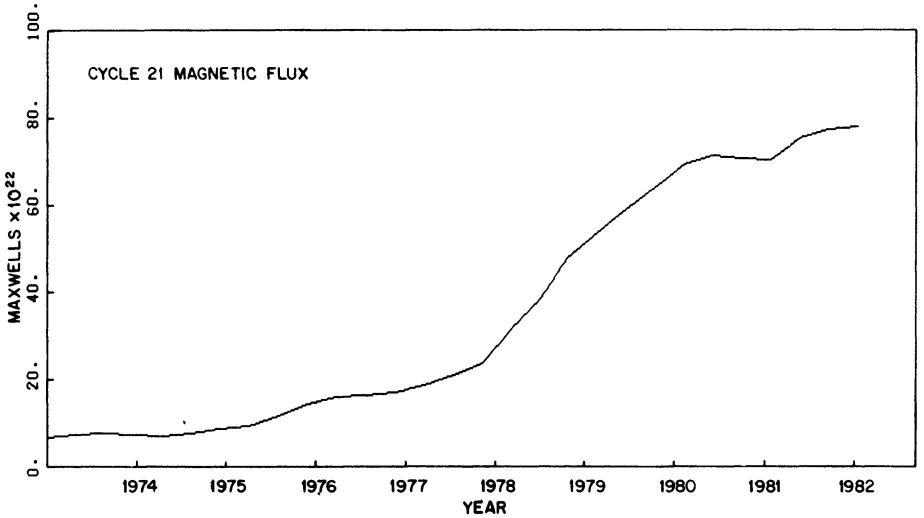


Fig. 4 (Top) Average velocity of the westward flowing zone of the torsional wave associated with Activity Cycle 21. (Bottom) Total magnetic flux in Cycle 21. Data is averaged over intervals of 12 Carrington rotations. Data from north and south hemispheres is combined. Magnetic fluxes were summed over a latitude band of width 0.47 in sine latitude, centered on the shear zone of the torsional velocity wave. The velocity increases $\sim$1 year before the rapid rise in magnetic flux.

zones has continued to rise since that time. This continuing increase in magnetic flux is presumably due to the presence of fewer but larger active regions at the current time, compared to the time of spot maximum. A similar effect was seen in Cycle 20, with the spot maximum in 1968.8 while the magnetic flux continued to increase until 1970.3.

4. INTERPRETATION

The most interesting result of this study is the possibility of predicting the onset of solar activity with a lead time of ~ 1 year. The amplitude increase of the westward flowing zones of the torsional wave can serve as a marker of the impending rapid rise of sunspot and magnetic activity on the surface. Close observations of the torsional wave during the next spot minimum will test whether this is a reliable harbinger of activity.

The correlation of only the westward flowing zone amplitudes with the later activity increase also indicates that it is those zones which are the most physically meaningful in the operation of the wave. It appears that we must understand a mechanism which accelerates the westward flow (faster rotation), rather than a mechanism which decelerates the eastward flow (slower rotation). Some explanations of the torsional wave, for example, invoke a deceleration of the eastward zones by magnetic tension forces; such a model seems inconsistent with the constancy of the eastward flow amplitudes and the activity correlation of the westward flow.

The lag of the magnetic activity relative to the torsional velocity increase provides further evidence that the wave is not an artifact of small-scale activity-related velocity fields (e.g., Evershed flow). Previous papers have shown that the wave and magnetic activity do not have the perfect correlation one expects of an artifact; the time difference reinforces that conclusion.

The interpretation of the time variation of the rotation difference between the north and south hemispheres (Section 2B) is unclear. The small amplitude does not allow a clear determination of an 11-year period, in contrast to the variations in $\underline{B}/\underline{A}$ and $\underline{C}/\underline{A}$. The phase relative to the activity cycle is not obviously important. Further, the general symmetry of the magnetic activity makes a hemispheric rotation difference difficult to explain in terms of a dynamo mechanism, unlike the oscillations of wavenumber 1 hemisphere^{-1} and higher. A simple explanation in terms of the surface imbalance of magnetic flux does not work.

ACKNOWLEDGEMENTS

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DISCUSSION

GOKHALE: **Are there any basic difficulties in determining the north-south asymmetries by including *odd* powers of sin θ in the expansion of the rotation rate?**

HOWARD: **I suppose the effect might show up in a term of odd power in sin θ , but we have not tried it. In general we find that it is best to solve for as few terms as possible.**

LIVINGSTON: **You have ascribed the temporal increase of total flux past sunspot maximum to the subsequent emergence of large regions containing a lot of flux. Could an alternative mechanism be the distribution (by random walk) of flux of umbral origin over the entire disk, thus making this flux more available to sensing by the magnetograph?**

HOWARD: **This mechanism may contribute to the phase lag of the flux, but I think the flux disappears rather quickly from the surface of the sun, so the size of the regions must be an important factor.**

STIX: **If the upper limit of cellular velocities is 10 m s^{-1} *per longitudinal wave number*, then what is a possible velocity of actual cells, which may consist of a whole spectrum of Fourier modes?**

HOWARD: **The actual limit is quite small for some configurations, of course, but the lifetime of the cells also enters in a complicated way. Long-lived cells have a much lower limit. Remember that the results apply to cells, which are extended in the latitude direction.**

GIOVANELLI: I think that the torsional oscillation is the most important discovery concerning the solar cycle that has been made in recent times. It contains the clue to the whole cycle mechanism. Our thanks should be due to the whole Mt. Wilson team for this magnificent new phenomenon.

ROXBURGH: At the levels you are talking about, you should be able to pick up, or should have had to subtract, the gravitational redshift from the surface of the sun. Do you find this systematic effect?

HOWARD: No, because we do not have an absolute velocity scale. Until this summer, all we have known is the position of a line in mm at the focus of our spectrograph. We have not known what the wavelength is at all. So, to find the residual velocities, we simply average all the velocities over the sun and call that zero.

KUKLIN: The westward zonal streams or local accelerations of the sun's rotation are connected with an increased pressure difference in direction from the pole to the equator. May we conclude from your results that in average the pressure inside the sunspot zone is larger than in quiet regions of the sun?

HOWARD: We have not thought about this effect in these terms. We believe that it is a deep-seated phenomenon, not a surface effect driven by pressure differences.

BONNET: If you could increase the accuracy of your velocity measurements, would you expect some additional velocity patterns to show up between the main patterns which are presently evident?

HOWARD: The rms velocity-signal error in our spectrograph in about 15 $\mathrm{m\,s^{-1}}$. Improving that greatly or reducing it to zero would have little or no effect on the results I have just shown. Systematic instrumental effects are much more important, and we know less about them. But effects from solar velocity fields (i.e. supergranular motions) also set an important limit, and it is not so easy to avoid this.

SHEELEY: Have you made Dopplergrams in Zeeman-insensitive lines to check for possible cross-talk between the Doppler and Zeeman signals?

HOWARD: Yes, and there seems to be no influence from the Zeeman effect.

KOTOV: I believe that you have found a very interesting and important phenomenon in the Sun, which is quite similar in some sense, as I said yesterday, to the jet-streams clearly seen in the giant planets, for example in the Jovian atmosphere. But I wonder whether you have checked the possibility of a significant influence of the spectral line asymmetry potentially appearing in active regions, which are drifting towards the equator during the solar cycle. Thus they can, in principle, produce certain lanes in the Doppler maps. Have you estimated the amplitude and time behaviour of the effect of active regions?

HOWARD: We have considered this possibility. But for several reasons we have concluded that it cannot explain the observed torsional oscillations. A curious configuration of line asymmetries would be required, antisymmetric about the north-south axis of active regions on average and about the central meridian of the sun. Furthermore, we see active regions only at latitudes lower than about 30°, whereas the torsional motions appear to start near the poles.