PART 1

BASIC OBSERVED PARAMETERS OF THE SOLAR CYCLE

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DIFFERENTIAL ROTATION AND GLOBAL-SCALE VELOCITY FIELDS

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Abstract. A review is given of the observational and theoretical background of global-scale velocity fields on the solar surface. A newly-developed method of reduction of the Mount Wilson velocity data is described, and the results from this new method are compared with the results of the old method. A preliminary analysis is made of the new results over a short time interval. Small-scale latitude irregularities in the differential rotation are shown to exist. Variations in time which occur in the rotation rate are broadly distributed in latitude and longitude. Although a non-solar (instrumental) cause cannot be found for these variations, such a cause cannot be ruled out at this time. Global-scale non-axisymmetric velocity field patterns intermediate between solar diameter and super-granular scale are shown to exist on the solar surface as predicted by theory.

1. Introduction

Review of the Problems, Both Observational and Theoretical

In 1961, Babcock showed, after the suggestion of Cowling (1953), that the stretching of the general magnetic field in longitude inside the Sun by differential rotation (equatorial acceleration) can explain the basic phenomenon of the solar cycle, i.e., Hale's polarity rule. This idea was formulated by Leighton (1969) into a mathematical form, numerical solutions of which demonstrated the basic behavior of the solar cycle. Thus the study of the differential rotation has come to be of great importance for understanding the solar cycle, which is the basic underlying process of solar activity. However, Cowling (1933) has shown that a steady axisymmetric velocity field, such as the differential rotation, cannot maintain the general axisymmetric magnetic field by itself. Among other things, the dynamo action of fluid motions of a non-axisymmetric nature has come to be considered a necessary supplementary mechanism for generating and maintaining the general magnetic field (Parker, 1955; Steenbeck and Krause, 1969). However, the nature of the non-axisymmetric motions has been unknown. Earlier, small-scale turbulent convection, such as granulation and supergranulation, were considered possible candidates. However, the necessary supplementary mechanism, called the regeneration action in general, or α-effect, or Γ-effect, requires the influence of rotation on the fluid motions, and since this influence from the smaller space and time scales is small, there is doubt whether the granulation and supergranulation can provide the necessary regeneration action.

Another kind of large-scale velocity field has been suspected to exist inside the convection zone – so large that we call it global-scale. Two independent suggestions of such a global-scale velocity field were made in 1965. One is by Bumba and Howard (1965), who suspected its existence from the organized behavior of the global-scale magnetic field. The other is by Ward (1965), who studied the proper motions of sunspots and found a correlation in their movements: spots rotating faster than the average tend to move toward the equator, and those rotating slower move

Bumba and Kleczek (eds.), Basic Mechanisms of Solar Activity, 19–35.

toward the poles. There still remains some question about whether these motions reflect motions of the fluid; however, if we regard this as a valid correlation in the fluid motions, it is evident that angular momentum is being transported toward lower latitudes, and this can act as a mechanism to create the equatorial acceleration (Starr and Gilman, 1965).

The nature of the global-scale velocity fields has been a subject of controversy because there are three possible modes of fluid motions in general in a rotating spherical shell, *i.e.*, acoustic or sound waves, Rossby waves, and the convection mode (Yoshimura, 1974). Since the space and time scales of this velocity field are large, the possibility of a sound wave mode is ruled out. The early investigators regarded it as a Rossby wave mode (Ward, 1964, 1965; Kato, 1969; Kato and Nakagawa, 1969; Gilman, 1969a, b). However, these motions of the Rossby wave mode, flowing mainly horizontally, are difficult to excite in the solar situation because there is no major force to move them horizontally. Meanwhile the study of the third possibility – the convection mode – was started by Durney and Skumanich (1968), and Durney (1968a, b). Then Busse (1970), Durney (1970), and Yoshimura and Kato (1971) found in succession that the convective modes that are most easily excited by the superadiabatic gradient in the convection zone, in other words which have the greatest growth rate and lowest critical Rayleigh number, can actually excite and maintain the equatorial acceleration. The convective modes with smaller growth rates can accelerate the higher latitudes and not necessarily the equator (Yoshimura and Kato, 1971; Yoshimura, 1972a). Moreover, this convective mode, especially the mode with the greater growth rate, which has a sector pattern in longitude, was shown by Yoshimura (1971) to be able to explain the organized behavior of the global-scale magnetic-field distribution, such as the existence and characteristics of unipolar magnetic regions and of active longitudes, especially their rigid body-like rotation (Babcock and Babcock, 1955; Bumba and Howard, 1965; Howard *et al.*, 1967; Wolfer, 1897; Losh, 1939; Brunner-Hagger, 1944; Eigenson *et al.*, 1948; Becker, 1955; Warwick, 1965; Dodson and Hedeman, 1968; Svestka, 1968a, b). Since the sector structure of the magnetic field in interplanetary space is also due to the organized solar-surface magnetic field (Wilcox, 1968), the dynamics of this interplanetary sector structure can also be regarded as subject to the dynamics of the global-scale velocity field of the convection mode. Besides this global-scale ordering of solar activity, many local characteristics of the structure or dynamics of active regions have been found to be organized, i.e., the faster rotation of sunspots than the fluids (Howard and Harvey, 1970), the preponderance of preceding spots of bipolar sunspot groups (Grotrian and Künzel, 1950), the tilt of the bipolar axes of the groups (Brunner, 1930), the forward inclinations of the normal axes of the magnetic fields of sunspots (Maunder, 1907; Minnaert, 1946), the association of the characteristics of active regions with the presence of older active regions in the vicinity (Martres, 1970), and the correlations among the characteristics of active regions stated above (Weart, 1970, 1972; Sawyer and Haurwitz, 1972). All these effects are shown to be explainable by the velocity and magnetic fields associated with the global-scale convection mode (Yoshimura, 1973). Thus, the existence of a global-scale velocity field inside the Sun may be regarded as fairly certain.

If we admit the existence of the global-scale convection, then the necessary supplementary process to drive the solar cycle can be provided by convection. This has been shown by Yoshimura (1972b), and the numerical simulation of the solar cycle due to the dynamo action of the global convection has succeeded in explaining many basic characteristics of the solar cycle (Yoshimura, 1975a); and moreover has predicted a characteristic evolution of the general magnetic field at the surface, which was confirmed by analyzing the Mount Wilson magnetic synoptic chart data (Yoshimura, 1975b).

In recent years the techniques of the observational study of differential rotation have been improved. Earlier studies depended mainly on the movement of tracers, such as sunspots. Thus the detection of short time-scale variations in the rotation was impossible. Modern electronic technology has made it possible to detect the velocity field of the solar surface to a sensitivity approaching 5 m s^{-1}. A systematic study of the differential rotation using such sensitive measurements was first made by Howard and Harvey (1970). One of the results of this study is that the differential rotation varies day by day and week by week.

Temporal variations on the rotation rate of the Sun have been noted almost since the first days of spectroscopic rotation determinations. Halm (1904) observed differences between the rotation rates he determined in 1901–02 and 1903. H. H. Plaskett (1916) observed variations in the rotation rate of the Sun over intervals of a few days with an amplitude of about 0.15 km s^{-1}. He also proposed a secular variation of the rotational velocity. Evershed (1931) also found evidence for variation of the rotational velocity with time.

Some investigators have proposed that the observed variations are instrumental in origin (i.e., J. S. Plaskett, 1912). In particular De Lury (1939) suggested that the variations observed could be explained by the varying presence of scattered light near the solar limb – the early spectroscopic observations were invariably made near the limb of the Sun. Such a sweeping object is difficult to answer after the fact, and the effect of De Lury's paper seems to have been to discourage further work in the field for many years. Apparently no attempt was made to verify experimentally that scattered light was an important factor in such measurements.

Hart (1954) showed that scattered light need not be an important factor in such measurements, and discovered variations in line-of-sight velocity in the solar surface which we now know to correspond to the supergranulation pattern. She attributed the previously reported variations in rotation rate to the existence of this pattern. It seems unlikely, however, that a velocity pattern with a scale as small as that of the supergranulation could be responsible for rotation rate changes such as those reported by Halm (1904), Plaskett (1916), and Evershed (1931), whose results show a broad latitude dependence.

Howard and Harvey's (1970) and Howard's (1971) results are derived from sensitive photoelectric measurements, and hence are even accurate near the central meridian, thus greatly reducing the risk of influence by scattered light. Also, these measurements generally cover the solar surface, so that the influence by small-scale velocity fields is greatly reduced. The same sort of temporal variations seen earlier are also seen in these photoelectric measurements. Variations in the rotation rate may occur in a period of a few days, or over a month or two. In addition, there is some evidence for a secular change in the rotation rate of the Sun. The nature of the variations seen by Howard and Harvey (1970) is not clear since, in their method, data over the full disk are used and fitted by a least-squares technique to a functional form of the differential rotation, including an approximation to the radial dependence on the disk of the limb redshift. Any global-scale non-axisymmetric velocity field will affect the resulting rotation and limb redshift results in an unpredictable fashion.

This paper presents in a preliminary way a new method to analyze the Mount Wilson Doppler data taken at the 150-ft Solar Tower Telescope. This new method separates the effects of the differential rotation, limb redshift, and global-scale velocity field in order to derive more accurately the characteristics of each of these phenomena. The analysis is still in progress, and the results presented here are preliminary ones.

2. A New Method to Analyze Global-Scale Surface Velocity Fields: the Differential Rotation

The Mount Wilson magnetograph observations have been described elsewhere (Howard and Harvey, 1970), and the reduction of the velocity data to obtain rotational velocity as a function of latitude was described in the same paper in great detail.

In the present study we shall describe a newly-developed technique of reduction for the same kind of data. This new method provides us with a check on many aspects of the earlier reduction method, and provides us with a comprehensive method of examining the global-scale velocity patterns on the solar surface.

The corrections for the background velocity effects – the orbit and axial rotation of the Earth – are essentially identical to the earlier reduction technique. We start, then, with a grid of about 10 000 points covering the entire solar disk. (At the time the observations for this study were made – summer 1974 – the scanning aperture size was 17.5″ square. Currently the aperture size is 12.5″ square.) For each point we have a velocity signal which represents the velocity of the photosphere observed in the wings of the Fe I λ 5250.2 line. The 'zero' level of the velocity signal is unknown. The scan of the Sun is an east-west raster, starting at the north or south pole of the Sun and requiring a total of about 90 min to complete. Thus any slow drift of the background velocity, due to the instrument or a change in the barometric pressure or to some other cause, can result in a change in the background velocity, which then will vary from pole to pole on the Sun. However, in the time required for a single east-west scan – approximately one minute – there is no chance of an instrumental drift that can significantly affect the velocity signal. Thus the derived rotation rate will be unaffected.

At any latitude, if the intrinsic rotational velocity, which is assumed not to depend on central meridian distance, L, is denoted by V, then the line-of-sight component of this velocity, which is the quantity measured by the magnetograph, is given by

$$V_m = V \sin L. \qquad (1)$$

Thus, if we plot V_m against $\sin L$, we expect to see a straight line with slope of V.

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A complicating factor in this analysis is the limb redshift, which is very difficult to account for precisely because its magnitude and position dependence are not well known. A remarkable feature of the new method of reduction that is described here is that the effect of this shift is largely eliminated in the rotation determination.

The data are divided into 5 latitude zones, starting from the equator in each hemisphere. In each of these latitude zones a background 'zero' velocity level is calculated by averaging all the velocity signals (converted to km s^{-1}) within 50°, or in some cases 15°, of the central meridian. This reference zero signal is subtracted from all the velocity signals for that 5° zone. Thus the velocity field considered after this step is the velocity field referenced to the central meridian region. The next step is to convert negative values of sin L to positive sin L, and for those negative sin L points the signs of the velocity signals are reversed. This has the effect of a 180° rotation about the origin in the plane of the $V-\sin L$ plot of the points with negative sin L. (Refer to Figure 1.) From this array of points, a slope is determined, assuming that

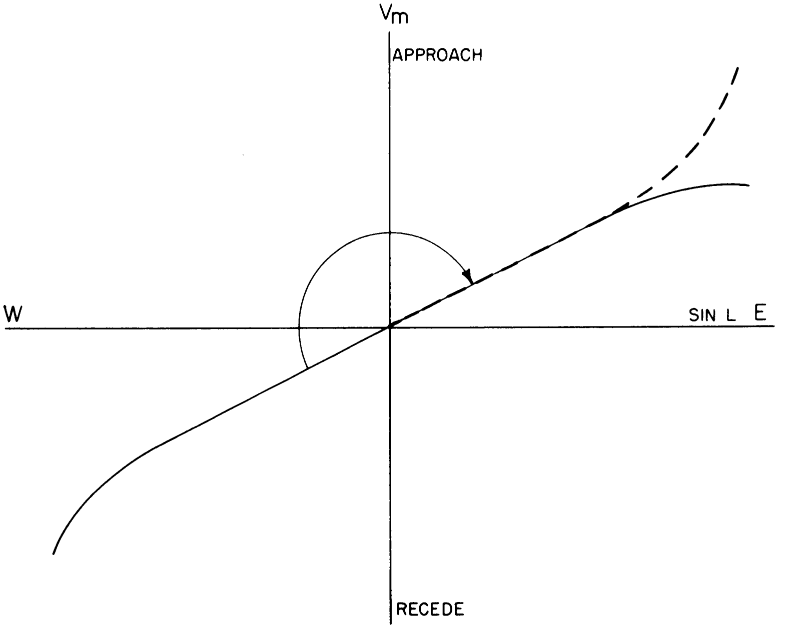

Fig. 1. A schematic representation of the velocity-sin L curve showing the limb redshift and the rotation at one latitude zone. The dashed curve represents the effect of rotation of the left half of the curve about the axis in the plane of the plot in order to minimize the effect of the limb redshift in the process of the least squares fitting of the rotation curve to the observed data. The observed points are scattered around the solid curve and have an arbitrary zero point. In this figure the zero has been corrected.

the straight-line solution passes through the origin. Points with $|\sin L| > 0.8$, i.e., $|L| > 53°$, were not included in this slope determination. The advantage of this folding technique is that the effect on the slope of the line of the limb redshift is essentially cancelled if the redshift is symmetric about the central meridian. Limiting the slope solution to points within 53° of the central meridian further reduces the influence of the limb redshift because the magnitude of this shift is greatly reduced at this distance from the limb – to about 50 m s^{-1} at the equatorial latitudes.

In the solutions using the method derived above, the probable errors in the slopes for the latitude zones equatorward of 50° were rarely as much as 10 m s^{-1} and generally about half that figure. This is less than 0.5% of the rotational velocity. Poleward of 50° the errors were a little larger, but rarely greater than 25 m s^{-1}. The number of points involved in each independent slope determination was generally greater than 600 for the equatorial latitudes, around 400 at 30°, and down to about 30 at 70°.

The slope of each 5° latitude zone gives directly the average rotational velocity of that zone in km s^{-1}. The solution in each zone is independent of the others; no points are included in more than one zone. Table I gives the results for a typical day for the various latitude zones.

TABLE I

Slope results for 8/14/75

Lat. zone	No. of pts.	V km s^{-1}	p.e. km s^{-1}	ω μ rad s^{-1}
+75–+80	43	0.288	0.013	1.91
+75–+75	83	0.439	0.014	2.10
+65–+70	116	0.632	0.012	2.37
+60–+65	180	0.756	0.012	2.35
+55–+60	226	0.934	0.010	2.50
+50–+55	272	1.078	0.009	2.54
+45–+50	350	1.196	0.015	2.54
+40–+45	395	1.357	0.008	2.64
+35–+40	443	1.527	0.008	2.77
+30–+35	483	1.629	0.007	2.78
+25–+30	540	1.751	0.007	2.84
+20–+25	555	1.836	0.007	2.86
+15–+20	607	1.915	0.006	2.88
+10–+15	613	1.986	0.006	2.92
+ 5–+10	595	2.040	0.006	2.96
0–+ 5	618	2.024	0.006	2.91
− 5– 0	620	2.051	0.006	2.95
−10–− 5	593	2.028	0.007	2.94
−15–−10	553	2.000	0.006	2.94
−20–−15	526	1.922	0.006	2.90
−25–−20	489	1.858	0.007	2.89
−30–−25	432	1.759	0.008	2.85
−35–−30	374	1.643	0.008	2.80
−40–−35	347	1.520	0.009	2.75
−45–−40	274	1.352	0.010	2.64
−50–−45	221	1.218	0.010	2.59
−55–−50	163	1.048	0.011	2.47
−60–−55	115	0.899	0.014	2.40
−65–−60	77	0.765	0.014	2.38

3. Comparison with the Results from the Old Reduction Technique

In the original reduction technique described by Howard and Harvey (1970), all the points on the solar disk are analyzed in one large least-squares solution to obtain the coefficients of an expansion in latitude:

$$\omega = a + b \sin^2 B + c \sin^4 B. \tag{2}$$

An additional term, $e(1 - \cos \rho)^2$, was included to account for the limb redshift.

Such an equation has some disadvantages because any global-scale velocity field will be mixed into the solution in a complicated way, and the real cause of variation in any of the coefficients cannot be determined without addition analysis. However, such a formula has been used for the representation of the differential rotation since the earliest days of Doppler measurements, and it turns out to provide a rather accurate description of the average large-scale latitude dependence of the rotation that is determined by the new method.

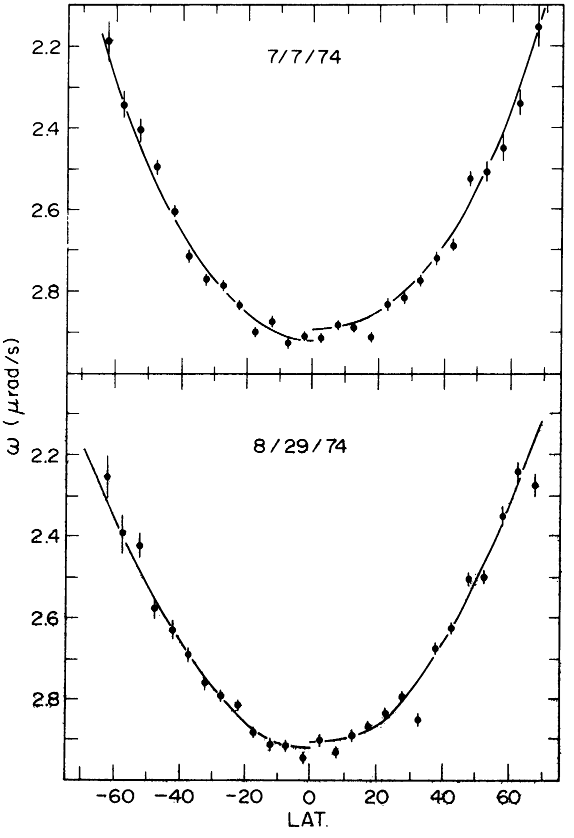

Fig. 2. Rotation results for the two dates indicated. The solid curves represent the old solution for solar rotation for each hemisphere separately, *i.e.*, the solution for ω using the derived coefficients a, b, and c in Equation (2). The filled circles are the slope solutions for each 5° latitude zone. The vertical lines represent probable errors in the slopes.

It is reasonable to suppose, however, that such a formulation cannot account for possible small-scale structure of the rotation. Figure 2 shows two examples of the results from the old analysis using Equation (2) and the new method using the slope reductions. There are evidently small-scale latitude features that cannot be represented by Equation (2). The large-scale shape of the latitude dependence, however, is well represented by the old analysis.

The smallest scale features seen in Figure 2 are clearly significant because they are at least several times greater than the errors. It is also evident that they are not long-lived because they are not similar on the two examples shown. A further investigation into this small-scale latitude dependence of the rotation is planned.

Such a fine structure in the latitude dependence has been noted by Deubner *et al.* (1975). It appears from Figure 2 that averaging the data north and south of the equator, as these authors have done, is not justified. Furthermore, their conclusion that there are humps in the rotation rate at active latitudes seems to be not verified in the small sample of data shown in Figure 2 and other samples analyzed so far.

4. Preliminary Analysis of the Rotation Slope Results

Slope reductions as described above were run for the regular Mount Wilson full-disk magnetogram data for the interval 1974, July 15 through September 14. Figure 3 shows a plot of the equatorial velocities – the latitude zone $-5°$ to $+5°$ – in this interval. On the same plot is the equatorial velocity derived from the old analysis – the parameter a. Clearly the agreement between these two reduction methods is good.

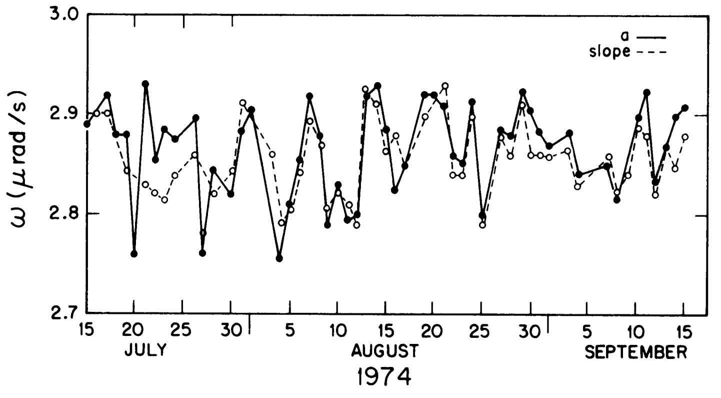

Fig. 3. The variation with time of the equatorial rotational velocity of the Sun. The filled circles and solid line represent the coefficient a from Equation (2), and the open circles and dashed line represent the slope solutions for the latitude zone $+5°$ to $-5°$. The same raw data are used for both solutions.

The most striking feature of this plot is the regular variation seen in the equatorial velocity. The angular velocity seems to oscillate, especially in the interval July 25 to August 20, with a period of about 6 or 7 days. The amplitude of this variation is about 4%, which corresponds to about 80 m s^{-1}.

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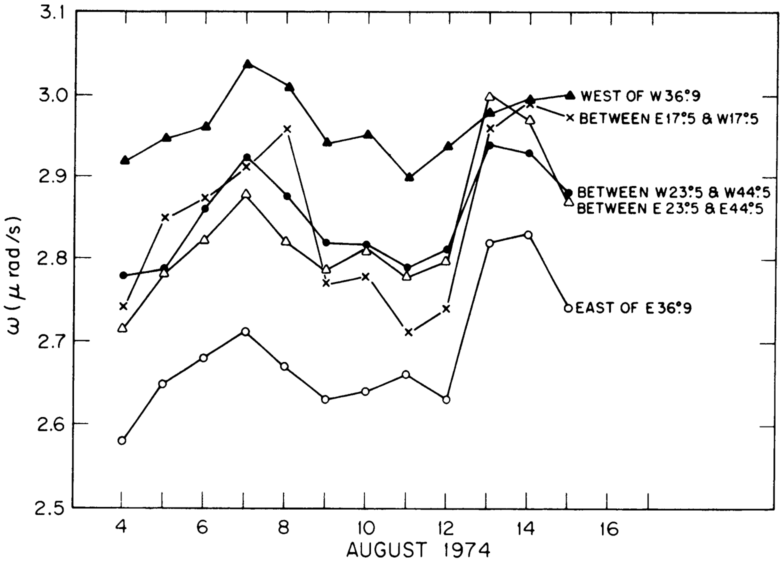

Fig. 4. The variation with time of the slopes of the velocity-sin L curves determined at the various zones of different central meridian distances indicated. These data are from the latitude zone $+15°$ to $-15°$.

In order to investigate this effect in more detail, we determined the slopes from segments of the $V_m - \sin L$ curves for the equatorial region. Figure 4 shows for the interval August 4 to August 15 the angular velocities for the various zones of central meridian distance indicated. Although there are some differences between the shapes of the curves, the basic location of the two peaks seen in this interval is the same.

If the variations seen in Figure 3 were due to a stationary or quasi-stationary global-scale pattern of east-west motions rotating with the Sun, then one should expect that, as this pattern rotated, the slopes in different parts of the disk would peak at different times. In other words, in Figure 4 we would expect to see phase differences in the location of the peaks as we look at different central meridian zones. The fact that there are no such phase differences indicates that the whole zone from ± 0.8 in $\sin L$ changed its slope together. Thus the whole visible equatorial region accelerated and decelerated roughly in unison.

Note that the differences in average ω of the various curves in Figure 4 are caused by the fact that no correction is made for the limb redshift in this analysis – there is no folding of the data about the central meridian here – and the redshift affects the slopes of the curves differently in the east and west hemispheres. One may presume that the redshift does not vary with time and thus does not affect the shapes of the curves in Figure 4, only their constant vertical displacements.

Figure 4 refers to the latitude range $\pm 15°$. We examined the latitude dependence of the velocity variations by examining the latitude range 35° to 65° in both the north and south hemispheres. Figure 4 shows the rotation velocities determined from the slopes in various central meridian zones in these latitude ranges. Although there are some minor differences between these curves and those in Figure 4, the overall

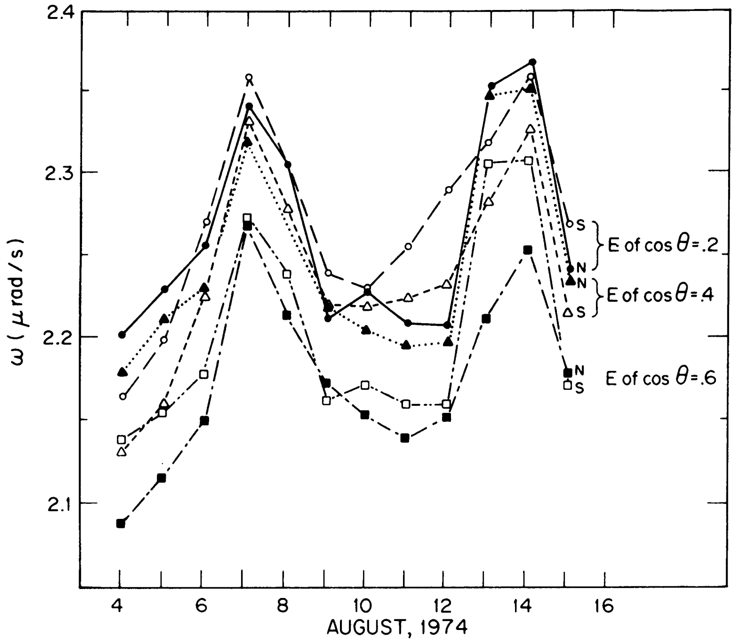

Fig. 5. The variation with time of the slopes of the velocity-sin curves determined at the various zones of different central meridian distances and in the latitude zone 35° to 65°, north or south as indicated.

appearance of the two diagrams is quite similar; the peaks appear at the same times.

The tentative conclusions to be drawn from Figures 4 and 5 are, first, that the short-period variations in rotational velocity seen during this period resulted mainly from axisymmetric accelerations and decelerations of the photospheric gas, and effects from a global-scale velocity pattern are small compared to that of the axisymmetric variations, if present at all; and, second, that these accelerations and decelerations extended over a wide range of latitude and longitude. Further study of this phenomenon is planned.

An alternative explanation, of course, is that the axisymmetric variations are due to some instrumental effect. That is, that there may be some problem with calibration, instrument alignment, or some other factor not originating on the Sun, which causes the variations seen in Figures 4 and 5. At the moment a nonsolar cause for the velocity variations cannot be ruled out. Some tests have been made in an attempt to isolate an instrumental origin for the variations, but no means of reproducing the magnitude of the effect has been found. Altering the balance on the photomultiplier tubes at the exit slits so as to offset the line profile can change the derived rotation velocity, but to achieve the magnitude of the observed effect requires an unreasonably large offset – so large that at the extrema it is difficult to hold the line with the line-centering servo. Similarly, decollimating the telescope will alter the resulting rotation velocity, but to achieve the observed effect requires an unreasonably large decentering. Variations in the spectrograph dispersion could account for the effect, but the dispersion is measured daily as a part of the calibration procedure, and the day-to-day variations in this quantity are rarely more than a fraction of a percent. The measured dispersion is used in velocity determinations for each day's observations. The dispersion enters directly into the calculation for the velocity in km s^{-1}, so an error of a fraction of a percent in the dispersion will result in an error of the same percentage in the relative velocities, and hence of the same percentage in the slope of the $V_m - \sin L$ curve. For any of these instrumental effects, even if the magnitude of the velocity change could reasonably be accounted for, it is difficult to conceive how such a regular pattern of variations could result. Also, the fact that the earlier observers noted variations quite similar to those seen in Figures 4 and 5 is an argument in favor of their solar origin. Nevertheless, until more analysis has been done we cannot completely rule out some nonsolar explanation for these velocity variations.

5. A New Method to Analyze Global-Scale Surface Velocity Fields: the Non-axisymmetric Velocity Field

The main purpose of the slope analysis is to derive the differential rotation from one day's observation. However, the differential rotation thus obtained is not necessarily the true differential rotation, which is by definition the axisymmetric part of the longitudinal component of the velocity field of the Sun. We observe on one day less than one half the circumference of the Sun, and the true differential rotation should be derived from data around the whole circumference at one instant. Thus the effects of a nonaxisymmetric velocity field of a scale of the order of the solar diameter, the largest-scale non-axisymmetric velocity field, can alter the appearance of the differential rotation derived from one day's observation.

If the differential rotation does not vary on a time scale of a rotation or less, then we can separate the differential rotation from the largest-scale non-axisymmetric field. This could be done by constructing a velocity field synoptic chart by subtracting the average rotational velocity at each latitude from each day's results. Some examples of such synoptic charts will be presented below; however, if the differential rotation does vary with a time scale smaller than one month, then one cannot derive the true rotation without observing the Sun simultaneously from several directions in interplanetary space.

If the lifetime of the largest-scale non-axisymmetric field is also longer than one rotation, then it is possible to separate in the analysis the differential rotation from this large-scale non-axisymmetric field. In the pattern of the non-axisymmetric field there must, by definition, be boundaries in the velocity distribution, which at some times will lie near the central meridian. At these times, the slopes derived from the eastern and western sections of the solar disk should be different because in these two areas the direction of the field is opposite. Thus, by analyzing the differences of the slopes of the eastern and western data, we can examine the largest-scale non-axisymmetric velocity field, even though the axisymmetric differential rotation may vary. This approach is complicated somewhat by the effects of the limb redshift, which will increase the derived slope on one side of the central meridian and decrease it on the other side. In order to analyze the data in this manner, the instrumental effects that may affect the velocity signal must be minimized. This problem will be discussed again below.

The analysis presented in this paper has not proved decisive in sorting out the axisymmetric and the largest-scale non-axisymmetric components of the global-scale velocity field. This is due partly to the remaining doubt about the possible influence of unknown instrumental effects and partly to the small data sample analyzed here. A more comprehensive analysis is planned for the near future, which should enable us to isolate the variation of the differential rotation from the effect of the largest-scale non-axisymmetric velocity field. For the moment we can say only that the effect of this non-axisymmetric field, if it is present at all, is small in amplitude compared with the axisymmetric variations in the results of the slope analysis.

Such difficulties affect only our analysis of the differential rotation and the largest-scale non-axisymmetric velocity field. We are able to analyze the non-axisymmetric fields with scale smaller than the solar diameter, using data from one day's observation. That is, by subtracting from the velocity data the differential rotation derived from the slope analysis and the limb redshift, it is possible to obtain a non-axisymmetric velocity-field pattern with a scale smaller than the solar diameter but larger than supergranules, which manifests itself as 'residual velocities' in this procedure. The limb redshift correction presents us with some difficulties, however. If it is constant in time, which seems a reasonable assumption, then we can obtain a value of the limb redshift as a function of central meridian distance by averaging the data of many days. However, if it is not constant in time, then we cannot determine whether the non-axisymmetric velocity field is due to a real velocity field or to whatever effect causes the limb redshift. If these two effects vary with different time scales, it still might be possible to separate them.

At any rate, assuming the limb redshift to be a constant effect, we can analyze the non-axisymmetric velocity field of scale smaller than a solar diameter. There are two ways to display this field from the data we have. One is to plot the residual velocities (after subtracting the differential rotation and the limb redshift) for one day's observation. This method has been used by Howard (1971) and Hendl (1974). The fact that the large-scale fields are horizontal somewhat limits the usefulness of this approach, because one views a different component of the large-scale motions in different parts of the solar disk. The second method is to construct a synoptic chart of the non-axisymmetric velocities at some central meridian distance zone – of the east or west limb of the central meridian – for each day's observation. Such a synoptic chart from the limb data shows mainly the longitudinal component of the non-axisymmetric field, and a chart obtained from central meridian data shows the latitudinal component of the field.

A plot showing synoptic charts from limb data is shown in Figure 6. With data as complicated as these velocity measurements, one must be very careful that instrumental effects are not present; however, in the case of the analysis of these non-axisymmetric velocity fields with scales smaller than that of the diameter of the Sun, we feel confident that they represent the true velocity field on the Sun, since the subtraction is done from data of one day and at least the questions of variation of calibration day by day does not affect the results very much.

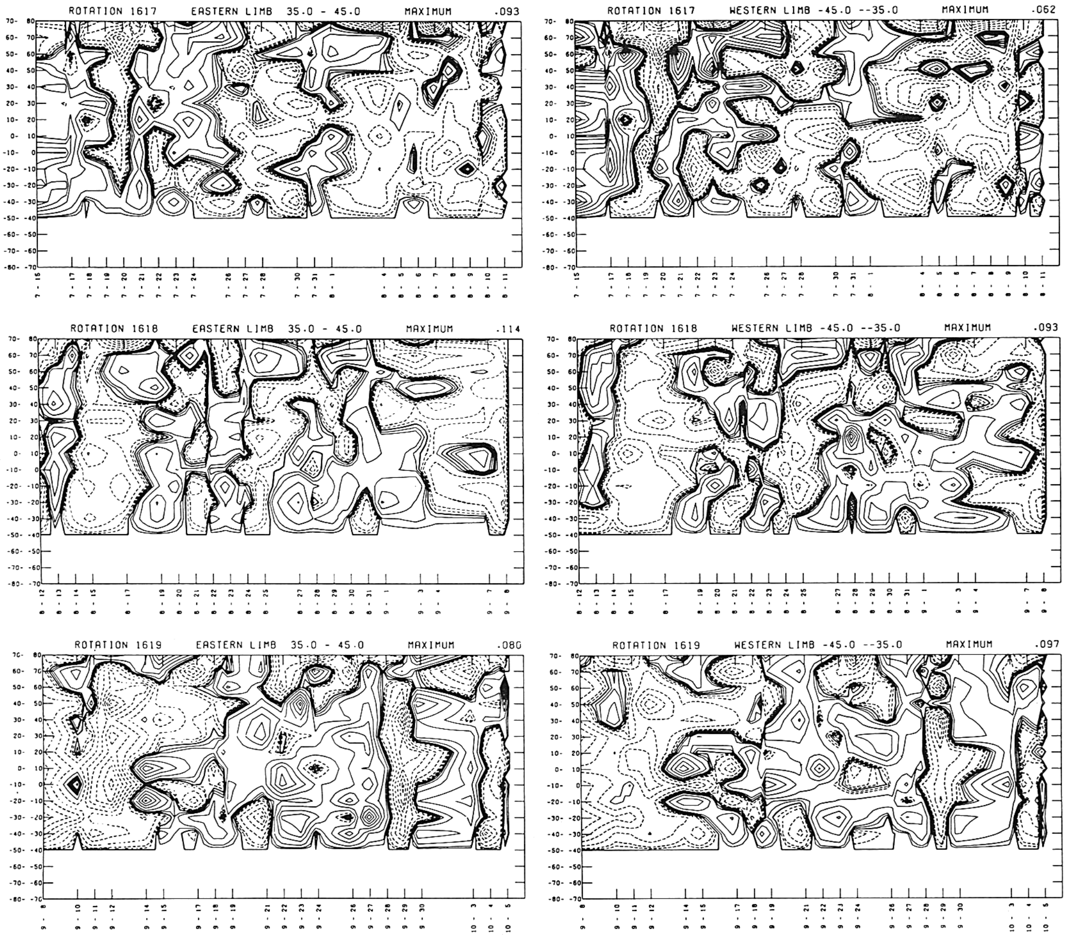

Fig. 6. Synoptic chart representations of the non-axisymmetric velocity fields with scales smaller than the solar diameter but larger than the scale of supergranules. The synoptic charts are for rotation numbers 1617, 1618, and 1619 and for eastern and western longitude zones of $\pm 35°$ to $\pm 45°$. The dates of observation are designated at the bottom of each Figure while the latitudes are shown on the left-hand side. In this case $10° \times 10°$ square averaging in longitude and latitude was done to cancel the small scale velocity noise due to such effects as the 5 min oscillation, supergranulation, and granulation. The zero-reference point was adopted as that of the central meridian zone from $-15°$ to $15°$ in longitude. The data southwards of $-50°$ in latitude were omitted because in this season, the Sun tilts northwards and south polar regions were not observable. The effect of the limb redshift was corrected after subtracting the averaged velocity in longitude. Note that there are coherent features elongated in latitude and that these features remained for 3 rotations although the shape of the features was affected. Note also that the data points were obtained after subtracting the effect of rotation from the daily observation and hence the variation of the rotational results shown in Figure 7 did not affect the results of the feature. The positive feature in the eastern (western) part shows the region rotation faster (slower) than the averaged rotation derived from the one day observation, and vice versa. These features are presumed to be real features of the global-scale non-axisymmetric velocity field which has been predicted by theories. Especially its elongated feature confirms that the mode expressed by the sectorial associated legendre function P_n^n dominates, although several other modes seem to exist.

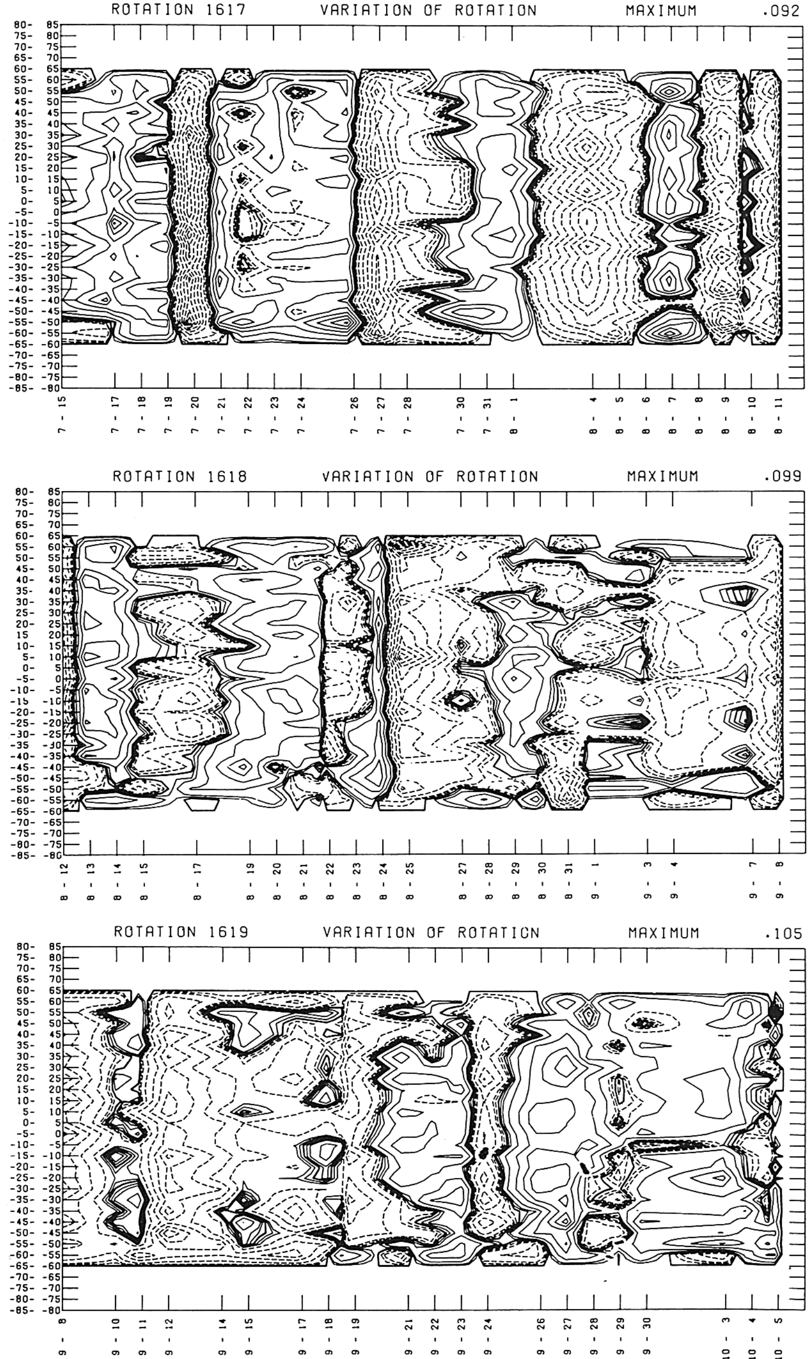

Fig. 7. Synoptic charts of the variations of differential rotation for the same period as Figure 6. However, the rotation is derived for each 5° latitude zone. The charts show the deviation from the average rotation of each rotation number. The data poleward of 60° were omitted because the results there are less well determined. Note that the variations occur in unison over the whole latitude range and that the feature does not last for 3 rotations. This means that such variations do not represent a true feature of the non-axisymmetric velocity field and cast some doubts on the reality of this variation of the rotation.

We see in Figure 6 that there are regions where the horizontal velocity differs significantly from the rotational velocity. If there were no systematic non-axisymmetric velocity field larger than the supergranules, then these synoptic charts would consist of only weak random patterns. However, it is evident from Figure 6 that there are velocity features that are coherent in space (latitude) and time (longitude), and that some of the features persist over at least three rotations. The dimensions of these features are about 30°, or 200 000 km. If these features represent more than one mode of the velocity field that has been studied theoretically, then their dynamics could be quite complicated, since different modes have different propagation velocities.

Figure 7 shows synoptic charts of the variation of solar rotation as derived by the slope analysis. These charts show the deviation from the average rotation rate for each Carrington rotation. It is clear that variations occur often in unison over a wide range of latitude, and that such 'features' do not persist for even 3 rotations. Such behavior raises serious doubts about the reality of these velocity changes, as mentioned above. Such changes are not due to a global-scale non-axisymmetric velocity field, and may not originate on the Sun. A further search for instrumental effects will be pursued. Note that these features should be detected as a correlation of *a*, *b*, and *c*, in the old analysis of the northern and southern hemispheres. However, as explained above, these correlations do not necessarily reflect the global-scale non-axisymmetric velocity field.

We may conclude from Figure 6 that a large-scale surface velocity field exists on a scale larger than the supergranules. Such a field has been predicted to exist deep inside the convection zone from the work of various investigators as mentioned above. The preliminary results described here show that this non-axisymmetric field also appears (overshoots) on the surface. This is encouraging because we have a means of studying what is going on inside the convection zone by examining the surface dynamics of the Sun. The observational study of the large-scale dynamics of the solar photosphere will be continued with the Mount Wilson data. It will be necessary to study the data of many years because the time scale of the phenomenon is long.

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DISCUSSION

Gilman: (1) What is the magnitude of the residual velocities? (2) Can you see any correlations between north and south hemispheres in either the variations of differential rotation with time, or in residual velocities?

Howard: (1) The maximum residual velocity in each diagram is about 0.1 km s^{-1}, and the contour lines are some tens of meters per second. (2) The rotation variations are symmetric about the equator, the residual velocity variations appear not to show this symmetry.

Deubner: Did you also compare the position in latitude of irregularities of tne differential rotation with zones or position of centers of activity? It appears from recent results of Vazques and myself, that the latitude of both these features is strongly correlated. It is of interest in this context to note that in

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measurements of differential rotation obtained during the period of June this year when no spots were present at all, the irregularities mentioned before were much less conspicuous.

Howard: We found no such correlation in this interval.

Kuklin: (1) I had at my disposal an old series of your observed velocities published in *Solar Physics* in 1970. It seems to me that the increase of rotation velocity is connected with the appearance of large sunspot groups eastward from the central meridian, and conversely the decrease of rotation velocity is connected with the appearance of large sunspot groups westward from the central meridian. Have you found such effects? (2) Can you explain why at your slide the rotation velocity (2.3) is 20% less than the standard one (2.8)?

Howard: (1) I have examined only the data shown in these slides, which represent a short interval. For them I found no such effects. (2) These data represent high latitudes where the angular rotation rate is lower.

Giovanelli: The problem of interpreting velocities from line profiles is well known – under some conditions, one can even get velocities of the wrong sign! Can you be confident for such small velocities as reported there may not be errors introduced by variations in conditions in the line-forming large areas of the surface, e.g., plages distribution of magnetic points across quiet areas which may affect the low chromosphere or upper photosphere!

Howard: I agree that this is a serious worry. In the past we have examined this possibility by observing with $g = 0$ lines or lines that are not weakened in magnetic filaments. Such observations are quite similar to the $\lambda 5250$ observations.