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Rotation of the Coronal Magnetic Field

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Rotation of the Coronal Magnetic Field

J. T. Hoeksema and P. H. Scherrer

Abstract: The coronal magnetic field rotates differently than the photosphere. The field configuration of the corona can be calculated from the observed photospheric field using a potential field model. Correlation of the field patterns at different latitudes with a lag near one solar rotation shows much less differential rotation than observed in the photospheric field; however, the peak is very broad and determines the rotation rate rather poorly. Consideration of longer lags reveals a more complex rotational structure and indicates different rotation rates in the northern and southern hemispheres. Spectral analysis of the equatorial dipole component of the coronal field reveals an organization into just a few discrete rotation frequencies which are apparently present simultaneously. Spectral analysis of the field at different latitudes shows that the frequencies are present simultaneously, but in different hemispheres, and that the southern hemisphere fields rotate more slowly than those in the north in solar cycle 21.

I. Introduction

Magnetic structures in the corona rotate differently than the underlying photospheric field structures. The photospheric plasma and magnetic fields rotate differentially with a synodic period of about 27 days near the equator and more than 30 days near the poles. The coronal fields show much less differential rotation than the photosphere. This behavior has been noticed previously in the rotation of coronal holes (e.g. Timothy, Krieger,and Viana, 1975; Bohlin, 1977), in the rotation of the white light corona (Hansen, Hansen, and Loomis, 1969; Parker, Hansen, and Hansen, 1982; and Fisher and Sime, 1984), and in the emission line corona (Antonucci and Svalgaard, 1974).

For our analysis, the coronal fields have been calculated from observations of the photospheric field using a potential field -- source surface model. Schatten et al. (1969) and Altschuler and Newkirk (1969) first developed the model independently. It has since been evaluated, modified and applied to new data by several investigators (e.g. Adams and Pneuman, 1976; Altschuler et al., 1976; Schulz et al., 1978; Levine, 1982; Hoeksema et al., 1982, 1983), who find that it is generally useful for reproducing the large-scale features of the coronal and interplanetary field.

Knowing the measured photospheric field values, computation of the coronal field reduces to a simple boundary value problem under the assumptions 1) that at some height above the photosphere, called the source surface, the field lines are all radial, drawn outward by the accelerating solar wind and 2) that between the photosphere and the source surface the field is a potential field. The calculation provides the coefficients of the multipole components of the field and the field values at the source surface. The calculation is performed each 10° in Carrington longitude and the results are combined to produce the best estimate of the coronal field. The photospheric data are low-resolution high-precision observations made at the Wilcox Solar Observatory (WSO) at Stanford. Corrections are made to the data for the zero level offset and the incomplete measurement of the polar field strength. The source surface is located at 2.5 solar radii which gives the best overall agreement of the predicted IMF polarity with the measured IMF polarity. More complete descriptions of the data and model can be found in Hoeksema et al. (1982, 1983) and Hoeksema (1984).

To determine the rotation rate we have used three techniques. The first is the autocorrelation method. Using a series of field values computed at 5 degree intervals for many rotations, the autocorrelation was determined for a range of lags for each of 30 latitude zones to derive the differential rotation profile. From this we found the rotation rate of the structures having relatively short lifetimes, but with rather poor resolution. The second method was to decompose the field into its component parts, dipole, quadrupole, etc., at regular intervals, forming a time series. The power spectra of these time series gave the rotation rates of the various large-scale components of the field. In the final method the power spectrum of the field values at each latitude was computed. Using this method the rotation rates for the longest-lived structures were determined.

We have found a difference in rotation rate between the northern and southern hemispheres. From 1976 to 1985 the southern coronal fields rotated more slowly than the northern hemisphere fields. Parker, Hansen, and Hansen (1982) found that the white light coronal structures in the northern hemisphere rotated somewhat more slowly than those in the south during the previous solar cycle.

The present study clarifies the results of several previous studies of photospheric, coronal, and interplanetary field rotation. Wilcox et al. (1970) studied the rotation of the photosphere using an autocorrelation technique applied to the Mt. Wilson magnetic field measurements. They found that at lags of one or two rotations the field rotated with the well-known differential rotation curve, but that at longer lags the derived rotation became less and less differential. Rather it approached a 27 day rate near the equator (latitudes less than 25°) and 28 days at higher latitudes. They interpreted this to mean that the longer lived field patterns rotated faster than the shorter lived field structures. We believe that this can be reinterpreted to mean that multiple rotation rates were present concurrently, but that it took lags of several rotations to resolve them. The question of why there are only two dominant rotation periods remains unanswered.

Earlier studies of the large scale field (Hoeksema, 1984 and Hoeksema and Scherrer, 1984) in terms of the multipole components have characterized coronal rotation in terms of a few discrete rotation periods. In particular, the equatorial component of the dipole field has been shown to rotate with dominant periods near 27 and 28.2 days. The present study shows that these signals arise from the field configurations in the northern and southern hemispheres respectively.

The interplanetary magnetic field (IMF) also appears to have two basic periods of rotation, one very close to 27 days and one between 28 and 29 days. These are the same rates we have found in the two coronal hemispheres. These same periods have been observed during the past six solar cycles (Svalgaard and Wilcox, 1975).

II. The Autocorrelation Method

Some coronal field structures have relatively long lifetimes, at least several rotations. Therefore, a reasonable way to determine the rotation rate of the corona is to compute the autocorrelation of the field at lags near the expected rotation rate for each latitude. The maximum autocorrelation will occur at the the lag corresponding to the actual rotation rate for that latitude. Figure 1 shows the rotation rates of the coronal structures determined from the first peak in the autocorrelation function. The rotation rate found for each of the 30 latitude bins for which we compute the field is shown by a '+' symbol. Fitting these points to a curve of the standard form gives a relationship Rotation = $13.2 - 0.5 \sin^2\phi$ degrees per day (synodic), shown with the solid bold curve. For comparison we also plot the rotation rates of coronal holes (dot-dashed line, Bohlin, 1977); of solar features such as prominences, coronameter enhancements, magnetic field patterns, white light and 5303 enhancements (dotted line labeled PCMF, Bohlin, 1977); of long-lived sunspots (long-dashed line, Newton and Nunn, 1951); and of the

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Figure 1: The differential rotation curves for various solar features. The long dashed line shows the Newton and Nunn (1951) curve for recurrent sunspots; the dotted line shows the synodic rotation rate for photospheric features (Bohlin, 1977); the rotation of coronal holes is shown by the dash-dot line (Bohlin, 1977); the solid line is the differential curve of the photospheric plasma measured using doppler shifts(Scherrer et al., 1980.); and the heavy solid line is the best fit rate of the coronal fields determined in this study. The plus symbols show the actual rates determined from the autocorrelation analysis. Each curve has an error of approximately 0.1 degree/day.

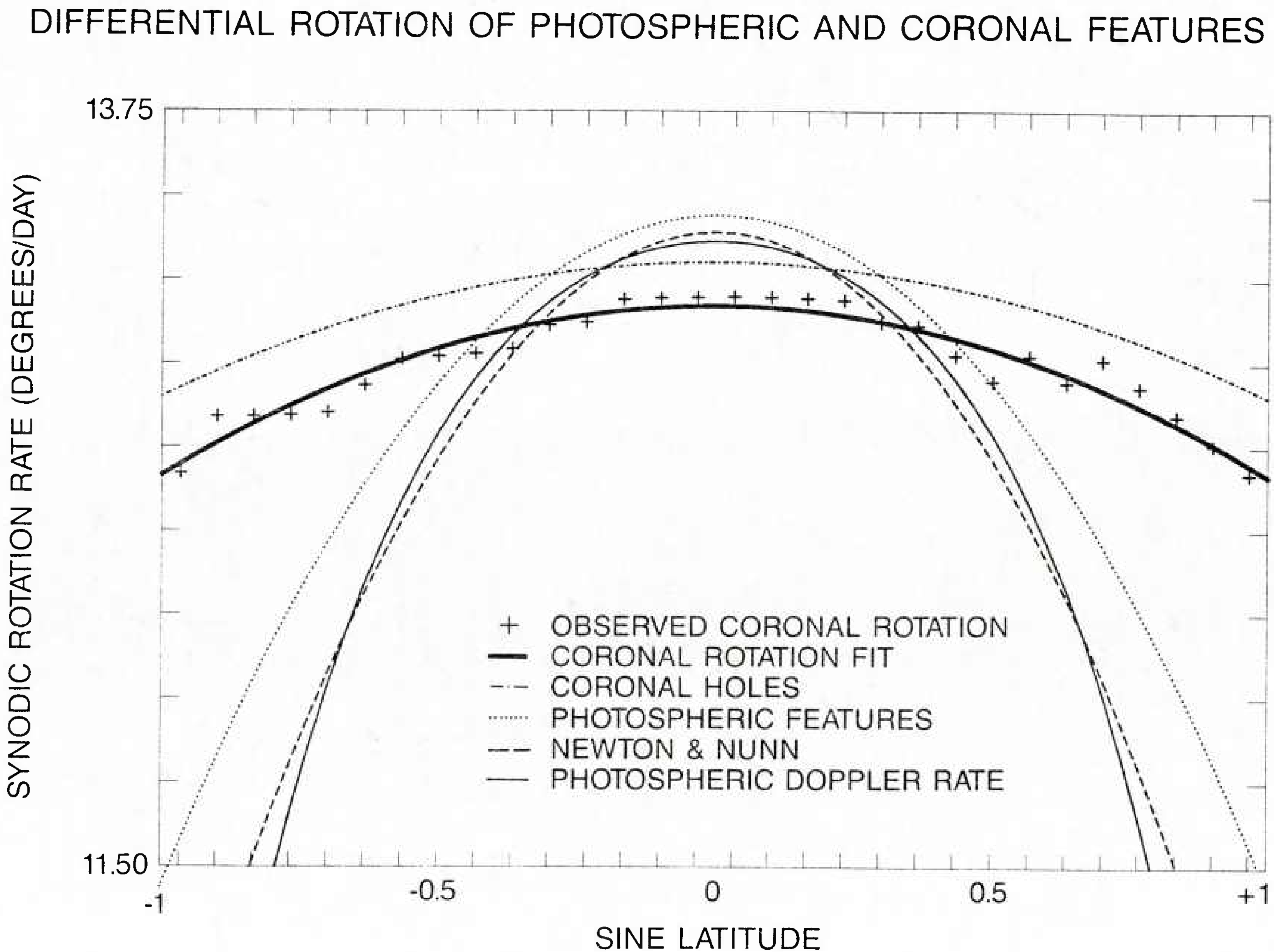
DIFFERENTIAL ROTATION OF PHOTOSPHERIC AND CORONAL FEATURES
13.75
11.50
SYNODIC ROTATION RATE (DEGREES/DAY)
-1
-0.5
0
0.5
+1
SINE LATITUDE
OBSERVED CORONAL ROTATION
CORONAL ROTATION FIT
CORONAL HOLES
PHOTOSPHERIC FEATURES
NEWTON & NUNN
PHOTOSPHERIC DOPPLER RATE

Figure 1

photospheric plasma determined from doppler measurements (solid, Scherrer et al., 1980.)

The rotation curve for the coronal magnetic field is, not too surprisingly, much like that of coronal holes (Timothy, Krieger, and Viana, 1975; Bohlin, 1977) and the coronal green line structure (Antonucci and Svalgaard, 1974). The field at the source surface rotates much less differentially than the large-scale photospheric field, the photospheric plasma, or long-lived sunspots. Fisher and Sime (1984) found a coronal rotation rate of 13.22 - 0.53 $\sin^2\phi$ degrees per day (synodic), in excellent agreement with the present study. Sheeley and Harvey (1981) found a rotation rate of 28.0 days for high latitude coronal holes observed before 1979, in good agreement with the present data.

The autocorrelation method is limited by it relatively poor resolution. The first peak in the autocorrelation is very broad, particularly at higher latitudes where the relatively uniform polar fields are the most important. The resolution of our observations is poorest and the model is least tested near the poles. The rate determined in this way is the conglomerate rate of both the short- and long-lived fields and the fields of all longitudes for the entire time interval 1976 to 1986. This method provides no way to differentiate the rotation rates of different constituents of the coronal field, whether those constituents are distinct spatially or temporally or have different lifetimes.

One way to increase the resolution is to look at the peaks in the autocorrelation at higher multiples of the rotation period. Figure 2 is a contour map of the autocorrelation computed for each latitude for lags from 0 to 10.5 rotations. There are 30 points spaced equally in sine latitude from south, at the bottom of the figure, to north, at the top. The lag increases from zero on the left to 10.5 Carrington rotations on the right. The tick marks are at Carrington rotation intervals of 27.275 days. The roughly vertical shaded ridges of high correlation correspond to multiples of the rotation rate and determine the differential rotation curve. The first ridge was analyzed to create Figure 1.

The high latitude fields are highly correlated for many rotations. Even after ten rotations the autocorrelation is at least 0.9. This shows the strong influence of the uniform polar fields. However, one can still see ripples in the autocorrelation which allow determination of the rotation rate.

At lower latitudes structure becomes increasingly evident at greater lags. At smaller lags the contours are roughly symmetric north and south of the equator. Even so, there is a hint in the northern hemisphere of a secondary peak in the autocorrelation near a half rotation. This corresponds to a 4-sector structure in the IMF.

With increasing lag the differences between the solar hemispheres become more and more obvious. In the northern hemisphere the peaks remain rather symmetric and there is little evidence of differential rotation, i.e. the ridges remain vertical. The longer lived fields seem to rotate somewhat more rapidly than the shorter lived fields. Consider the locations of the recurrence peaks relative to the Carrington tick marks. At high northern latitudes the peaks occur more and more to the left with increasing lag, implying a rotation rate that increases with lifetime. For the seventh and subsequent peaks the rotation is faster than the Carrington rate. A similar phenomenon has been noted by Wilcox et al., (1970) in an analysis of lower latitude photospheric fields.

Figure 2: A contour map of autocorrelation vs. lag for a range of latitude strips. The vertical axis is organized with 30 points equally spaced in sine latitude from south (bottom) to north. The horizontal axis shows lags from 0 to 10.5 Carrington rotations. The tick marks are at Carrington rotation intervals. The dashed contours show negative correlation. The contours are drawn at the levels indicated and shaded above the contours 0.1 and 0.7. Darker shading corresponds to higher autocorrelation values. The ridges spaced approximately one Carrington rotation apart determine the rotation rate. The overall correlation decreases with increasing lag, but the pattern remains evident. Note that in the north the first peaks occur just after the Carrinton ticks, but at longer lags they preceed the ticks. The southern structure is more complex, splitting into multiple peaks by the eighth or ninth recurrence, alway following the Carrington ticks.

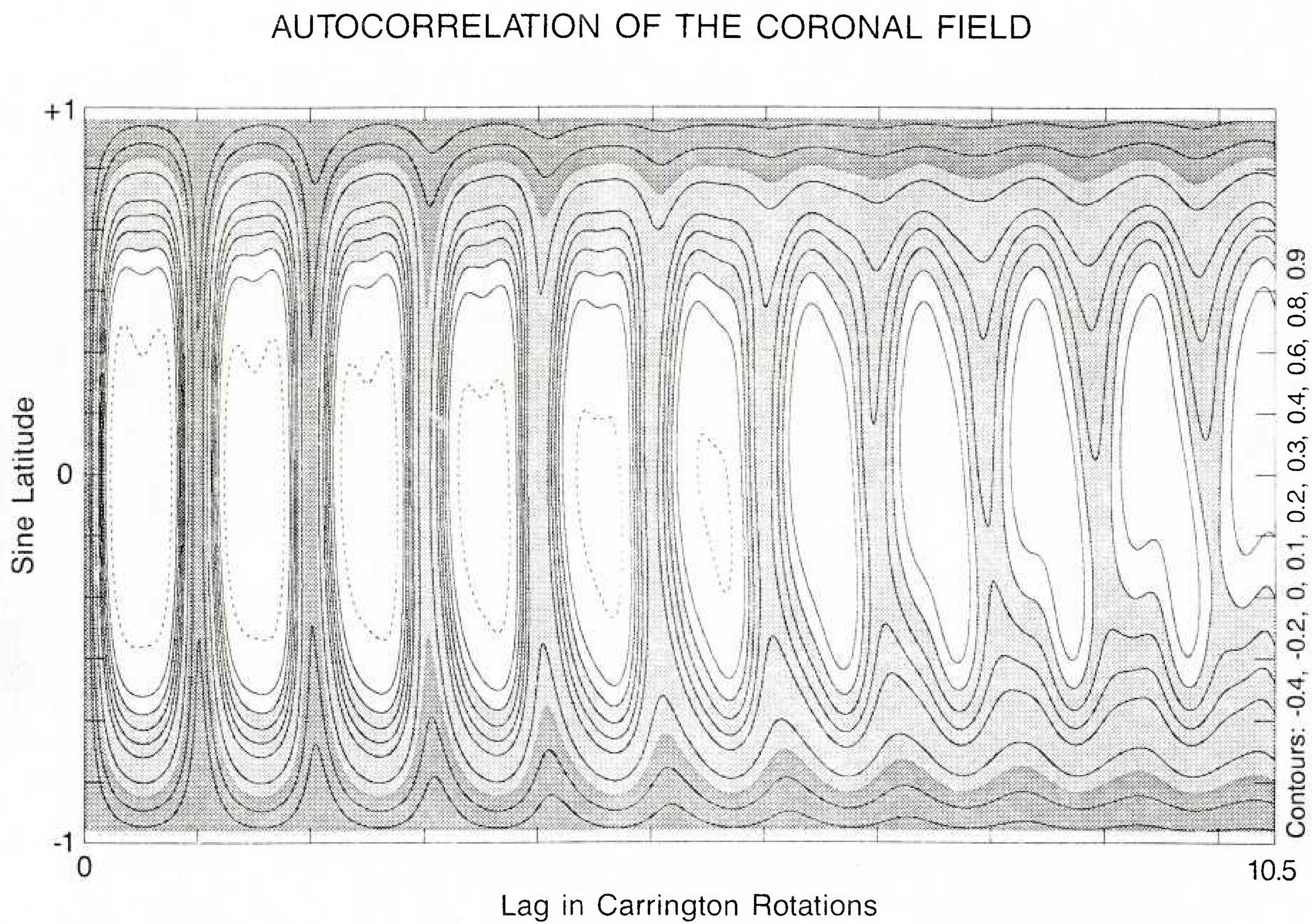
AUTOCORRELATION OF THE CORONAL FIELD
+1
0
-1
Sine Latitude
0
10.5
Lag in Carrington Rotations
Contours: -0.4, -0.2, 0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 0.9

Figure 2

In the south successive peaks broaden with increasing lag, tending toward longer periods, and there is more obvious differential rotation. By the eighth or ninth recurrence interval there is clear evidence for a splitting into two basic rotation periods in the mid-latitude southern hemisphere. The south rotates more slowly than the northern hemisphere. At higher southern latitudes the field structures rotate at much the same rate with increasing lag, a rate somewhat slower than the Carrington rate.

This is a very curious result. Why, over a ten year interval, should the northern and southern hemispheric fields rotate differently? Why should the northern fields roughly converge to a single rotation rate of about 27 days while the southern fields rotate slower on the average and at more than one rate? To investigate this more thoroughly we have performed a spectral analysis of the fields.

III. Spectra of Harmonic Coefficients

The potential field is computed using spherical harmonic functions. We have previously performed a spectral analysis of the equatorial dipole component of the coronal field (Hoeksema and Scherrer, 1984). Figure 3 shows the power spectrum of the equatorial dipole. The two largest peaks occur at 27.0 and 28.2 days. This corresponds extremely well to the frequencies observed in the northern and southern hemispheres of the source surface field (see below). Using only the spherical harmonics there is no way to distinguish between the contributions of the two solar hemispheres. Rather the impression is of two superposed, cospatial field structures simultaneously rotating at different rates. We

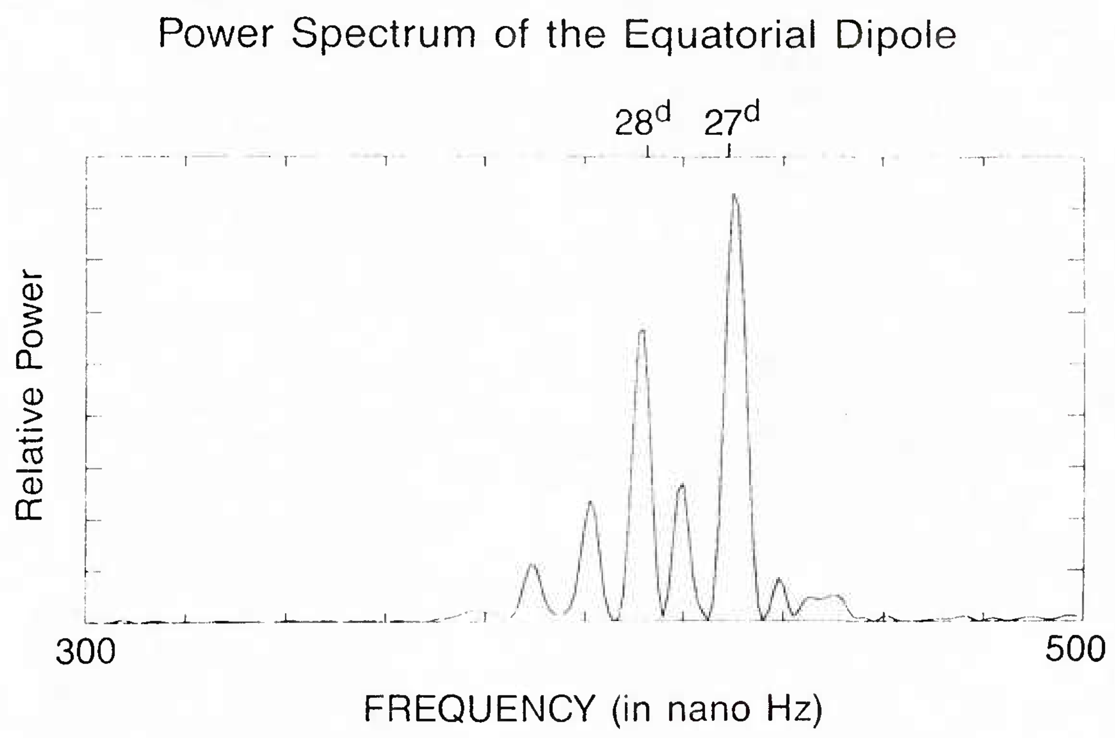

Figure 3: The power spectrum of the equatorial dipole field. The primary peaks are at 27.0 and 28.2 days.

suspect from the autocorrelation analysis that the two major peaks are due to field structures rotating differently in the north and south. The spectrum of the IMF polarity in this frequency range looks very similar to the spectrum of the equatorial dipole component. That individual IMF polarity structures with different rotation rates arise at different solar locations and latitudes has been noticed previously (e.g. Levine, 1978; Hoeksema et al., 1980; Hoeksema, 1984; Sheeley and DeVore, 1986.)

IV. Spectral Analysis of Field Rotation vs. Latitude

An alternative way to determine the rotation frequency is to compute the power spectrum of a time series formed from a latitude strip of the coronal magnetic field. We expect to see power at the rotation rate and at very low frequencies due to field evolution. There will also be some power at multiples of the rotation rate due to organization of the field on smaller spatial scales. Because we have a ten year span of data with no gaps, the only significant side band structure should be due to the observing window; the fact that only half of the sun can be observed at a given time will redistribute the spectral power among the harmonics of the rotation period. From the analysis in the Section II we would expect to see a rotation rate in the northern hemisphere at about 27 days and a different rotation rate or rates in the southern hemisphere at about 28 days.

Figure 4 shows a contour map of the power spectra. The lower axis runs in frequency from 300 to 500 nanohz. The vertical axis is once again sine latitude. The power spectrum of the normalized field values is computed for each latitude; the resulting spectra are assembled to make this plot. The power is clearly divided into just a few peaks in each strip, forming ridges in the contour map. The most prominant ridges span quite a large range of latitude. The ridge on the right corresponds to a 27.0 day rotation and the left ridge to a rate of 28.1 days. The 27-day ridge is centered slightly to the north and the 28-day ridge significantly to the south.

The power is distributed through the spectrum differently in the polar and equatorial regions. Near the equator about 60% of the power is in the 300 to 500 nanohz band and about 30% in the 600 to 1000 nanohz band (the first harmonic.) Toward the poles, more and more power is concentrated at very low frequencies (less than 50 nanohz); from over 90% at the most poleward latitudes down to around 30% at 35°. In the 300 to 500 nanohz band the power ranges from less than 5% at the poles to over 50% at 35°. Power varies from less than 1% at the poles to about 20% at 35° in the 500 to 1000 part of the spectrum. There is very little power between 50 and 300 nanohz or at frequencies greater than 1000 nanohz at any latitude. The integrated power associated with the fundamental rotation frequency is about twice or more the power of the first and higher harmonics at all latitudes. For comparison the first harmonic power is also plotted in Figure 4 at half frequency, but with dashed contour lines.

The power is clustered at a very few dominant rotation periods. These periods are observed over a significant range of latitudes. The 27-day rotation ridge is the strongest and most important north of the equator, and it is also significant south of the equator. The 28-day ridge is much stronger than the 27-day ridge in the southern hemisphere, but not as significant north of the equator. There is little evidence of differential rotation, though there are some very weak ridges at higher latitudes at longer periods. The rotation seems most organized by hemisphere. Notice that the smaller ridges in this spectrum occur at the same frequencies as the smaller power peaks in Figure 3, the power spectrum of the equatorial dipole.

In contructing this plot the data for each latitude have been normalized so that the average value is 0 and the variance is 1.0. This is to limit the dominance of the active latitude fields which have much larger field values. The results for the unnormalized field are almost identical. The above methods may tend to emphasize the contributions of intervals when the field is strongest.

Much attention is paid to the polarity structure of the interplanetary medium. The IMF does not show the same structure of field strength observed on the source surface, though the polarity pattern is the same. For completeness the source surface field values were converted to polarity values and the analysis repeated. This decreases the relative influence of strong field regions and time intervals of greater field strength, emphasizing instead the polarity *patterns*. The results were essentially the same.

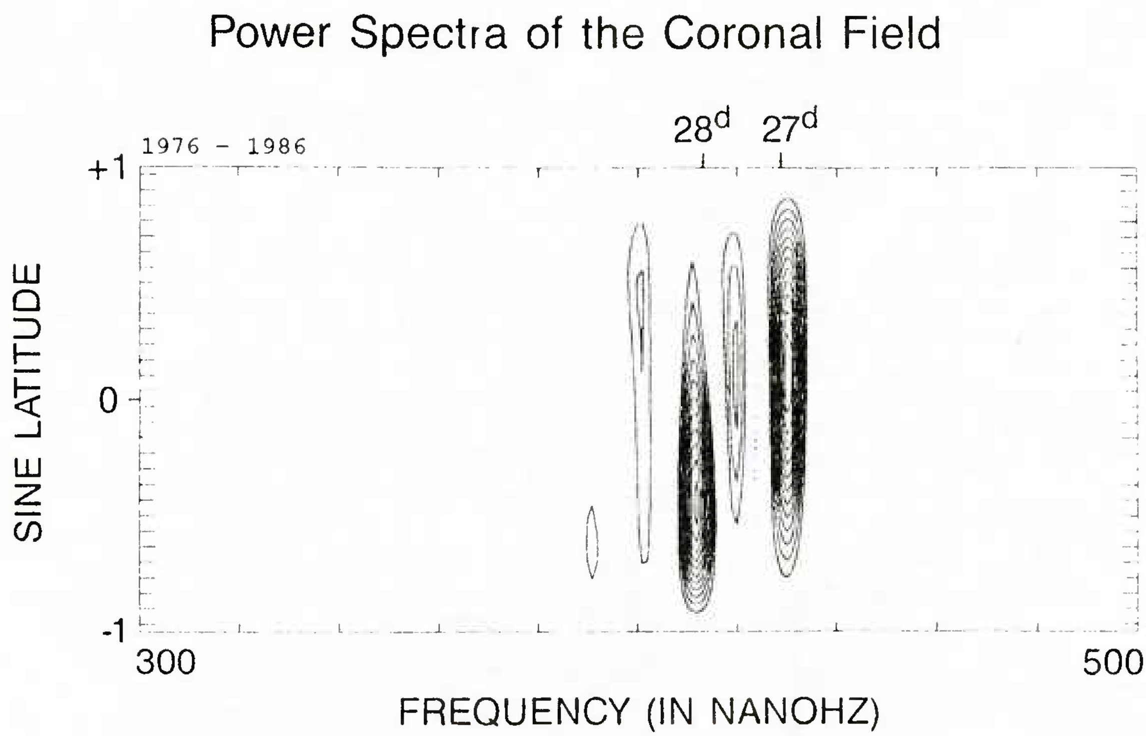

Figure 4: A contour map of power in the frequency range 0.3 to 0.5 μhz for various solar latitudes. The vertical axis shows solar latitude in 30 equal step of sine latitude from south (bottom) to north. Frequency, on the horizontal axis, increases from 0.3 to 0.5 μhz. This includes frequencies corresponding to the solar rotation rate. The period in days is marked on the upper axis. The power spectra are computed from normalized latitude strips of the magnetic field on the source surface. Most of the power is concentrated at 27-day and 28.1-day periods. The 28-day power comes mostly from the southern hemisphere. The corresponding periods are marked on the upper axis. Power at the first harmonic is plotted with dashed lines at the same contour levels.

There was less power at higher latitudes and the 27- and 28-day ridges extended over slightly smaller latitude ranges. The smaller ridges changed somewhat more. The ridge at 29 days was greatly reduced and the ridge between the 27- and 28-day ridges was somewhat enhanced.

Using the usual assumption that the polarity pattern expands radially from the source surface, spacecraft at different latitudes should see different patterns and different recurrence rates in the IMF. We at Earth sample the fields which extend to the ecliptic, very near the solar equator, and so see both 27- and 28-day structures.

What are some limitations of this method? 1) There is the possibility of observational aliasing. 2) The power spectrum analysis looks for coherent signals over a very long time period. 3) It is difficult to sort out the origin of power at multiple harmonics of the rotation period.

Observational aliasing could arise because of the limited resolution of the Wilcox Solar Observatory instrument. Measurements of the sun are made with a 3 arc minute aperture. This provides for 11 independent observations from north to south. The observed points are then interpolated to form synoptic charts with 30 points from north to south and 5 degree resolution in Carrington longitude. Because the interpolation reaches out to several of the nearest observed points, a signal in one observed scan line could contaminate a range of adjacent latitudes in the synoptic charts. Thus a strong rotation signal from one scan line could conceivably appear over a large fraction of one hemisphere. Since the potential field calculation is in part a further smoothing, the problem could be accentuated.

To check this hypothesis we obtained high resolution synoptic chart data from the National Solar Observatory (NSO), courtesy of John Harvey. These data have resolution of 180 points north - south and 1 Carrington degree in longitude. Consequently, we could *average* the data into the same resolution as our synoptic charts rather than *interpolate* as required for WSO observations. After performing the potential field model calculation on the interval Carrington Rotation (CR) 1645 to CR 1755, we completed the analysis necessary to generate a frequency vs. latitude plot similar to Figure 4. The time interval is slightly different, but not significantly. There is essentially no difference in the results for the NSO and Stanford data. All of the power ridges are slightly less extended in latitude. The northern ridges are slightly shifted to the north and the southern ones slightly to the south. The frequencies are the same.

A second possible aliasing arises from the potential field computation method. Finding the solution requires the global solar field over a complete Carrington rotation, which implies a fixed coordinate system with a uniform rotation rate. Accordingly, portions of the sun having rotation rates other than the Carrington rate may be improperly treated. Furthermore, it takes about 27 days to collect the field data for the entire sun. To minimize these problems, the solution to the global coronal field is computed once beginning each 10° in longitude. Only the central portions of the computations are combined to form the source surface synoptic charts. This minimizes the mismatch between the fixed coordinate system and the differential solar rotation and the effects of field evolution during the extended data collection interval, which are most severe near the beginning and end of a rotation wide data window.

How should we interpret the results of the power spectrum analysis, which are simple to interpret only for coherent signals? The peaks in the power spectrum are narrow. Straightforwardly interpreting the peak widths as lifetimes for the modes indicates a lifetime as long or longer than 10 years, the length of the data. Another possible interpretation might be that there are relatively few occurences of a given frequency having different phases. In that case the spectrum would be split into a number of narrow peaks each shifted from the actual frequency. For example, the power ridge at 27.5 days could be an alias of the 27-day peak due to the finite lifetime of rotating structures. Equivalently there could be a small secular frequency shift.

A rotational signal having a lifetime comparable to a solar cycle seems at first somewhat incredible. Especially after observing the large changes in the field structures on the photosphere and the source surface from 1976 to 1986 (Hoeksema et al., 1983; Hoeksema and Scherrer, 1986). On the other hand, previous analysis of the IMF polarity pattern (Svalgaard and Wilcox, 1975) has revealed very long-lived structures having rotation rates very close to 27 days and 28.5 days in six solar cycles.

One way to begin to solve this question is to analyze the spectra of subsets of the data. We have divided our data into three independent intervals, each long enough to resolve the interesting peaks: CR 1642 - 1681 (May 1976 to May 1979), CR 1682 - 1721 (May 1979 to May 1982), and CR 1722 - 1761 (May 1982 to May 1985). We analyze these intervals as above, normalizing the subintervals for each latitude and plotting the contour map of the power spectra in Figure 5.

We find that in each interval there is a peak near 27 days and a peak near 28 days. In each interval the 27-day peak is located to the north of the 28 day peak. To the resolution allowed by the length

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Figure 5: Contour maps of the power spectra as in Figure 4 for the three subintervals discussed in the text. The resolution of these spectra is poorer because of the decreased time interval. There is some change in the frequencies of the ridges from interval to interval, but the character of the structure is similar during each of the subintervals. Power at the first harmonic is again shown with dashed contours.

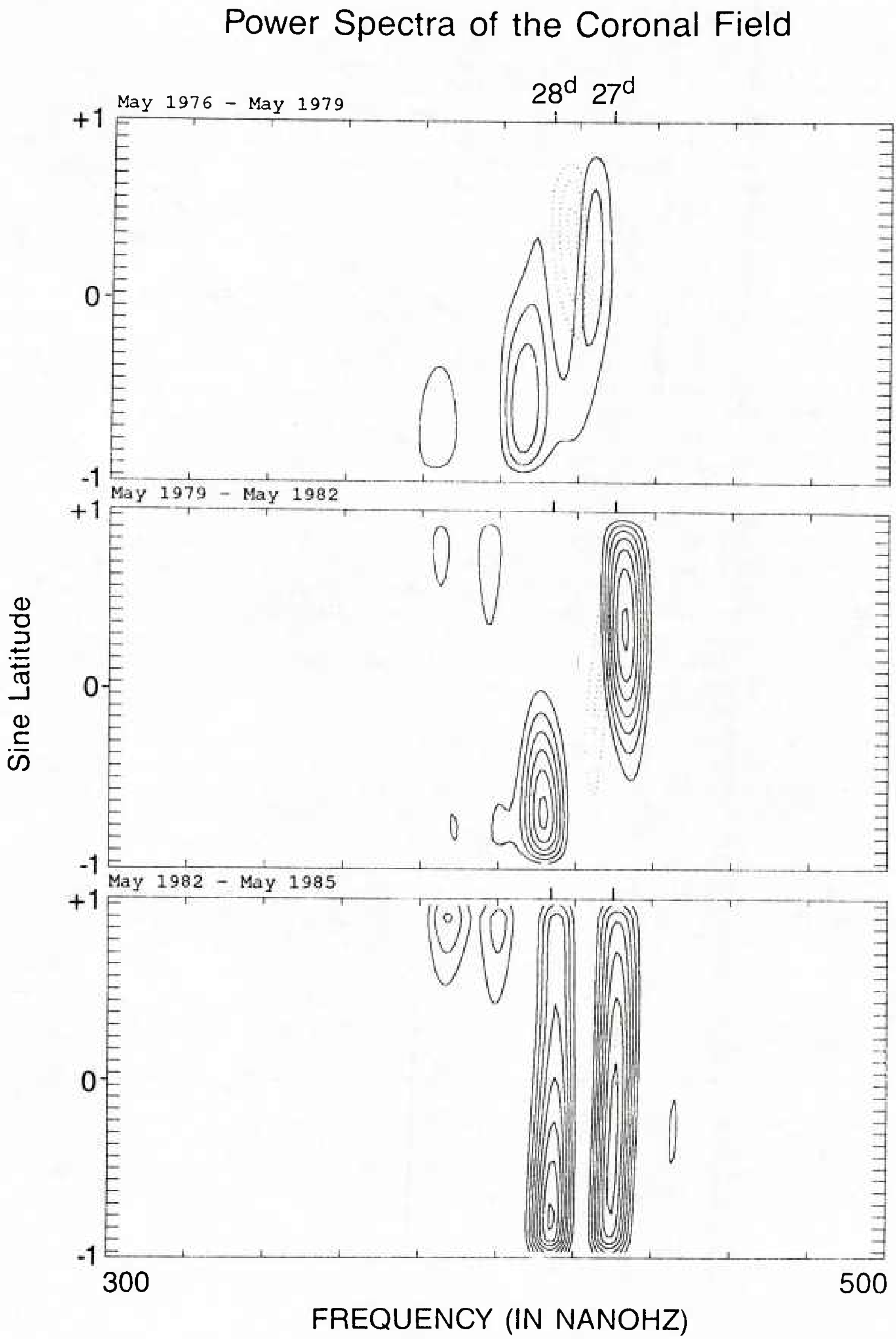
Power Spectra of the Coronal Field
28d 27d
May 1976 - May 1979
May 1979 - May 1982
May 1982 - May 1985
+1
0
-1
Sine Latitude
300
500
FREQUENCY (IN NANOHZ)

Figure 5

of the intervals (~1/40 rotation = 3/4 day) the peaks occur at the same frequency throughout the cycle. There does seem to be a slight increase in frequency with time, but less than the resolution of the data. In the first two intervals the latitudinal separation of the peaks is somewhat greater; the peaks are much more extended in latitude during the final interval. It is also interesting that during the first interval only, there is a significant amount of power at the first harmonic of the rotation frequency (shown by dashed contours); this suggests that a 4-sector structure is most prominent during this interval. This 4-sector structure seems to rotate with a period of 27.7 days and is most prominent in the northern hemisphere.

This analysis shows that the bimodal rotation persists in the coronal field during the entire solar cycle and that the rotation periods change relatively little during the cycle.

A final concern regards the power at shorter periods, particularly at multiples of the rotation frequency. There is some natural power at these frequencies as we can see from the multipole components of the coronal field (Hoeksema and Scherrer, 1984 and the discussion above). There is also some contribution to the higher frequencies from the rotation signal (and vice versa) because of the side bands of the observing window. The relative importance of the higher multipoles is dependent on time during the solar cycle. For the present we will ignore the power at higher frequencies since it is usually only a small fraction of the total power.

V. Discussion

There have been several studies of coronal rotation using coronameter observations of brightness over the solar limbs. Bright regions are generally related to coronal magnetic structures with the brightest regions corresponding to the neutral line. See Wilcox and Hundhausen (1983) or Bruno, Burlaga and Hundhausen (1984) for a comparison of the potential field model and coronameter determinations of the neutral line near solar minimum. Hansen, Hansen, and Loomis, (1969) did one of the first such studies. They found that from 1964 to 1967 coronal brightness features rotated faster at higher latitudes than the photosphere.

Parker, Hansen, and Hansen (1982) studied coronal rotation during solar cycle 20 also using coronameter data. They applied the maximum entropy spectral analysis (MESA) technique to the data. They compared their results with autocorrelation methods and found good agreement. It should be noted that they tuned the MESA filter order to produce one and only one peak in the spectrum in the 22 - 35 day range for each latitude.

Their results support the conclusion that the coronal fields rotate more rapidly than the photosphere. In particular, the coronal fields rotate more rigidly than the surface; however, the general corona rotates more differentially than coronal holes. They also found that differential rotation decreased with increasing altitude. The rotation rate after 1970 was faster than before 1970. They also note a possible asymmetry between the northern and southern hemispheres: "the southern polar regions seemed to rotate faster, on average, than the northern polar regions during solar cycle 20." If their analysis is correct, it is the opposite of the asymmetry we find in cycle 21, implying that north - south difference in rotation rate may be cycle related.

Fisher (1982) analyzed the rotation rate from coronameter measurements of the coronal brightness in 1980 and 1981. During that interval the polar regions rotated every 28.0 days and the active region structures at about 27.6 days. During such a short interval, discriminating between the peaks is difficult. As seen from the autocorrelation analysis, the peaks may be relatively poorly determined. His results differ from ours for a number of reasons. First of all, the rotation rates were reported for just two zones, one from 50°N to 50°S and the second combining the regions from 50° to the pole in each hemisphere. This precludes finding a difference in the rotation rates of the two hemispheres. The coronameter measurements are made significantly lower in the corona, thus we would expect more similarity to the photospheric differential rotation curve. Furthermore, the coronameter observations near maximum have a very substantial contribution from transient activity-related events. Such events are more directly tied to the photospheric magnetic field activity and so are more likely to show a different rotational profile than the higher altitude coronal fields we compute.

Fisher and Sime (1984) determined the rotational characteristics of the white light corona from 1965 to 1983. They found a differential rotation curve for the corona at 1.3 and 1.5 solar radii of 14.21 - 0.57 $\sin^2\phi$ degrees (sidereal) per day, corresponding to a synodic rate of 13.22 - 0.53 $\sin^2\phi$ degrees per day, which agrees very well with the function derived in this study. They used the autocorrelation method described in Section II above and showed figures very much like Figure 2 in this paper. Their analysis considered the data in yearly pieces, determining the rotation rate versus latitude for each year separately, and finally combining the data from each year to find the time averaged rotation rate. Fisher and Sime compared their results with the rotation rates of features observed in the potential field model data (Hoeksema, Wilcox, and Scherrer, 1983) and found good agreement.

The autocorrelation analysis reported in Section II showed no obvious north - south asymmetry, nor did it show two different rotation rates when considering only the first recurrence peak, even with many years of data. Determining the first recurrence period in the autocorrelation analysis from just one year of data would not allow a separation of the two rotation modes we have found. It was not until the 7th or 8th peak that the two rotation rates were resolved in Figure 2. So it is not surprising that the asymmetry and different periods went undetected.

Fisher and Sime determined a lifetime for coronal magnetic structures of between 45 and 60 days near the equator and between 45 and 100 days in the polar regions, depending on the phase of the solar cycle. This determination was based on the value of the correlation at a one rotation lag. Because the coronameter data is more sensitive to activity related structures with relatively short lifetimes and because of the inability of the first peak in the correlation to resolve different rotation rates (broadening and flattening the peak, therefore decreasing the inferred lifetime), we feel this method may underestimate the lifetimes of the coronal structures to which our method is sensitive.

Fisher and Sime also considered the rotation rate versus phase of the solar cycle and found that at all latitudes the rotation rate is related to the level of activity with a lag of two years from the minimum in rotation rate to the minimum in activity. If we consider only the peak near 27 days in our analysis of the shorter data intervals, the peak for Interval I (1976 - 1979) occured at 27.3 days, Interval 2 (1979 to 1982) was found to rotate at 26.75 days, and the final interval (1982 to 1985) at 26.9 days. These are not significantly different from 27 days given the length of the intervals, but tend to show a longer period during the rising phase and the shortest period at solar maximum. How closely these results should compare with those of Fisher and Sime is not clear because of the blending of the two rotation rates in their analysis and their increased sensitivity to shorter-lived features.

These studies were not sensitive to the characteristics of coronal rotation determined in the present paper. By considering short time intervals and lags in the autocorrelation methods, it is impossible to resolve multiple rotation periods separated by only one day. By averaging the results from the northern and southern hemispheres, the ability to distinguish between them was lost. The MESA spectral analysis was limited to finding only one peak in the period range of interest but did detect a difference between the solar hemispheres.

Wilcox et al. (1970) studied the rotation of the photospheric field from 1959 to 1967 using the autocorrelation method. At lags of one or two rotations they recovered a standard differential rotation curve much like that of long lived sunspots; at longer lags (up to ten rotations) roughly rigid rotation was discovered over a relatively large range of latitudes (up to 25° north and south) of about 27 days. At latitudes up to 40° the rotation rates seemed to converge to a period near 28 days. This was interpreted to mean that photospheric *features* rotated at the differential rate of the plasma while the longer lived field *patterns* rotated rigidly. The photospheric data has a great deal more structure and is somewhat less organized on the large scale than the coronal field, so it is difficult to compare to the present results. However, in light of the analysis of Section II, it is possible that both rates were present at shorter lags as well; there was just not enough resolution in the autocorrelation technique to resolve them.

The interplanetary field pattern rotates with periods of 27 days and 28 to 29 days (and sometimes both) during different parts of each solar cycle (Svalgaard and Wilcox, 1975.) If the different rotation rates really do originate in different solar hemispheres, that implies that the equatorial heliosphere is more strongly linked to one hemisphere or the other during different parts of the cycle. It is difficult to trace interplanetary sectors to field structures in the photosphere, but such attempts may support this implication (Hoeksema et al., 1980, Hoeksema 1984.)

The potential field model decomposes the coronal field into spherical harmonics. Looking at the rotation rates of the various multipole components, there is no way to determine the origin of different rotational components. The equatorial dipole shows multiple peaks at the rotation rates determined in the present study (Hoeksema and Scherrer, 1984.) But there is no way to determine the spatial structure or origin of the signals. In particular, there is no sensitivity to differences between the northern and southern hemispheres. This suggests that the spherical harmonics may not always be the best way to characterize the fields.

VI. Conclusions

Three major conclusions can be made from this analysis. First, the coronal field, in general, does not participate in the differential rotation observed on the photosphere. This has been observed before, but is still somewhat counterintuitive in light of the fact that the coronal fields in this study are calculated directly from the photospheric fields. Second, the fields rotate almost exclusively with two discrete periods, 27 days and 28 days. This is very surprising, though perhaps not totally unanticipated in light of previous studies of the interplanetary medium and geomagnetic activity. Finally, there is a marked north - south asymmetry in the rotation rate which extends over all of solar cycle 21. The northern hemisphere rotates more quickly than the southern hemisphere, the opposite of a possible asymmetry reported for the last solar cycle.

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References

Adams, J., and G.W. Pneuman, A new technique for the determination of coronal magnetic fields: a fixed mesh solution to Laplace's equation using line-of-sight boundary crossings, *Solar Phys., 46,* 185, 1976.

Altschuler, M.D. and G. Newkirk, Jr., Magnetic fields and the structure of the solar corona, *Solar Phys., 9,* 131, 1969.

Altschuler, M.D., R.H. Levine, M. Stix, and J.W. Harvey, High resolution mapping of the magnetic field of the solar corona, *Solar Phys, 51,* 345, 1977.

Antonucci, E. and L. Svalgaard, Rigid and differential rotation of the solar corona, *Solar Phys., 34,* 3, 1974.

Bohlin, J.D., Extreme-ultraviolet observations of coronal holes, *Solar Phys., 51,* 377, 1977.

Bruno, R., L.F. Burlaga and A.J. Hundhausen, K-Coronameter Observations and Potential Field Model Comparison in 1976-1977, *J. Geophys. Res., 89,* 5381, 1984.

Fisher, R., and D.G. Sime, Rotational Characteristics of the White-Light Solar Corona: 1965 - 1983, *Astrophys. J., 287,* 959-968, 1984.

Fisher, R., On the Nature of the Solar Corona Near the Maximum of Cycle 21, *Astrophys. J., 259,* 431-436, 1982.

Hansen, R.T., S.F. Hansen, and H.G. Loomis, Differential Rotation of the Solar Electron Corona, *Solar Phys., 10,* 135-149, 1969.

Hoeksema, J.T., Structure and Evolution of the Large Scale Solar and Heliospheric Magnetic Fields, Ph.D. Thesis, *Center for Space Science and Astrophysics Report CSSA-ASTRO-84-07,* 1984.

Hoeksema, J.T., and P.H. Scherrer, Harmonic Analysis of the Solar Magnetic Field, in *The Hydromagnetics of the Sun*, Proceedings of the Fourth European Meeting on Solar Physics, ESA SP-220, 1984.

Hoeksema, J.T., and P.H. Scherrer, The Solar Magnetic Field -- 1976 Through 1985, *Report UAG-94*, U.S. Dept. of Commerce, NOAA, Boulder, Co., 1986.

Hoeksema, J.T., P.H. Scherrer, and J.M. Wilcox, A two-sector solar magnetic structure with 29 day rotation, *Bull. Am. Astron. Soc, 12,* 474, 1980.

Hoeksema, J.T., J.M. Wilcox, and P.H. Scherrer, Structure of the heliospheric current sheet in the early portion of sunspot cycle 21, *J. Geophys. Res., 87,* 10331, 1982.

Hoeksema, J.T., J.M. Wilcox, and P.H. Scherrer, The structure of the heliospheric current sheet: 1978 - 1982, *J. Geophys. Res., 88,* 9910, 1983.

Levine, R.H., The Relation of Open Magnetic Structures to Solar Wind Flow, *J. Geophys. Res., 83,* 4193, 1978.

Parker, G.D., R.T. Hansen, and S.F. Hansen, Coronal Rotation During Solar Cycle 20, *Solar Phys., 80,* 185, 1982.

Schatten, K.H., J.M. Wilcox and N.F. Ness, A model of interplanetary and coronal magnetic fields, *Solar Phys., 6,* 442, 1969.

Scherrer, P.H., J.M. Wilcox, and L. Svalgaard, The Rotation of the Sun: Observations at Stanford, *Ap. J., 241,* 811, 1980.

Schulz, M., E.N. Frazier, and D.J. Boucher, Jr., Coronal magnetic field model with non-spherical source surface, *Solar Phys., 60,* 83, 1978.

Sheeley, N.R., Jr. and C.R. DeVore, The Origin of the 28- to 29-day Recurrent Patterns of the Solar Magnetic Field, *Solar Phys., 104,* in Press, 1986.

Sheeley, N.R., Jr. and J.W. Harvey, Coronal holes, solar wind streams, and geomagnetic disturbances during 1978 and 1979, *Solar Phys., 70,* 237, 1981.

Svalgaard, L. and J.M. Wilcox, Long term evolution of solar sector structure, *Solar Phys, 41,* 461, 1975.

Timothy, A.F., A.S. Krieger, and G.S. Viana, The structure and evolution of coronal holes, *Solar Phys., 42,* 135, 1975.

Wilcox, J.M., K.H. Schatten, A.S. Tanenbaum, and R. Howard, Photospheric Magnetic Field Rotation: Rigid and Differential, *Solar Phys., 14,* 255, 1970.

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