Observations of Global Solar Magnetic and Velocity Fields

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The Sun's magnetic field varies on time scales of minutes, months, decades, and centuries. These changes drive variations in solar irradiance. Characteristics of the changing magnetic field reveal, at some level, how the solar cycle works. The basic 22-year magnetic cycle and corresponding 11-year activity cycle of the Sun are driven by the emergence of active regions. The frequencies of solar oscillations that probe the convection zone vary on the same time scale. While plausible explanations for the statistical properties of solar activity can be made, the details of flux emergence cannot be predicted. Global activity varies on other intermediate time scales as well.

Defining elements of a cycle as those sharing a common bipolar field orientation, the first signs of a cycle can appear at high latitudes up to 5 years before solar minimum and the final elements disappear at the equator several years after the following minimum – a span as long as 18 years. At a particular latitude waves of activity are spaced by 11 years. The torsional oscillation in solar rotation rate has similar characteristics.

The spatial distributions of total flux and large-scale polarity evolve quite differently: the total flux map resembles the butterfly diagram, moving from mid latitudes toward the equator during the cycle, while the net zonal flux has two maxima in each hemisphere that expand away from mid latitudes.

While each solar cycle shares these basic features, fixed by the action of the solar dynamo working within the convection zone, the details of each cycle are determined by the apparently random timing and placement of emerging flux and by the changing convective flow patterns.

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1. Introduction

"Last night I had a curious dream ..." Most of us can remember a vivid dream – of flying, of embarrassment, or of a repeating noise. The elements of the dream seemed very real and made some kind of sense, but when considered in a broader context (often just after the alarm clock stopped) it became obvious that some important fact had been ignored. In some ways our understanding of the global solar magnetic and velocity fields is similar. We have increasingly accurate measurements of any number of parameters that vary more or less in phase or out of phase with the 22 year solar cycle. However, our understanding of the connections between the various features, of the detailed physics of their formation, lifetime, and decay, and of their common underlying causes is in many cases uncertain, inconsistent, or incomplete.

As we attempt to make sense of all these data, it is important to keep this fundamental question in mind: How much of what we observe is fundamentally related to the solar cycle mechanism? We see sunspots, measure radio flux, sense changes in total irradiance, puzzle over differential rotation in the photosphere and convection zone, and observe the reversal of the Sun's polar fields, but how are these related to the dynamo that drives the cycle in the interior? Do the surface field patterns migrate toward the pole and there provide the seed for the subsequent cycle? Or are the surface patterns, like the wake of a boat, merely an indicator of something larger, and perhaps more interesting, happening elsewhere? It is always tempting to conclude that the things we can see (and the questions we can begin to answer) are also the important ones.

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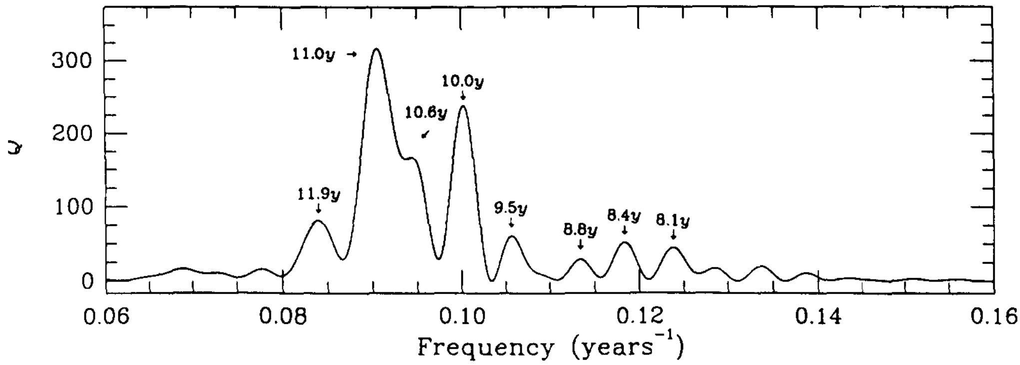

FIGURE 1. The periodogram of a 240-year time series of sunspot numbers shows the 11.04-year peak to be stronger than the other real periodicities in the record. "Q" is the intensity normalized to the total variance of the data (Donahue & Baliunas 1992).

In the remainder of this brief review, two main topics will be explored: the origin, distribution, and disappearance of flux in the photosphere, and the structure and variation of differential rotation and other large-scale solar motions. Continued progress on these questions coupled with improved understanding of the fundamental physical mechanisms operating on small spatial scales will enable the construction of a more complete picture of solar and stellar variations and of their influences on the Earth.

2. What is the life cycle of photospheric flux?

Magnetic flux patterns on the Sun vary with several characteristic time scales. The flux in all but the smallest elements appears to be concentrated entirely in intense kilogauss elements of small size, below the limits of spatial resolution. Associations of flux elements are seen as ephemeral regions, sunspots, active regions, and large-scale patterns including the polar field. The larger the scale of organization, the longer the lifetime. Individual sunspots and active regions live for days to months, nests of activity can persist as long as several years, the polar fields and gross level of activity vary with a 22-year period and it's 11-year harmonic. This paper presents observations of the largest scale features. Nevertheless, it is probably worth noting that the smallest intranetwork (IN) field elements are weak, but numerous and shortlived. Zirin's observations suggest that the total flux emerging in IN structures (10^{24} Mx per day) is about 100 times that in ephemeral regions and 10^4 that of active regions (Zirin 1987). About 30% of the IN elements in quiet regions disappear each day. Because the field orientation of INs is random, their contribution to the large-scale field patterns is probably negligible.

Sunspots, the most easily observed solar features, provide the longest direct observational record of solar activity. The record shows that each solar cycle is unique. Most recently Donahue & Baliunas (1992) demonstrated that solar cycles since 1750, as parameterized by the sunspot number, vary significantly in magnitude, profile, and period. Figure 1 shows the straightforward periodogram computed from the 240-year record. More recent quantitative observations of parameters such as radio flux, flare occurrence, and magnetic flux support this result. Though variations in period are smaller in recent cycles, even the earliest sunspot data are sufficiently accurate to show these variations are real. Observations of other stars show similar kinds of variations, including the simultaneous presence of multiple periodicities and Maunder-minimum like intervals.

The total solar flux varies with the solar cycle, but the strong field regions associated

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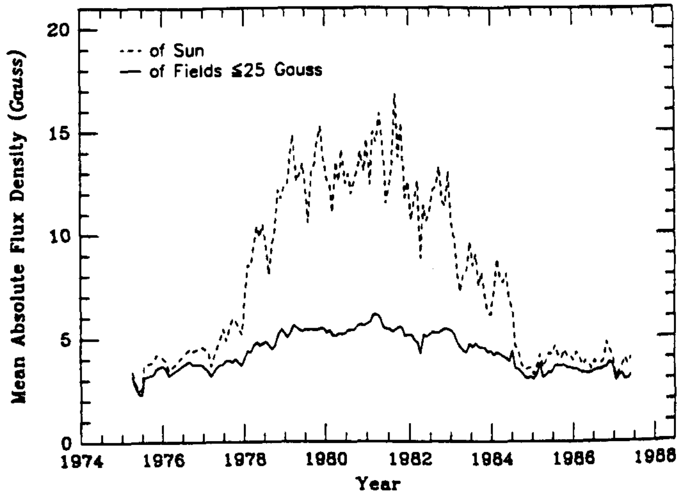

FIGURE 2. The variation of the strong-field and weak-field components of the total solar flux measured at KPNO. The total weak-field flux varies less than a factor of 2 from minimum in 1976 to maximum in 1979-80; the strong-field flux varies by more than a factor of 15. The total solar flux varies by at least a factor of 5. Some of the spiky peaks in the strong-field can be associated with individual activity complexes, but others are more globally distributed (Rabin *et al.* 1991).

with active regions account for almost the entire change (see Figure 2). This implies that at least 70% of the AR flux disappears in place (Rabin *et al.* 1991). Variations in strong-field flux can sometimes be associated with the evolution of particular active region complexes. The quasi-periodic pulses may be associated with the rates of flare occurrence. The north-south asymmetry of the flux is reflected most strongly in the strong-field regions, but is revealed in the weak-field regions as well.

The polar field provides an important component of the weak-field flux, particularly around solar minimum. The polar field is sometime regarded as an important indicator of the strength of the following sunspot cycle. One measure of the polar cap fields is shown in Figure 3. The polar fields have roughly constant magnitude near solar minimum (1976 and 1986) and reverse their polarities near solar maximum (1980 and 1990). Ignoring the annual variation due to the inclination of the Earth's orbit to the solar equator, the asymmetry in polar field strength in 1985–87 is quite apparent. In 1976–77 the asymmetry was not present and the average polar field strength was 25% less. The polar field appears to form as the result of the poleward migration of following-polarity flux from the active region zones (see Figure 5).

A one-dimensional parameter is not sufficient to describe the solar cycle. The latitudinal evolution of the flux patterns reveals something about the cycle mechanism. The progression of active region locations from mid-latitudes toward the equator through the cycle is well known. The "butterfly" diagram can be extended using the locations of plages. The plages appear earlier in the cycle and at higher latitudes than sunspots. Figure 4 shows how the field associated with two solar cycles overlaps for several years near solar minimum. Here elements from a cycle are identified by the orientation of the bipolar field structures. Observations of coronal brightness (Altrock 1988), polar facu-

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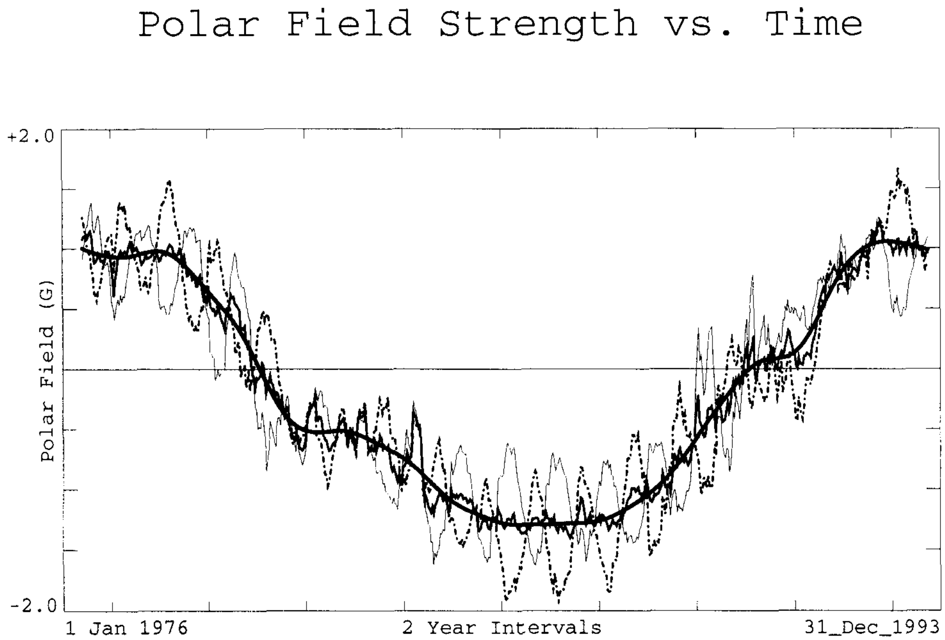

FIGURE 3. The Sun's polar field strength for a 17-year period showing two polarity reversals. This line-of-sight field measurement made in the polemost 3 arcmin aperture of daily magnetograms taken at the Wilcox Solar Observatory, covers latitudes from about 55 degrees to the pole. The light solid and dashed lines show the northern and southern pole strengths; the sign of the southern pole has been reversed to simplify intercomparison. The broader solid lines show the smoothed and unsmoothed averages of the two poles. The inclination of the ecliptic to the Sun's equator and the strongly peaked geometry of the polar field cause the annual variation of the individual polar caps.

lae (Callebaut & Makarov 1992), and the torsional oscillation in Doppler rotation rate (LaBonte & Howard 1982) appear to confirm that features associated with a particular solar cycle are present on the Sun for as long as 18 years, though the patterns at any given latitude repeat (with opposite sign) every 11 years.

Another feature of the large-scale field is the net polarity, shown in Figure 5. Panel 1 (bottom), showing total flux, has the same butterfly shape as Figure 4. The net flux (panel 2) emerges at mid latitude shortly after solar minimum in Cycles 21 and 22. Generally the leading polarity region expands toward the equator, while the following polarity region expands toward the poles. The boundary between the two remain roughly fixed. The polar field reverses when the following polarity region reaches high latitude. The reversal resulted from two components in Cycle 21: a gradually expanding antisymmetric flux pattern (panel 4, top) and a series of fast-moving surges that appear to have the same sign in the northern and southern hemisphere (panel 3). In Cycle 22 the gradually expanding term seems to dominate. The arrival times of the various features are associated with the changes in polar field strength shown in Figure 3. Similar polarity maps of previous cycles back to 1870 derived from Hα observations show very similar patterns (Makarov & Sivaraman 1989).

Stenflo and Gudel (1988) have decomposed the zonal solar field into harmonic coefficients. The amplitudes and phases of the first seven odd (antisymmetric) modes provide enough information to reproduce the shape of the low-latitude sunspot zone and the high-

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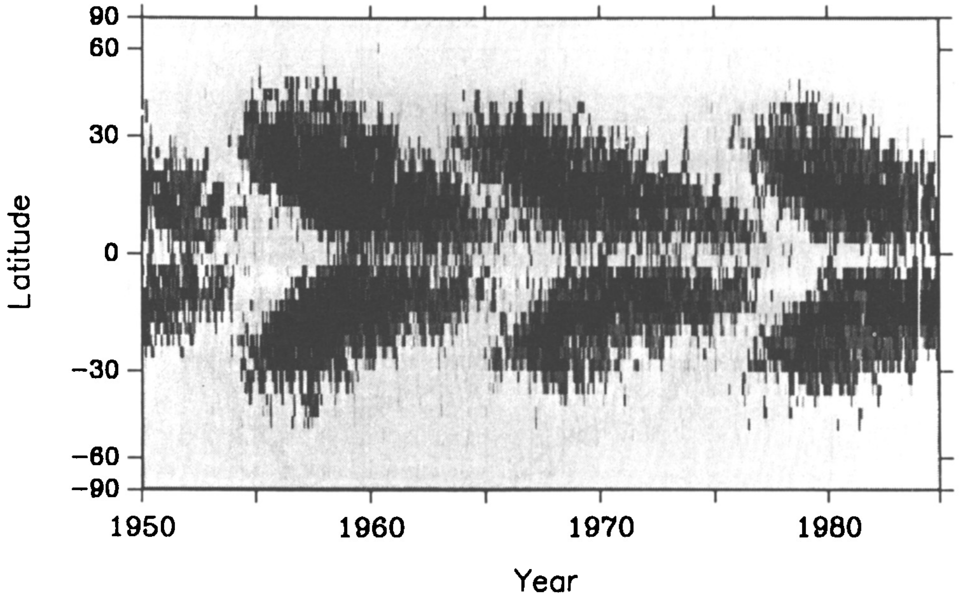

FIGURE 4. The butterfly diagram of calcium plage regions (courtesy J. Lean) indicates how solar cycles overlap for several years. Plage data are summed in bins of 0.05 of sine latitude for each month from 1950 to 1984. Darker shading indicates increased plage area (Harvey 1992).

latitude polar faculae from 1960–1985 (Callebaut & Makarov 1992). This may provide an important clue to the structure of the solar dynamo.

3. Large-scale velocity patterns

The most prominent feature of the large-scale solar velocity field is differential rotation (Figure 6). The variations of differential rotation with time are small and closely associated with magnetic field patterns. Various methods for determining the rotation rate give slightly different results. The main difficulties with tracers are temporal evolution and local flow fields. The problems with Doppler measurements are magnetic contamination of the line profile and systematic errors.

The presence of the torsional oscillation was first detected in Doppler measurements (LaBonte & Howard 1982) and later in magnetic tracers (Snodgrass 1991). The maximum shear of the plasma rotation occurs at the latitude of maximum magnetic flux emergence. The tracer pattern seems to be displaced equatorward by about 10 degrees. Recently the same signature has been found in tracer measurements (Komm *et al.* 1993) by correlating magnetic field maps obtained on consecutive days. Figure 7 shows that between 60 degrees and the equator a region of faster-than-average rotation moves equatorward from 1977 to 1986. Extended to higher latitudes this pattern supports the extended solar cycle concept.

Finally, if magnetic field patterns with only the largest size scales are considered, an interesting north-south asymmetry appears. Figure 8 (after Antonucci *et al.* 1990) shows the results of calculating the power spectrum of the time series of magnetic observations at each solar latitude. The frequency range plotted is only sensitive to hemispheric-scale patterns rotating with roughly the solar rotation period. During most of Cycle 21 the southern hemisphere rotated with a 28-day period, while the north had a 27-day rotation

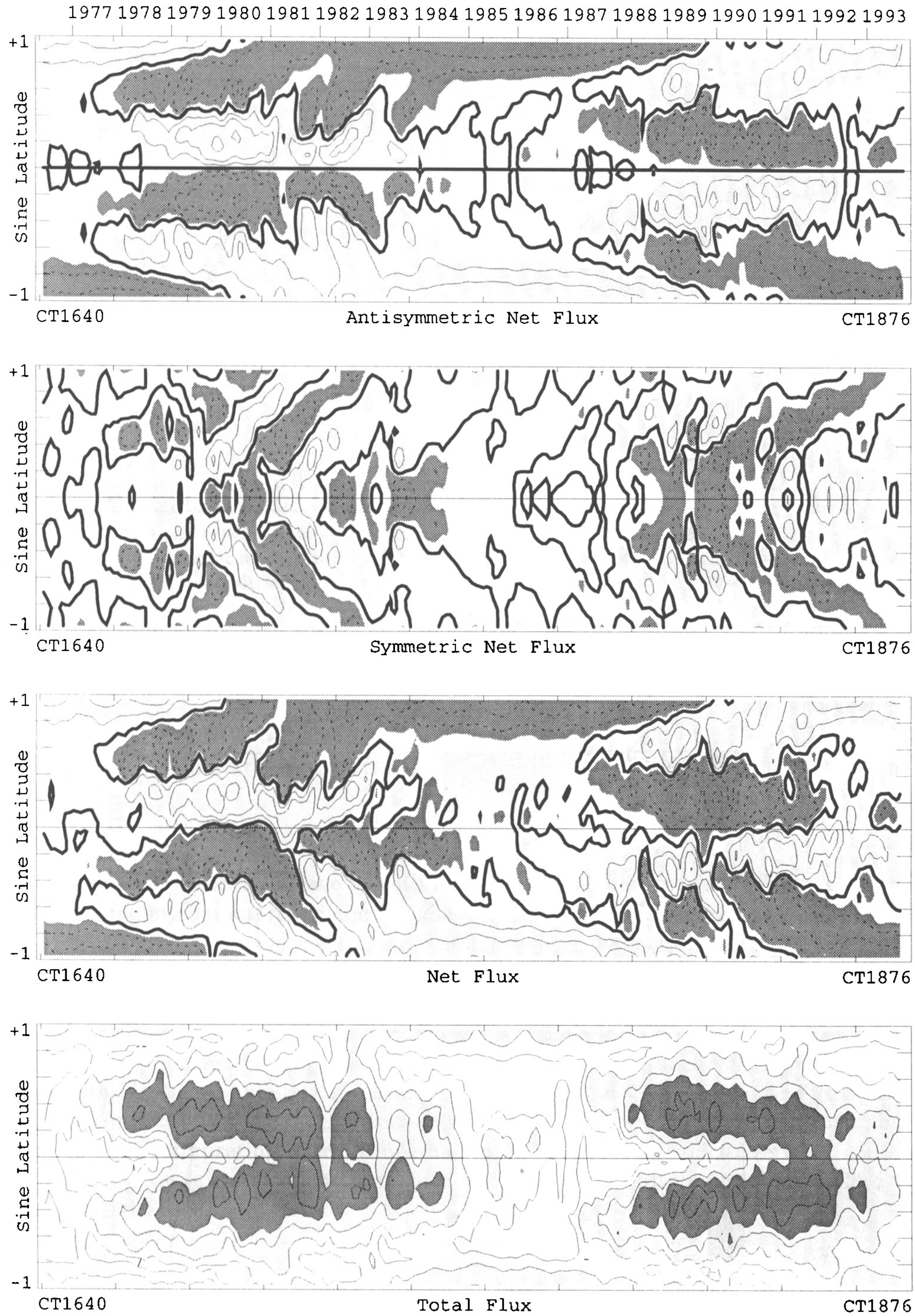

FIGURE 5. Zonal solar flux versus time since 1976. The bottom panel shows the total absolute flux computed for each Carrington rotation from WSO synoptic charts. The second panel shows the net flux computed for each rotation. The top two panels show the symmetric and antisymmetric components of the net flux. A three rotation triangular smoothing has been applied to the data. Note the precipitous decrease in flux in mid 1992.

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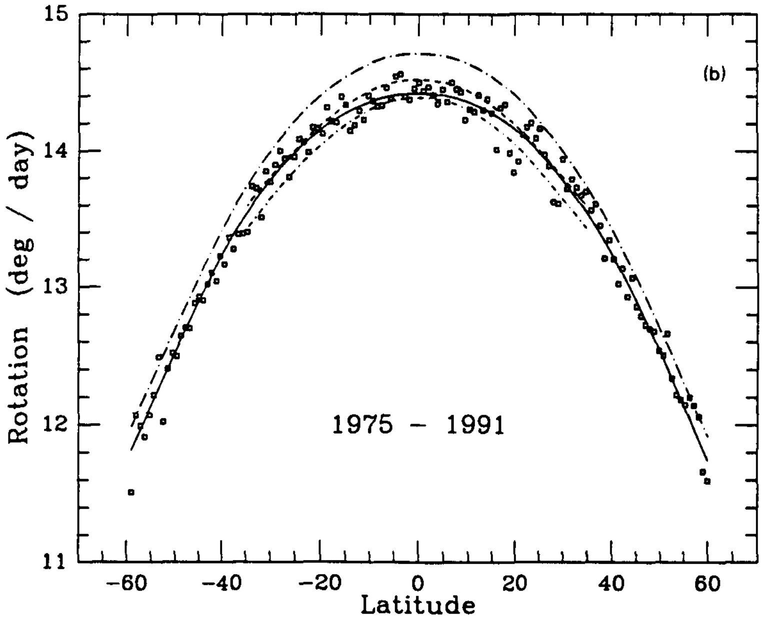

FIGURE 6. The average differential solar rotation rate (sidereal degrees/day) derived from correlations of the small-scale magnetic field pattern on consecutive days. Active regions have been excluded in this figure. The solid line shows a fit to the data. Rotation rates of other tracers are also shown: supergranules – dot-long dash; sunspot group – dot-short dash; and individual sunspots – short dash. The equatorial Doppler rotation is less than 3% faster than this magnetic rate (Komm *et al.* 1993).

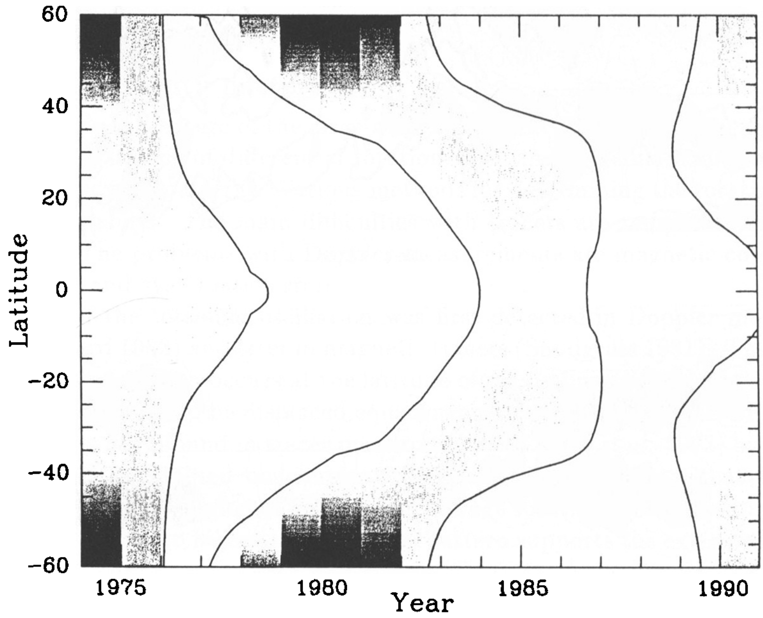

FIGURE 7. A map of the differences from the average differential rotation rate. Again active regions have been excluded (though the result is similar). The contour lines show 0 difference from the average curve shown in Figure 6. The darker regions rotate more rapidly than average (Komm *et al.* 1993).

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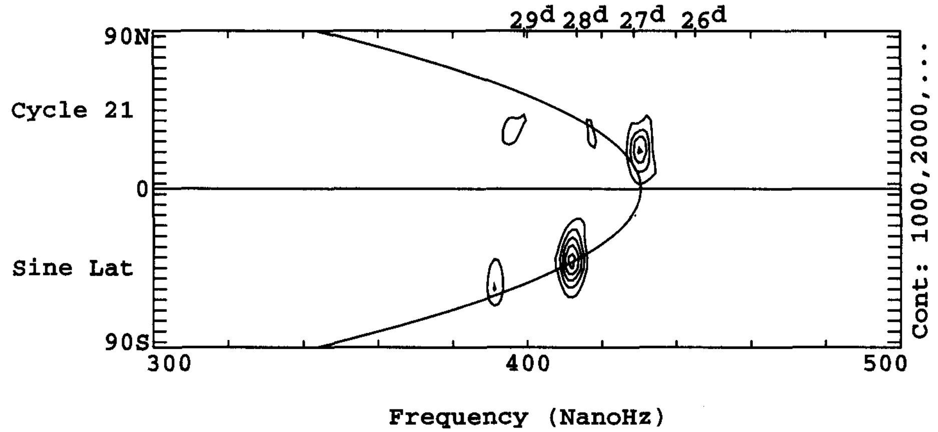

FIGURE 8. Solar rotation of the large-scale magnetic field for Solar Cycle 21. The power spectrum of the field at each latitude in the frequency range near the solar rotation period shows that the hemispheric scale patterns rotate at discrete rates that fall near the Newton & Nunn (1951) differential rotation curve. However the rates are different for Cycle 21 in the northern and southern hemispheres.

period. These are the most common periods observed in the interplanetary magnetic field since 1926. The same periods are seen in the photospheric field measured at Wilcox Solar Observatory (WSO), National Solar Observatory/Kitt Peak (KPNO), and Mt. Wilson Solar Observatory (MWSO) and in the computed coronal field. Cycle 22 has shown a similar strong asymmetry only during the declining phase of the cycle.

4. Conclusions

Unfortunately these data leave us with more questions than answers. Though progress is being made in characterizing the variable Sun, as shown throughout this volume, the key links between the cycle mechanism, the large-scale magnetic and velocity patterns, and the small-scale field elements are unclear. Evidence for the extended solar cycle makes the timeworn Babcock-Leighton model of the solar cycle appear more and more inadequate, even as a heuristic device. Dynamo models have problems reproducing the observations when accounting for helioseismologically determined differential rotation with depth. Until we understand physics of the generation and evolution of small-scale field, the connection to the mechanisms of solar variability will remain empirical at best. A real key for interpreting observations has to be determining which are truly causally related to the cycle mechanism. Somehow we must rouse ourselves enough to find the missing insight.

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