AN 'EXTENDED SOLAR CYCLE' AS OBSERVED IN Fe XIV

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Abstract. Investigation of the behavior of coronal intensity above the limb in Fe XIV emission (530.3 nm) obtained at the National Solar Observatory at Sacramento Peak over the last 23 years has resulted in the confirmation of a second set of zones of solar activity at high latitudes, separate from the Main Activity Zones (MAZ). Localized high-latitude intensity maxima, which I will call High-latitude Emission Features (HEF), are observed at 0.15 solar radii above the limb throughout the solar cycle. They persist long enough at a given latitude to be visible in long-term (e.g., annual) averages. I identify two types of HEF. Poleward-moving HEF, which may be identified with the 'Rush to the Poles' phenomenon seen in polar-crown prominences, were first seen to appear in this investigation near latitude 60° in 1978. In 1979 equatorward-moving HEF branched off from the poleward-moving HEF (which continued on to reach the pole in 1980) at a latitude of 70° to 80°. They evolved approximately parallel to the MAZ. Near solar minimum, these HEF evolved into the MAZ of cycle 22, and the emission continues its path towards the equator, where it should disappear soon.

Currently, it is clear that the pattern seen earlier is repeating. The poleward-moving HEF became apparent near the beginning of 1988 near 50° to 60° latitude. The northern poleward-moving HEF reached the pole and disappeared in 1990. The southern poleward-moving HEF moved more slowly, reaching the pole and disappearing in 1991. The equatorward-moving HEF that are the precursors of cycle 23 appeared in 1989 to 1990 and began to move approximately parallel to the MAZ of cycle 22. Based on inferences from previous cycles, we can expect these HEF to continue to the equator, with emission ceasing there near 2009. These recent observations increase the evidence for an 'extended' solar cycle that begins every 11 years but lasts for approximately 19–20 years.

1. Introduction

The accepted length of the solar activity cycle has been fixed at approximately 11 years for more than a century. Theoretical and empirical models (e.g., Babcock, 1961) have been developed to explain the single activity wave in each hemisphere, running from approximately 30° latitude to the equator. However, an inspection of 'butterfly diagrams' of sunspots will reveal that an overlap of up to three years may exist between adjacent cycles. The concept of overlapping cycles brings into question some of the single-valued models. This paper describes a high-precision observation of overlapping activity and suggests that this may represent evidence for an 'extended solar cycle' (cf., Wilson *et al.*, 1988) lasting up to 20 years.

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2. Previous Work

Wilson *et al.* (1988) reviewed some previous observations of coronal activity, ephemeral regions, and large-scale velocity patterns (particularly the so-called Torsional Oscillations (TO)), which have a bearing on the question of overlapping or extended solar cycles.

The possibility of observing activity in the visible near the poles would seem to be restricted to observations of phenomena above the solar limb, due to foreshortening effects. Thus, observations of the visible corona above the limb would hopefully yield more reliable results on the possibility of high-latitude activity. Unfortunately, since the corona is optically thin in the visible, and is on the order of a million times darker than the disk, such observations are extremely difficult. However, high-latitude activity near the poles was observed by Hansen *et al.* (1969) in the white-light or K corona. Unfortunately, their reported observations covered only the time immediately prior to solar maximum and thus only discovered that the well-known ‘Rush to the Poles’ phenomenon is visible in the white-light corona, at an altitude of 0.125 solar radii ($R_\odot$) above the limb. This phenomenon was first discovered through observations of prominences. These observations, showing local maxima in the standard deviation of coronal intensity occurring from 50 to 80° latitude, demonstrate the power of observing weak activity above the limb.

Fisher (1982) reported a case of high-latitude emission in the K corona (up to 75° latitude) in 1981. D. G. Sime (private communication) reports that a search for consistent high-latitude activity in the K corona has had negative results. He suggests that this may be a result of longer integration paths and/or greater heights of observation.

Sýkora (1980) analyzed 30 years of observations of the Fe XIV 530.3 nm coronal line. Unfortunately, these observations were obtained only up to latitude 60°. Nonetheless, he did observe emission extending to 40° in one or two cycles and 50° at the beginning of cycle 19. In an analysis similar to that contained here, he found that this ‘high-latitude’ emission moved continuously to the equator over the ensuing 11 years.

In another significant observational paper bearing on this subject, Martin and Harvey (1979) analyzed the global distribution of ‘ephemeral’ active regions, which live for less than a day and are approximately 10 Mm across. They demonstrate the existence of ‘high-latitude’ ephemeral regions having the polarity characteristics of solar-cycle-21 active regions, but occurring as early as the maximum of cycle 20. Unfortunately, their observations are severely affected by foreshortening effects for latitudes > 50–$60°$. This severely restricts the possibility of observing the continuity of solar-cycle processes to latitudes near the pole. Thus, Martin and Harvey (1979) were only able to speculate that it is ‘conceivable that two solar cycles might exist on the Sun at all times’.

A seminal, but highly controversial, paper on the subject of overlapping solar activity cycles lasting up to 22 years must be considered to be that of LaBonte and

Howard (1982) (LH). This paper reports the discovery of TO on the Sun. LH show that, at any given time of the solar cycle, the latitudinal variation of the rotation of solar surface is characterized by alternating patterns of latitude zones that rotate slightly faster or slower than the average differential rotation rate. Focusing on the zones that rotate faster than average, LH show that they appear at latitudes of $> 70^\circ$ near solar minimum, and they travel to the equator over the ensuing 22 years. Since the leading edge of the fast wave is observed to coincide with the appearance of magnetic flux in the sunspot zone, LH hypothesize that the wave shear ‘winds up the magnetic field ... caus(ing) emergence at the surface’.

Theoretical justification for TO’s has been provided by Yoshimura (1981). He demonstrates that dynamo theory can produce waves at the solar surface that have similar properties to the observed TO’s. However, he points out that there are significant differences between the observed and theoretical waves.

Further fueling the controversial nature of TO’s is a paper by Snodgrass and Howard (1985) that re-analyzes the rotational data of LH. They conclude that, instead of a continuous 22-year pattern, TO’s consist of only a polar spinup followed by a wave originating near 45° latitude that progresses toward the equator. Such a discontinuous pattern tends to cast doubt on the idea that TO’s are a global phenomena and would also tend to weaken any argument that TO’s imply the existence of solar cycles that overlap significantly.

Giovanelli (1985) analyzed the effect of sheared flux tubes on differential rotation and obtained a result strongly supportive of the TO observations. He found a continuous fast-wave pattern that starts near 70° latitude, travels to the equator over approximately 18 years, and can be superposed on the fast-wave pattern of TO’s.

Altrock (1988) gave a preliminary report on the observations of high-latitude emission in Fe XIV 530.3 nm that will be used in this paper.

Bumba, Rušin, and Rybanský (1990) analyzed 22 years of emission in Fe XIV 530.3 nm from a homogeneous data set obtained from several observatories. They found some evidence for overlapping cycles, but concluded that the coronal emission only started one year prior to the sunspot cycle at latitudes of 45°.

Altrock (1992) extended the work of Altrock (1988) up to 1992 and confirmed that the patterns of coronal emission observed earlier were continuing.

Minarovjech, Rybanský, and Rušin (1996) reviewed a similar data set extending over 58 years. They found a polar branch (‘Rush to the Poles’) but also deduced the presence of a second branch moving poleward from 40° that turns equatorward at 70°–80° and continues on down to the equator. This continuous process takes 17 years, or 22 years if the first polar branch is included.

3. Observations

Daily observations of the solar corona are made at the National Solar Observatory facility at Sacramento Peak with the Emission-Line Coronal Photometer (Fisher, 1973; Smartt, 1982). These observations have been made continuously in the Fe XIV 530.3 nm 'green' emission line, with the exception of short gaps due to weather or equipment failure, since July, 1975. An earlier period of observations covered May 1973 to February 1974 (the *Skylab* era). The 40-cm-aperture coronagraph is used to form an occulted image of the corona, which passes through a narrow-band filter that spectrally discriminates at 100 kHz between the corona in an emission line and a continuum wavelength. This technique allows the sky-background contribution to be electronically subtracted. As a result, the data are frequently reproducible to less than one millionth of the brightness of the center of the solar disk at 530.3 nm. Scans are routinely made in skies as bright as 200–400 millionths.

The entrance aperture of diameter 1.1 arc min is scanned around the limb at radius vectors of 1.15, 1.35 and, variously, 1.25, 1.45, or 1.55 $R_\odot$. The output is sensed by a photomultiplier, digitized and recorded every 3° of latitude. Normally, only one set of scans is made per day. The current instrument also provides data in Fe X (637.4 nm) and Ca XV (569.4 nm).

Errors in the scan radius up through November 1977 caused the nominal $R/R_\odot = 1.15$ scan radius, for example, to vary throughout the year from approximately 1.15 to 1.20. Since the local intensity maxima at higher latitudes discussed below may be more concentrated to the lower radii, this could have the effect of producing fewer such maxima in these early years. In addition, since the signal is generally noisier at the larger radii, it is more difficult to detect the maxima, particularly the weaker maxima at high latitudes. The overall effect would be to reduce the visibility of such maxima at high latitudes. Nonetheless, the analysis will demonstrate the presence of (weakened) responses during this period consistent with the thesis of this paper.

4. Analysis

Inspection of individual daily scans, such as Figure 1, showed many instances of local intensity maxima at latitudes higher than the mid- to low-latitude Main Activity Zones (MAZ) of the solar cycle. Note the two high-latitude intensity maxima in Figure 1. The temporal behavior of any given high-latitude maximum is similar to that of coronal active regions occurring above the MAZ. The activity persists at an approximately constant level during the limb passage, resulting in a local maximum that slowly increases in intensity over 3 to 4 days and then disappears over a similar time scale. A comparison of emission-line data with K-coronameter data shows that many emission-line features in the MAZ are associated with coronal streamers (cf., Sime, Fisher, and Altrock, 1985). Although the properties of the

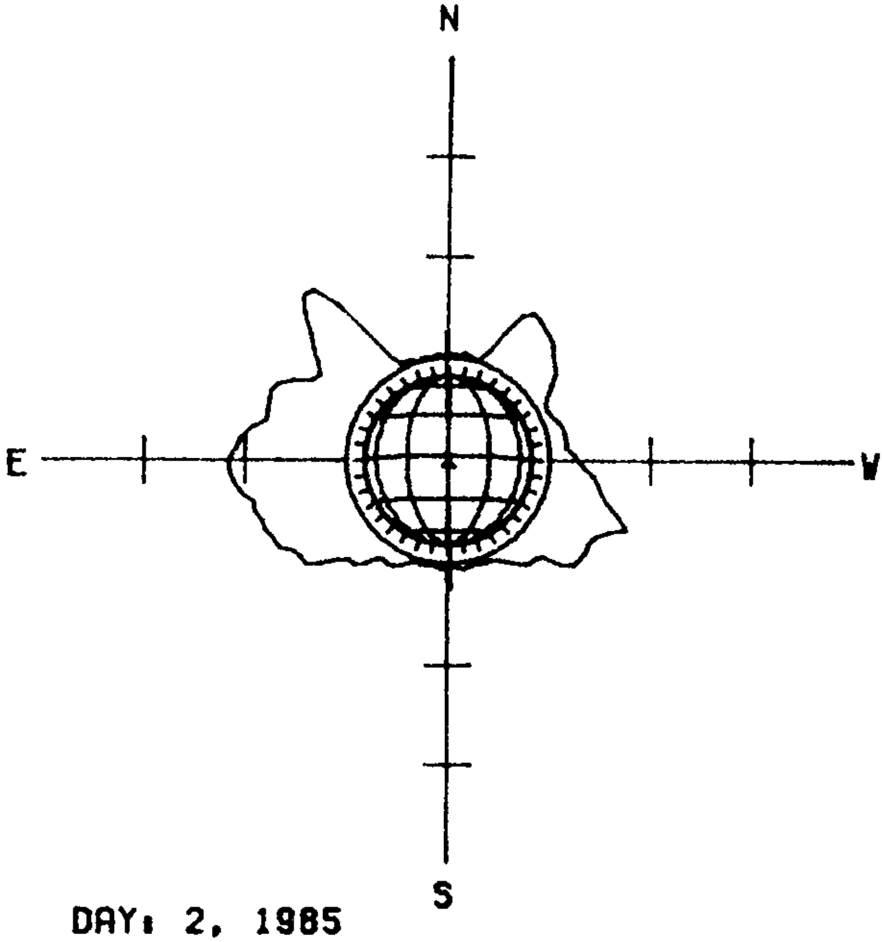

Figure 1. Sample coronal scan in Fe XIV 530.3 nm at 1.15 $R_\odot$ obtained at the National Solar Observatory facility at Sacramento Peak on January 2, 1985, with the 40-cm-aperture coronagraph and the emission-line coronal photometer. This is a polar plot of intensity with zero intensity at the unit circle of radius 5 millionths of the brightness of the disk. Note the high-latitude coronal emission regions in the northern hemisphere.

emission-line features in the MAZ and at high latitudes appear to be similar, I will refer to the high-latitude features as High-latitude Emission Features (HEF).

A more detailed examination of individual scans covering the last 23 years resulted in finding a systematic behavior of the HEF. They first appeared in zones of latitude near 70–80° around 1979, and their locus drifted toward the equator at a rate of approximately 5–6° yr^{-1}.

The first attempt to quantify these random observations of HEF on individual days was to compute annual average scans. In this procedure each daily scan in the Fe XIV line at 1.15 $R_\odot$ is simply summed into a register, and the final sum is

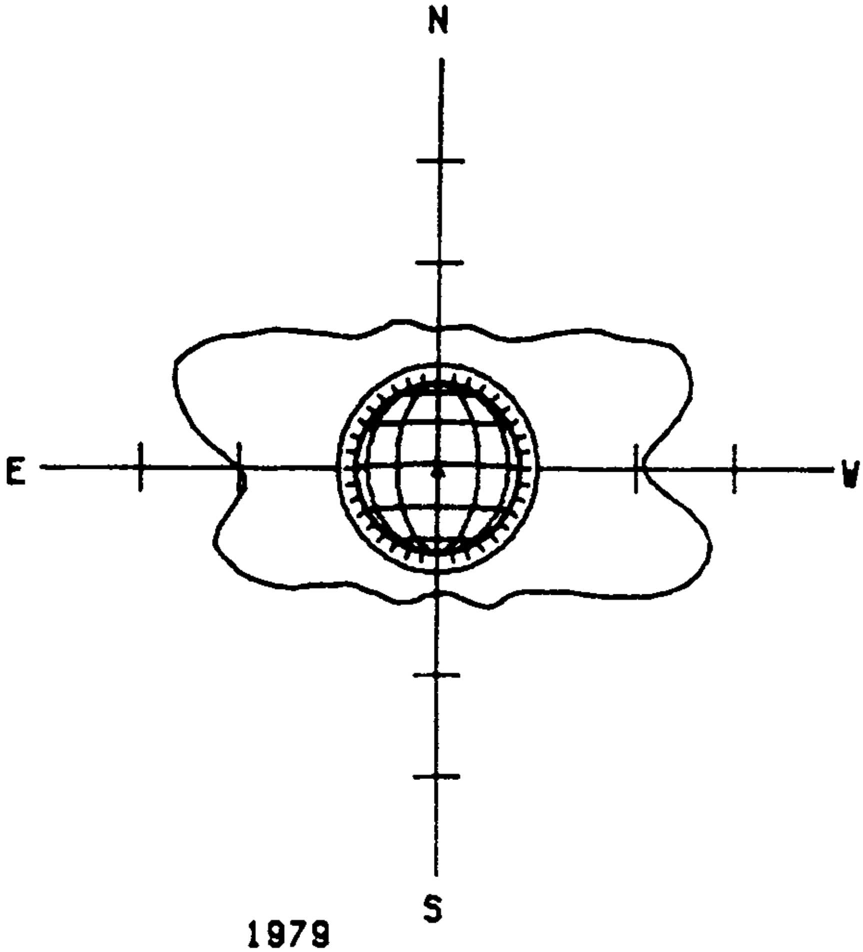

Figure 2. As in Figure 1, but an unweighted average of the best scans on each of 216 days in 1979. Note the intensity maxima produced by the main activity zones of the solar cycle and also the maxima produced by high-latitude coronal emission regions.

divided by the number of days observed. Figure 2 demonstrates clearly that not only are the MAZ of the solar cycle visible in 1979, but the HEF persist sufficiently over a year at the same latitude to produce significant local intensity maxima in the average.

The next step was to produce a single graph, similar to a ‘butterfly diagram’, that would demonstrate the solar-cycle behavior of the HEF. For this, a program was used that searches for local intensity maxima in the best 1.15 $R_\odot$ Fe XIV scan made each day. The data base used for this paper contains 4540 days having usable data. The algorithm searches each scan for features in which the intensity increased monotonically over two 3° latitude intervals and then decreased monotonically

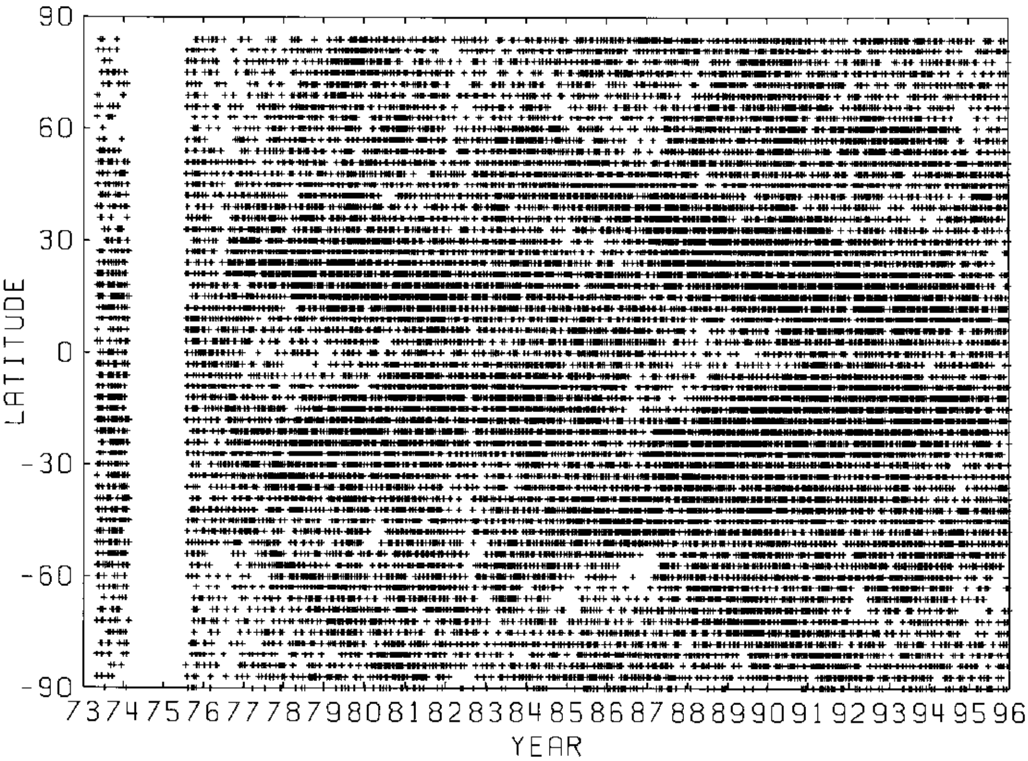

Figure 3. The latitude of each local intensity maximum of all usable scans as in Figure 1 from 1973 through 1995. Each of the 33 322 maxima is plotted as a single plus-sign.

over the next two. 33 322 intensity maxima were found by this procedure. Figure 3 shows the results. Each point represents a single intensity maximum. The MAZ of cycles 21 and 22 are clearly visible. There is evidence for patterns of HEF, but the precise character of the patterns is difficult to discern from this figure. It does seem clear, however, that a ‘Rush to the Poles’, similar to that seen by Hansen *et al.* (1969), occurs between 1976 and 1979 or 1980 (particularly clear in the southern hemisphere in 1978 and 1979) and between 1988 and 1991 or 1992.

To further display the solar-cycle behavior of the HEF, the density of points in Figure 3 is calculated at each latitude, averaged over a given time interval. This process allows us to correct Figure 3 for days of missing data by dividing by the number of good observing days in the given time interval. This is a *necessary and important step* in order to be able to correctly interpret the data. Figure 4 shows the density of HEF averaged over a year. The MAZ of cycles 20, 21, and 22 are clearly seen. Equatorward-moving HEF are first seen between 30 and 60° latitude in 1973. The unfortunate gap in 1974 and 1975 makes it difficult to infer solar-cycle patterns approaching solar minimum, but there is an indication that the equatorward-moving HEF seen in 1973–1975 continue across solar minimum and

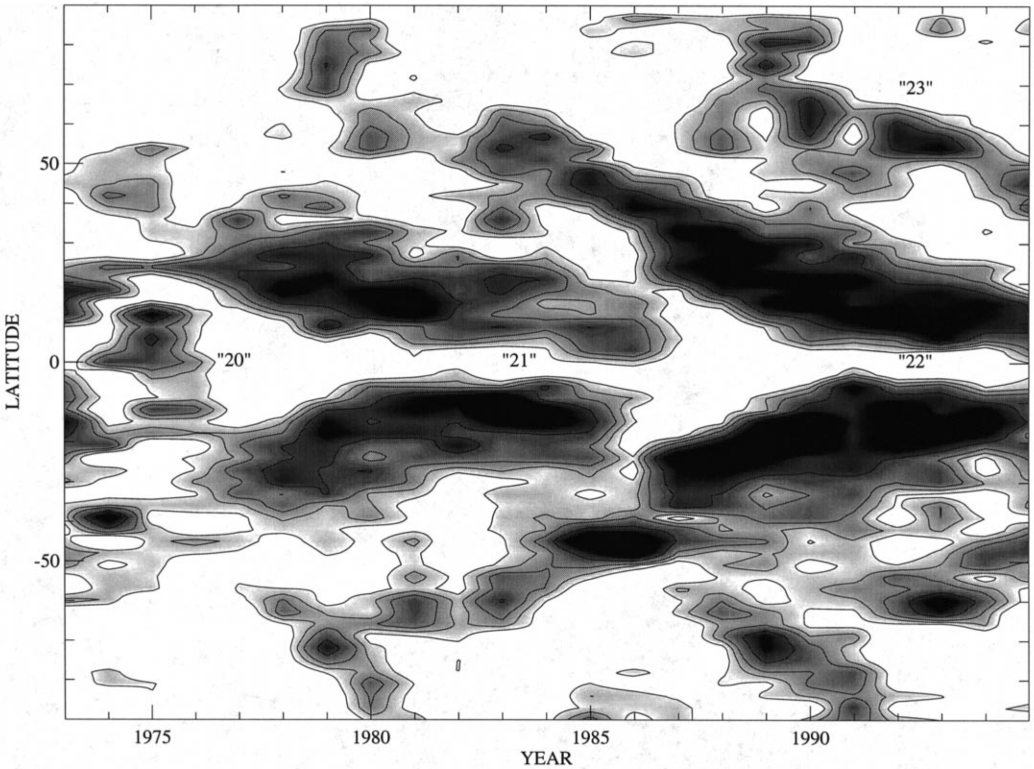

Figure 4. Contours of annual averages of the density of points in Figure 3. See text for detailed definition. Note the high-latitude emission features beginning in 1979 and 1989.

become the MAZ of cycle 21. This inference is made more difficult by the fact that coronal activity at the end of cycle 20 appears to be much less than that at the end of cycle 21; however, see the discussion of early observations at the end of Section 3.

Poleward-moving HEF are also seen in Figure 4. The observations of Hansen *et al.* (1969) indicated only that a maximum of *variability* of activity propagated towards the poles; this study confirms that it is the HEF that are propagating. A splitting of this process, resulting in the appearance of equatorward-moving HEF, first occurs near 70 to 80° latitude in 1979. Near solar minimum, the equatorward-moving HEF evolved into the MAZ of cycle 22, which continue their monotonic path towards the equator, where they should disappear shortly.

The poleward-moving HEF preceding the maximum of cycle 22 became apparent near the beginning of 1988 near 60° latitude in the north and south hemispheres. The northern poleward-moving HEF reached the pole during late-1989 to 1990, and north-polar emission effectively ceased near the end of 1990. The southern poleward-moving HEF moved more slowly, and the southern-most emission regions reached the pole in mid-1991. The equatorward-moving HEF that are the precursors of sunspot cycle 23 became clearly established in the northern hemisphere near the beginning of 1990 at approximately 70° latitude. The appearance of the equatorward-moving HEF in the south was less dramatic but probably began in mid-1990 near 70°. The centers of the equatorward-moving HEF are currently near 45° latitude. Based on inferences from previous cycles, we can expect the equatorward-moving HEF to continue monotonically towards the equator, becoming the MAZ in a few years.

Finally, I note the appearance of ultra-high-latitude activity near the poles from 1985 to 1987. There is a possible analog of this phenomenon in 1974, but it appeared in only one hemisphere and disappeared in 1975. The present phenomenon appeared in both hemispheres. It is not at all clear if such activity is connected with the ‘Extended Solar Cycle’ concept; however, it appears to be another new class of activity. Perhaps it corresponds to the polar vortex of Snodgrass and Howard (1985) or to the maximum of the axisymmetric component of the radial polar magnetic field found by Stenflo (1988).

The above properties clearly are occurring in both hemispheres at approximately the same time. Thus, in order to increase the signal-to-noise value, it seems reasonable to produce north–south averages of the maxima and their averages. Figure 5 demonstrates the results. The properties of the ‘Extended Solar Cycle’ are clearly seen.

Figures 6 and 7, showing approximately-semi-annual (actually 7-rotation, or 189-day) averages of Figure 3, indicates that the above properties do not disappear when shorter averages are taken. In Figure 6 one can see some evidence of secondary poleward surges of HEF; e.g., from approximately 1981 into 1982, starting from about 40° south and ending at about 75° south. However, the density of the surges are always minimum when compared with the density of the equatorward-moving HEF.

5. Discussion

Stenflo (1988) shows a plot of the axisymmetric component of the radial polar magnetic field from 1960 to 1985 that has the appearance of being an extended solar cycle (see also the discussion of this by Stenflo (1992)). However, if the observations of this paper are overlaid on Stenflo’s plot, the only regions of similarity are in the MAZ and in the ‘ultra-high-latitude’ activity discussed in Section 4. The HEF discussed here begin at much higher latitudes and move equatorward much faster than the field maxima shown by Stenflo.

This paper has not attempted to investigate the longitudinal variation of this phenomenon, but only the long-term latitudinal variation. Such an investigation is conducted in the spirit of many previous investigations of solar cycle variations; e.g., the ‘butterfly diagram’ of sunspot latitudes. Such studies are of interest even

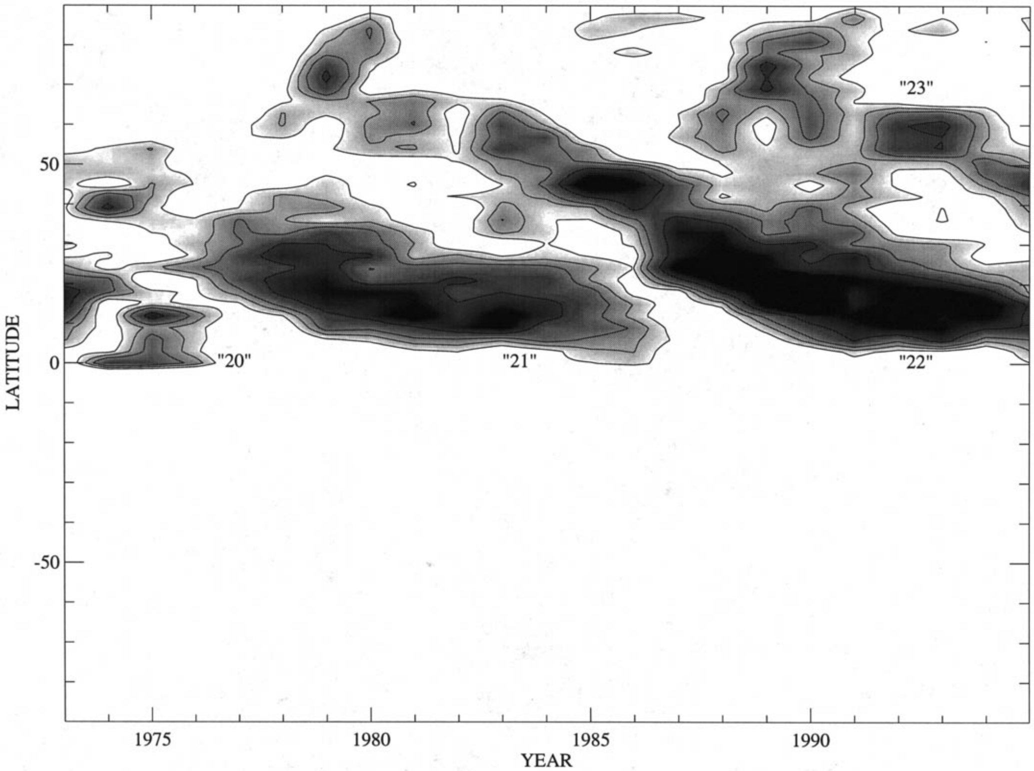

Figure 5. North–south average of Figure 4.

when strong longitudinal variation is suspected or known; e.g., active longitudes. However, the longitudinal variation of such activity is obviously of interest.

Hara (1996) has attempted to identify the HEF. He compares the intensities in annuli at 1.03 $R_\odot$ obtained from soft X-ray *Yohkoh* SXT images in the declining phase of the solar cycle (1992 to 1994) with the observations used in this paper and finds that he can also see HEF at the same position angles. He then refers to the original SXT images and indicates that the HEF appear to be associated with 'polar-side legs of large-scale coronal loops'. He notes that the HEF must be large-scale structures because they are seen at the limb for 5 to 10 days ('limb-lifetime'). This is similar to the limb-lifetime obtained in this paper (6 to 8 days), but in Section 4 I noted that low-latitude emission regions in the MAZ, associated with active regions, *also* have similar limb-lifetimes. Thus, one cannot discriminate between HEF and MAZ structures on the basis of limb-lifetime.

Inspection of Hara's Figure 9.3, which shows the SXT images, indicates that perhaps the most important feature of these HEF in the declining phase of the solar cycle is that they are the *structures that define the edge of the polar coronal holes*. Indeed, in some cases these structures do appear to be loop-like, but in those cases

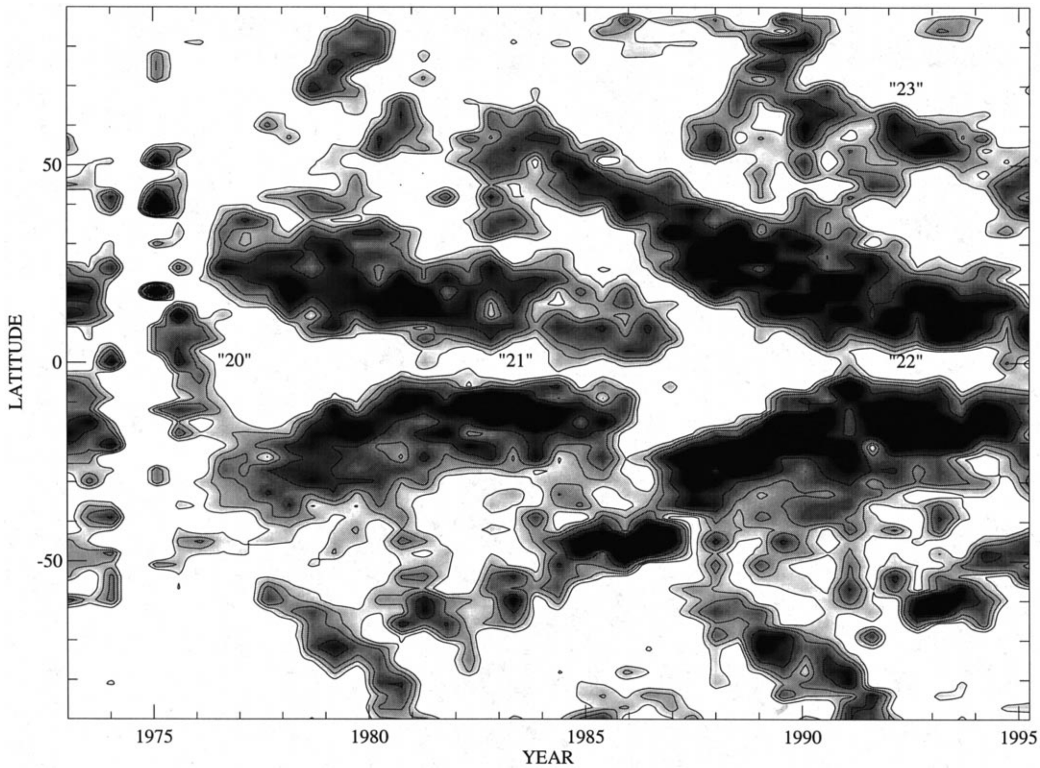

Figure 6. As in Figure 4, except for 189-day (7-rotation) averages.

they appear more likely to be the base of streamers. In other cases, no structure can be inferred, and the HEF appear just as amorphous emission regions. There seems to be no doubt, however, that the poleward shape of the HEF in the declining phase of the solar cycle is defined by the magnetic fields that define the edge of the polar coronal holes. Thus, the HEF in the declining phase of the solar cycle represent a very fundamental aspect of the solar cycle: the expansion of the polar coronal holes. So far, the nature of the HEF in SXT data as they merge into the MAZ during solar minimum and the rise of the next cycle has not been determined, but this is an obvious next step.

The observations and conclusions given in this paper are completely consistent with those given in earlier studies (Altrock, 1988, 1992; Wilson *et al.*, 1988). The nature of the high-latitude activity has not changed since these studies. There appear to be compelling reasons for reconsidering the theoretical basis of the solar activity cycle, in order to allow two cycles to be in progress most of the time.

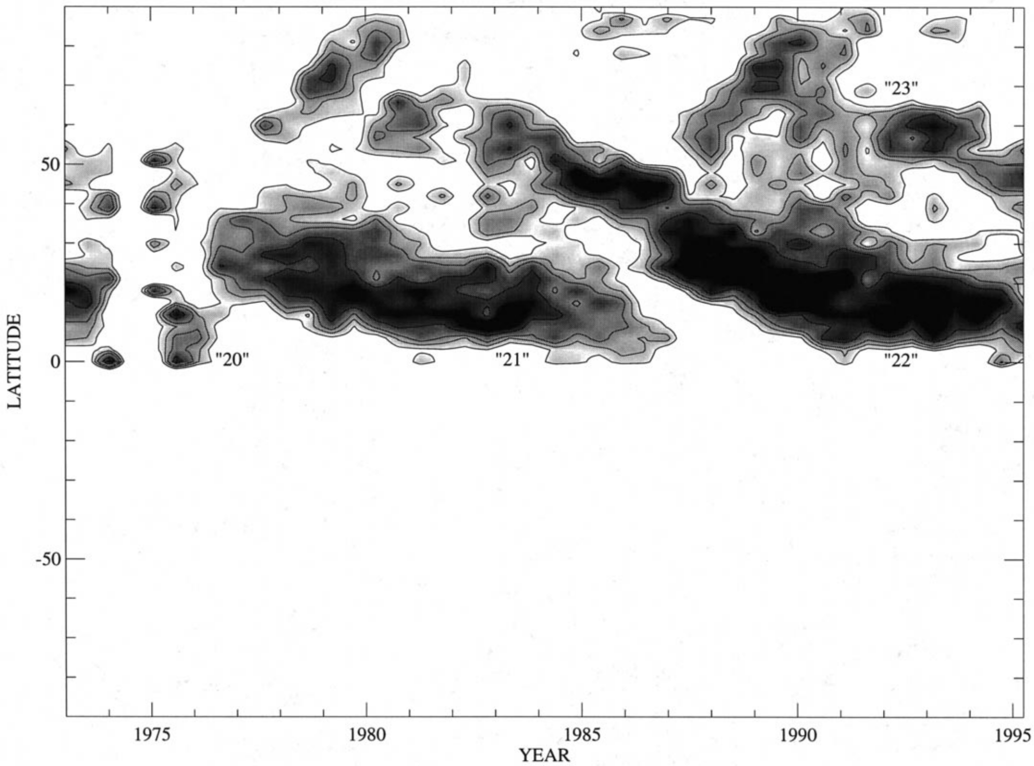

Figure 7. As in Figure 5, except for 189-day (7-rotation) averages.

6. Conclusions

I have presented evidence that the well-known 2–3 year overlap between solar cycles is much greater than any previous observations of lower-atmospheric activity have suggested. There is evidence that solar cycle 22 started in approximately 1979 near 70–80° latitude, and thus will last for approximately 17–18 years. Similarly, cycle 23 appears to have started in 1990. These conclusions appear to fit perfectly into the observations and explanations of TO's by, e.g., LH. Whereas they could only note that TO's did not seem to produce activity (by compressing the magnetic field) until they reached approximately 30° latitude, these observations appear to support the more logical conclusion that TO's produce activity at all latitudes. In fact, if Giovanelli's (1985) summary chart of TO latitude as a function of time is plotted on top of these data, it passes directly through the HEF from 1979 to 1985. In addition, I have clarified the observations of a 'Rush to the Poles' in the corona by Hansen *et al.* (1969) as being due to HEF. Finally, I have noted the unexplained appearance near the poles in 1985 of ultra-high-latitude activity.

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