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Investigation of the behavior of coronal intensity above the limb in Fe XIV emission (5303Å) obtained at Sacramento Peak Observatory over the last fourteen 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 emission peaks in Fe XIV 5303Å are observed through most of the cycle at high latitudes in individual daily scans, annual averages, and solar-cycle summary plots of the location of all local maximum intensities at $0.15R_{\odot}$ above the limb. These peaks evolve slowly over a period of days, consistent with the rotation over the limb of stable features, in a similar way to the lower-latitude peaks that are connected with active regions. The high-latitude coronal activity zones first appear at latitudes of 70 to 80°, 2-3 years after solar minimum. They evolve approximately

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VARIATION OF SOLAR CORONAL FE XIV 5303Å EMISSION DURING SOLAR CYCLE 21

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ABSTRACT

Investigation of the behavior of coronal intensity above the limb in Fe XIV emission (5303Å) obtained at Sacramento Peak Observatory over the last fourteen 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 emission peaks in Fe XIV 5303Å are observed through most of the cycle at high latitudes in individual daily scans, annual averages, and solar-cycle summary plots of the location of all local maximum intensities at $0.15R_{\odot}$ above the limb. These peaks evolve slowly over a period of days, consistent with the rotation over the limb of stable features, in a similar way to the lower-latitude peaks that are connected with active regions. The high-latitude coronal activity zones first appear at latitudes of 70 to 80°, 2-3 years after solar minimum. They evolve approximately parallel to the MAZ, with the average latitude decreasing at a rate of roughly 5-6° per year. After their appearance, they are present more or less continuously until the following solar minimum. Near solar minimum, the high-latitude coronal activity zones that appeared after the beginning of Cycle 21 monotonically evolved into the MAZ of Cycle 22. It thus appears that we have evidence for parallel overlapping solar cycles that begin every 11 years but last 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 new 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 the 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. In addition, some 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.

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.

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 less bright than the disk, such observations are extremely difficult. Sýkora (1980) analyzed 30 years of observations of the Fe XIV 5303Å 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. Here again, we see some further indication of overlapping solar cycles extending to higher than classical latitudes, but limited by the observations.

High-latitude activity near the poles has also been 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 $0.125R_\odot$ above the limb. This phenomenon was first discovered through observations of prominences, and it has been assumed to be connected with the arrival at the pole near solar maximum of magnetic flux associated with "follower" sunspots from the previous solar cycle (and thus a change in the background global magnetic field polarity). Observations of high-latitude activity that might be connected with overlapping solar cycles before, during, or after this epoch were either not attempted or not reported. However, 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) has also 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.

equator at a rate of approximately 5-6°/year reaching approximately 20-30° by 1987.

The first attempt to quantify these random observations of HLAR on individual days was to compute annual average scans. In this procedure each daily scan in the Fe XIV line at $1.15R_\odot$ is simply summed into a register, and the final sum is divided by the number of days observed. Figure 1b demonstrates clearly that not only are the MAZ of the solar cycle visible in 1979, but the HLAR persist sufficiently over a year at the same latitude to produce significant local intensity maxima in the average.

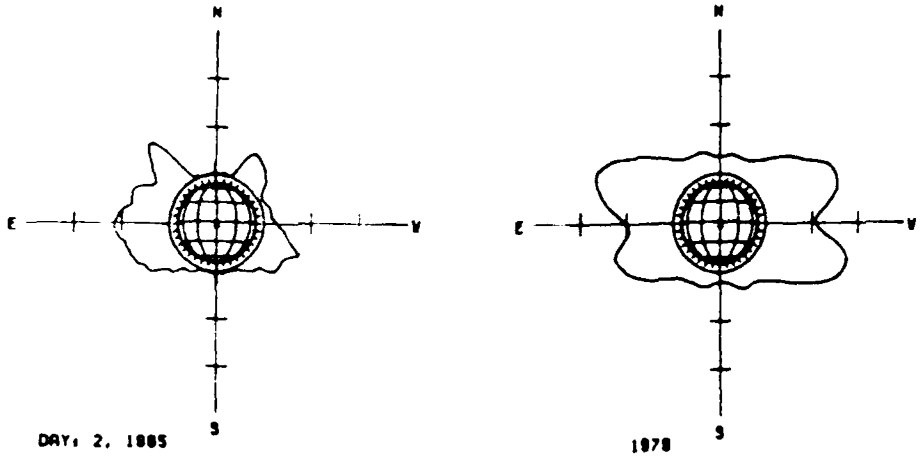

Fig. 1. a (left). Sample coronal scan in Fe XIV 5303Å at $1.15R_\odot$ obtained at the National Solar Observatory facility at Sacramento Peak on January 2, 1985, with the 40cm-aperture Coronagraph and Photoelectric Coronal Photometer. This is a polar plot of intensity with zero intensity at the unit circle of radius 5 millionths of the brightness of the disk. Note the high-latitude coronal active regions in the northern hemisphere. b (right). As in a., 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 active regions.

The next step was to produce a single graph, similar to a "butterfly diagram", that would demonstrate the solar-cycle behavior of the HLAR. For this, a program was used that searches for local intensity maxima in the best $1.15R_\odot$ Fe XIV scan made each day. The data base contained more than 2,450 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 over the next two. Over 16,600 intensity maxima were found by this procedure. Figure 2a shows the results. Each point represents a single intensity maximum. The MAZ of Cycle 21 are clearly visible. There is evidence for patterns of HLAR, but the precise character of these 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). The possible association of HLAR with prominences will be addressed in a subsequent paper.

In a further attempt to display the solar-cycle behavior of the HLAR, the density of points in Figure 2a is calculated at each latitude, averaged over some

3. OBSERVATIONS

Daily observations of the solar corona are made at the National Solar Observatory facility at Sacramento Peak (NSO/SP) with the Photoelectric Coronal Photometer (Fisher, 1973; Smartt, 1982). These observations have been made continuously in the Fe XIV 5303Å "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 40cm-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 5303Å. Scans are routinely made in skies as bright as 200-400 millionths.

The entrance aperture of 1.1 arcmin diameter is scanned around the limb at radius vectors of 1.15, 1.35 and, variously, 1.25, 1.45 or 1.55 solar radii ($R_\odot$). 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 (6374Å) and Ca XV (5694Å)

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.

4. ANALYSIS

Inspection of individual daily scans, such as Figure 1a, 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 1a. The temporal behavior of any given high-latitude maximum is similar to that of coronal active regions occurring over 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). Due to the similarity of the behavior of emission-line features in the MAZ and at high latitude, I will refer to the high-latitude features as *High-Latitude Active Regions (HLAR)*.

A more detailed search of individual scans covering the last 11 years resulted in finding an evident systematic behavior of the HLAR. They occur in zones of latitude that first appear near 70-80° latitude around 1979 and drift toward the time interval. Figure 2b shows the density of HLAR averaged over a year. We again see clearly the MAZ from 1977 to the present. We also see the MAZ of Cycle 20, beginning near latitudes of 10-20° in 1973 and ending near the equator in 1976. Different versions of this graph also show HLAR between 30 and 60° latitude in 1973 (some evidence of this is seen in Figure 2a). 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 HLAR in 1973-1975 may continue across solar minimum and become the MAZ of Cycle 21. This inference is made more difficult by the fact that activity at the end of Cycle 20 was much less than that nearing the end of Cycle 21.

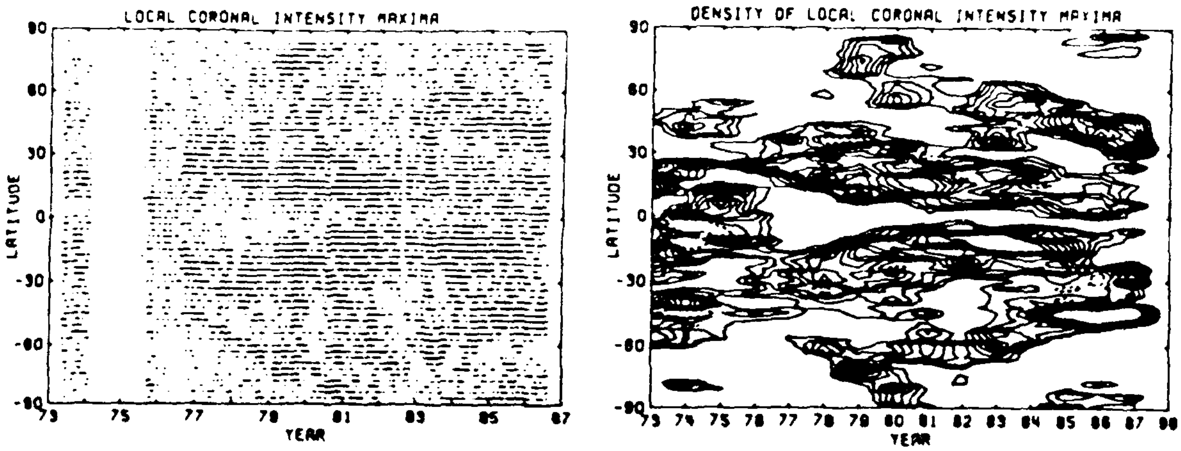

Fig. 2. a (left). The latitude of each local intensity maximum of all usable scans as in Figure 1a from 1973 through 1987. Each of the 17,000 maxima is plotted as a single point. b (right). Contours of annual averages of the density of points in a. See text for detailed definition. Note the high-latitude activity zones extending from 1979 through the present.

Figure 2b also confirms the "rush to the poles" phenomenon seen by Hansen et al. (1979). Their observations indicated only that a maximum of *variability* of activity propagated towards the poles; this study confirms that it is the HLAR that are propagating. A splitting of this process occurs near 70 to 80° latitude in 1979, and the lower-latitude branch is seen to migrate continuously toward the equator up through the present. By late 1987 the HLAR zones reached latitudes of 20 to 30°, similar to the behavior seen at this time in Cycle 20, but with much more activity. It seems reasonable to expect that, similar to the above speculative inferences from the last solar minimum, the HLAR zones will continue to migrate towards the equator and become the MAZ of Cycle 22.

Finally, we note the appearance of ultra-high-latitude activity near the poles in 1985, which persists into 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 appears in both hemispheres and has persisted for three years. If Wilson et al. (1988) are correct in suggesting that solar-cycle activity first appears at the poles, and remembering that the general level of activity at this solar minimum is much higher than at the previous minimum, these data suggest that the beginning of Cycle 23 may have occurred near the poles in 1985.

5. CONCLUSIONS

I have presented evidence that the well-known 2-3 year overlap between solar cycles is much greater than any previous observations of activity have suggested. I conclude that Solar Cycle 22 started in approximately 1979 near 70-80° latitude, and thus will last for approximately 19-20 years. This conclusion appears to fit perfectly into the observations and explanations of TO's by, e.g., LaBonte and Howard (1982). 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 high-density region of HLAR from 1979 to the present. In addition, I have clarified the observations of a "rush to the poles" in the corona by Hansen et al. (1979) as being due to High-Latitude Active Regions (although the nature of this activity has not been definitely established). Finally, I have noted the possible appearance near the poles in 1985 of Solar Cycle 23.

6. FUTURE WORK

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., LaBonte and Howard (1982). Such studies are of interest even when strong longitudinal variation is suspected or known; e.g., active longitudes. However, the longitudinal variation of such activity is obviously of interest, and future papers will address this point. In particular, identification of the specific features that make up the longitudinal averages will be investigated.

Another area of future investigation will be the behavior of these features during limb passage. If the features are streamers, and more-or-less radially oriented, then, to the extent that they may be visible when the streamer base is not on the limb, we may see a latitudinal variation of the intensity maximum during limb passage. Such an effect has been identified by Fisher (private communication) in the K corona. Any such effect in the Fe XIV data is expected to be significantly reduced relative to the white light data, due to the much-stronger dependence of the Fe XIV emission on electron density and the consequent much-steeper radial variation of its intensity. The intensity of an Fe XIV feature would be expected to peak very strongly at the time of limb passage and fall very quickly into the noise before and after limb passage. Any such latitude variation would be manifested as a slight smearing toward the pole of the location of the intensity maximum during limb passage. Correction for such an effect, if it exists, could result in a sharpening of the activity bands at higher latitudes. This effect cannot produce parallel activity zones separated by a minimum of activity, such as has been found in this study.

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