THE VARIATION OF SOLAR FE XIV AND FE X FLUX OVER 1.5 SOLAR ACTIVITY CYCLES

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ABSTRACT

This paper presents a new source of data on the solar output, namely "limb flux" from the one- and two-million degree corona. This parameter is derived from data obtained at the National Solar Observatory at Sacramento Peak with the 40 cm coronagraph of the John W. Evans Solar Facility and the Emission Line Coronal Photometer. The limb flux is defined to be the latitude-averaged intensity in millionths of the brightness of disk center from an annulus of width 1.1′ centered at a height of 0.15 $R_\odot$ above the limb of emission from lines at 6374Å (Fe X) or 5303Å (Fe XIV). Fe XIV data have been obtained since 1973 and Fe X since 1984. Examination of the Fe XIV data shows that there is ambiguity in the definition of the last two solar activity minima, which can affect the determination of cycle rise times and lengths. There is an indication that a constant minimum or basal corona may exist at solar minimum. Cycle 22 has had a much faster onset than Cycle 21 and has now overtaken Cycle 21. The rise characteristics of the two cycles were very similar up until Jul-Aug 1989, at which time a long-term maximum occurred in Fe X and Fe XIV, which could possibly be the "solar maximum". Another maximum is developing at the current time. Cycle 21 was characterized in Fe XIV by at least 4 major thrusts or bursts of activity, each lasting on the order of a year and all having similar maximum limb fluxes, which indicates that coronal energy output is sustained over periods in which the sunspot number declines significantly. Dramatic increases in the limb fluxes occur from minimum to maximum, ranging from factors of 14 to 21 in the two lines. Two different techniques to predict the epoch of solar maximum have been applied to the Fe XIV data, resulting in estimates of Apr 1989 (± 1 mo) and May 1990 (± 2 mo).

INTRODUCTION

There is currently a great deal of interest in evaluating various ground-based observations of the Sun that may be of use as inputs to models of the Earth's atmosphere. Until such time as full-spectrum solar observations are available from space, these ground-based observations will be the main source of information on how the solar output affects the atmosphere. This paper presents a new source of data on the solar output, namely parameters related to flux from the one- and two-million degree solar corona. I will present information on the observations and their calibration, their behavior throughout the solar cycle, comparison with other similar observations and how such observations may be used to predict the epoch of solar-activity maximum.

OBSERVATIONS

Observations are made at the National Solar Observatory site at Sacramento Peak with the Fisher-Smartt Emission Line Coronal Photometer (ELCP) (Smartt, 1982). This instrument photoelectrically records the solar corona when fed with the John W. Evans Solar Facility 40cm Coronagraph. It operates at high precision due to its ability to subtract the sky background from the signal in emission lines through use of a lockin amplifier oscillating at a rate of 100 kHz between the continuum and the lines at 6374Å (Fe X) and 5303Å (Fe XIV), which are formed at approximate temperatures of 1 and 2 MK, respectively. Reproducibility of successive scans is frequently to less than 1 millionth of the brightness of the solar disk at the given wavelength. Scans are routinely made in skies as bright as 200-400 millionths. A 1.1′ aperture is scanned around the limb daily at 1.15 $R_\odot$ (data at other heights and in Ca XV 5694Å will not be discussed in this paper). The output of the ELCP is sensed by a photomultiplier, digitized and recorded every 3° of latitude.

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Scans in Fe XIV have been made since 1973, and in Fe X since 1984 (scans of Fe X were made in 1983 but have not yet been examined in detail).

Absolute intensities in millionths of the brightness of the center of the disk at 6374Å and 5303Å are obtained by calibrating the system through a neutral density filter. Scans in latitude at 1.15 $R_\odot$ may be redefined to coronal "limb flux", F, by averaging over the entire 360 degrees of position angle. *The limb flux is therefore the latitude-averaged intensity in millionths of the brightness of disk center from an annulus of width 1.1′ centered at a height of 0.15 $R_\odot$ above the limb.* **I will denote the Fe XIV limb flux by F5 and that for Fe X by F6.** Such fluxes are of considerable interest because they are related to true 1MK and 2MK coronal fluxes.

This study is proceeding in parallel with a similar study by Yasukawa, Sime, Fisher and myself, which is using pseudo-full-disk fluxes from the same data.

CALIBRATIONS

In Jan 1983 the original birefringent 5303Å filter was replaced by 3 independent mica etalon filters. At this time the calibration procedures were re-evaluated, and a new calibration procedure was adopted. As a result, the earlier 5303Å calibrations were called into question. In order to investigate this uncertainty, a statistical study of the relationship between 27-day averages of the *sunspot number, R,* and the coronal limb flux F5 was done. Values of R were obtained from the NOAA National Geophysical Data Center CD-ROM NGDC01. A least-squares fit was calculated between F5 and R for (i) 1975-1982 and (ii) 1983-1986 (R has not been obtained yet for 1987-1989). Figure 1 shows the fit, FR = f(R), for (i). The fit for (ii) is similar, and the squares in Figure 1 show FR(ii). A statistical correction value, c(R), may be calculated for FR(i) such that the corrected values for (i), FR′(i), are given by FR′(i) = c(R)FR(i). An integral average value of c(R), c′, may be calculated for the observed range, $0<R<200$, from the least-square fits to (i) and (ii) by assuming that FR′(i) = c(R)FR(i) = FR(ii). The result is c′ = 0.995, thus indicating that no correction is required for the earlier results (in fact, a second correction factor of 0.74 needs to be applied to *all* of the data, but the figures do not reflect this correction).

SOLAR MINIMA IN FE XIV

Figure 2 shows 27-day-averaged values of F5 for 1976 and 1977. The "official" solar-cycle minimum of R was Jun 1976. The F5 minimum occurred for data

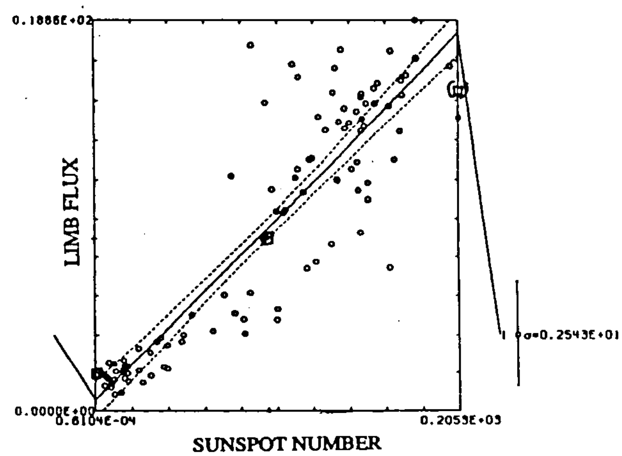

Fig. 1. Circles and lines: Values of Fe XIV "limb flux" (F5) (See text for definition) plotted vs. and linearly-fitted to values of the sunspot number R for 1975 to 1982. Squares: linear fit of F5 vs. R for 1983-1986 (the square in parentheses is extrapolated beyond the range of R for that period).

mostly from the month of Aug 1976 (location 2). Note the near-minimum that occurred in Mar 1976 (location 1) (F5 = 1.0 vs. 0.8 in Aug 1976). This may be considered an alternative minimum for F5.

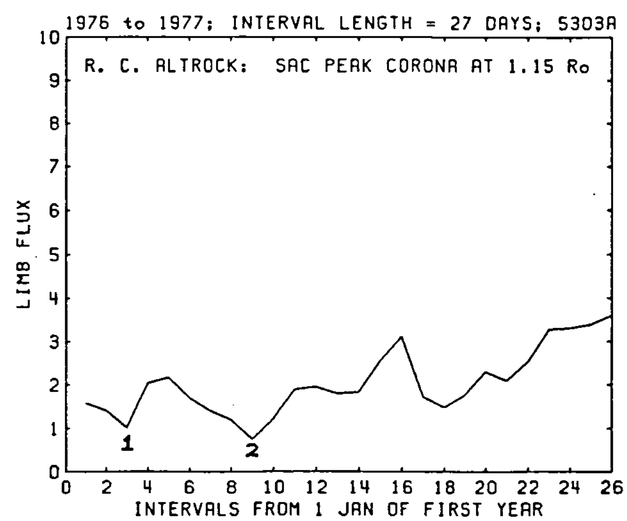

Fig. 2. 27-day-averaged Fe XIV "limb flux" (F5) (See text for definition) for 1976 and 1977.

Figure 3 is the same as Figure 2, but for 1986 and 1987. The official minimum of R was Sep 1986. The coronal minimum occurs in Aug 1986 (location 3) or Sep 1986. Note the secondary minimum in Jan 1987 (location 4) (F5 = 1.4 vs. 1.3 earlier). Comparing Figures 2 and 3 shows that the 1986 minimum had only slightly higher F5 than the 1976 minimum, perhaps indicating the presence of a constant minimum or "basal" corona. The resurgence of activity between Aug 1986 and Jan 1987 is due to a combination of one old-cycle region near the equator and one new-cycle region near 30° latitude. Soon after minimum the Cycle 22 flux began to increase rapidly over that of Cycle 21.

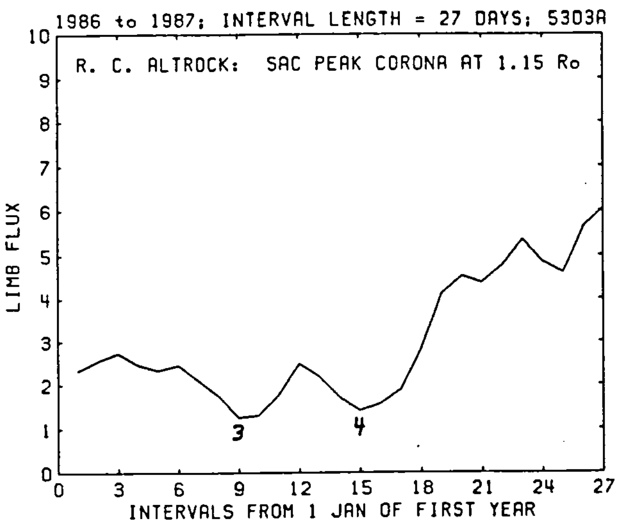

Fig. 3. 27-day-averaged F5 for 1986 and 1987.

THE SOLAR CYCLE VARIATION OF FE X AND FE XIV FLUX

Figure 4 shows **daily** values of F5 from 1973 to 3 Apr 1990. Note the expansion of the ordinate scale by a factor of 4 over that of Figures 2 and 3. This figure shows the rotational modulation as well as solar-cycle variation. Some of the variation is no doubt due also to noise from observational errors. However, it is clear that Cycle 22 has already overtaken Cycle 21.

Figure 5 is the same as Figure 4, but with 27-day-averaged F5. The dashed line shows the onset of Cycle 22 overlaid on the onset of Cycle 21 *solely* to show the similarity of the rise characteristics of the two cycles. The 27-day-averaged F5 has also surpassed the maximum of Cycle 21. Note the rather flat-topped nature of the F5 distribution relative to R during Cycle 21 and the multiple surges of activity lasting on the order of 1 year. The numbers below the curve indicate the respective minima as defined in Figures 2 and 3. The superimposed curves 1 and 2 are discussed below.

Figures 4 and 5 show that there was a large spike in Fe XIV flux in Jan 1989, reaching a daily value higher than at any other time in Cycles 21 and 22. Since that time, Figure 5 shows that the flux levels slowly rose to 20 to 30% higher than those of Cycle 21

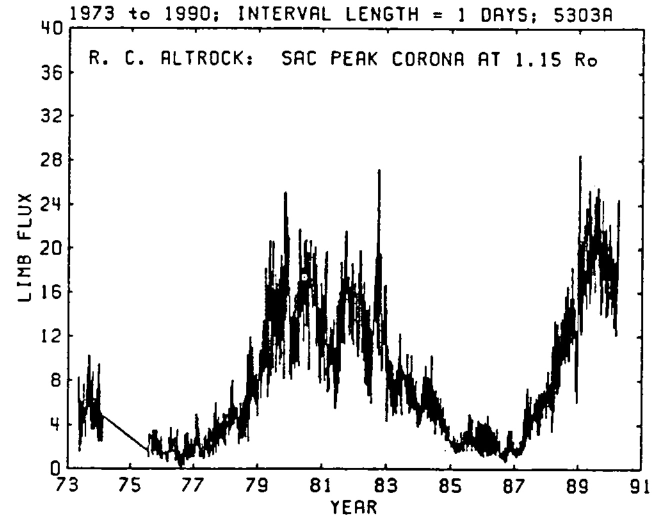

Fig. 4. **Daily** values of F5 from 1973 to 3 Apr 1990. Note the expansion of the ordinate scale by a factor of 4 over that of the two-year plots.

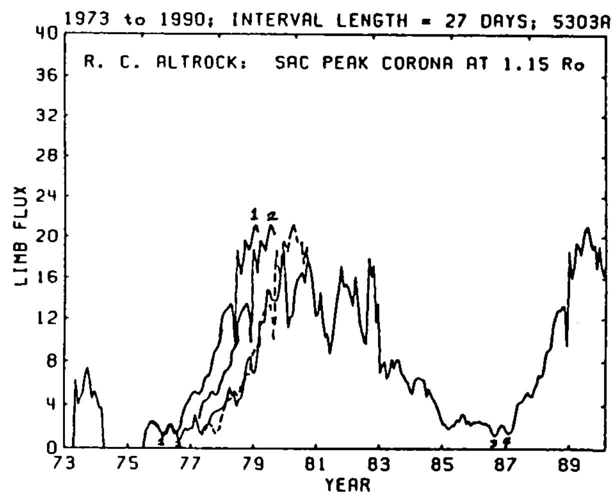

Fig. 5. 27-day-averaged F5 from 1973 to 3 Apr 1990. See text for details. Zero values denote no data.

in Jul and Aug 1989 and then slowly declined until Mar 1990. Figure 6 shows that the solar minimum and onset phases in Fe X have been similar to Fe XIV, with F6 showing an even more rapid onset than F5. A spike of activity in F6 occurred also in early 1989 (Jan to Feb) and the 27-day-averaged F6 reached a maximum slightly earlier than Fe XIV, in Jun 1989. After that major maximum, F6 has also been slowly declining. Figure 7 shows that since mid-Mar 1990 F5 has been increasing and has reached levels similar to those in last Jul and Aug. The value of 27-day-averaged F5 (19.6 as of 4/19/90) is still below the 1989 maximum value of 21.1. A resurgence to mid-1989 levels has also been

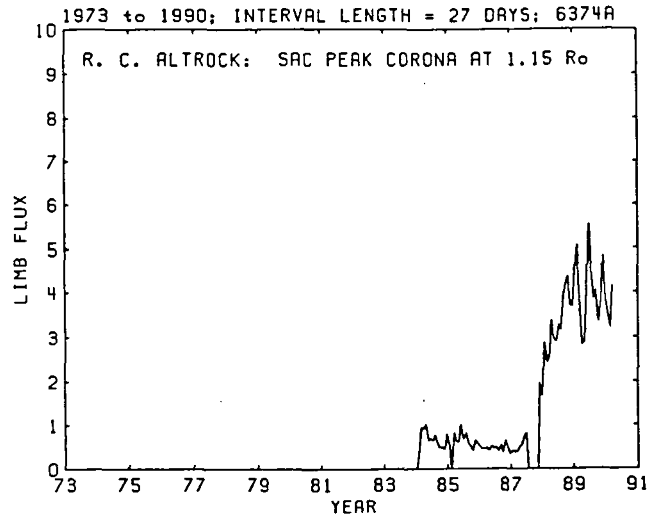

Fig. 6. 27-day-averaged Fe X limb flux (F6) from 1984 to 3 Apr 1990. Zero values denote no data. Note the factor of 4 difference in the ordinate scales of figures 5 and 6.

recently seen in F6. The 27-day value has reached 4.3, vs. 5.6 in 1989.

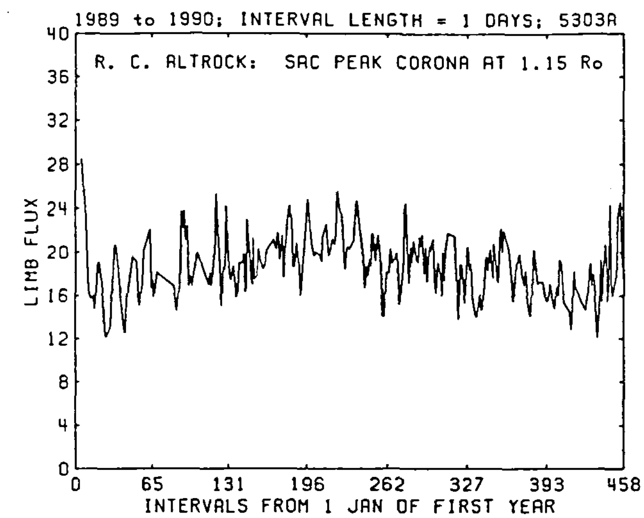

Fig. 7. Daily values of F5 from 1989 to 3 Apr 1990.

CALCULATION OF THE EPOCH OF SOLAR MAXIMUM

Method 1: Cycle 22 Lead Time Implies an Early Maximum

Curve 2 of Figure 5 shows the onset of Cycle 22 compared with Cycle 21 when minimum 3 (Aug 1986) is lined up with minimum 2 (Aug 1976)*. If curve 2 and the onset of Cycle 21 are compared, Cycle 22 appears to be leading Cycle 21 by approximately 9 months. If the "official" minima (Jun 1976 and Sep 1986) were aligned, the lead time would be 12 months. Since the rise time (minimum to maximum) for Cycle 21 was 42 months, and if the above lead times are interpreted as evidence for an earlier maximum, then this implies that the Cycle 22 rise time should be 42 months minus the lead time, which is 33 months from Aug 1986 or 30 months from Sep 1986. This results in estimates for the maximum of Cycle 22 of May 1989 and Mar 1989.

Curve 1 shows the situation when minimum 4 (Jan 1987)** is aligned with minimum 2. This aligns the "double minima" in 1976 and 1986-1987 referred to above and demonstrates how closely the two solar minimum epochs follow each other in this case. IF this 5-month shift were allowed, THEN Cycle 22 is leading Cycle 21 by 14 months. If the error were in 1976, then the Cycle 21 rise time would be increased to 45 months (Mar 1976 to Dec 1979), and the estimated Cycle 22 rise time would be 31 months from Aug 1986, for a solar maximum in Mar 1989. If the error were in 1986-87, then the current rise time would be 28 months from Jan 1987, for a solar maximum in May 1989.

We thus obtain estimates for Cycle 22 maximum of **between Mar and May of 1989**. However, we must also recognize that these calculations are based on the (necessarily-unproven) assumption that any lead of Cycle 22 over Cycle 21 may simply be subtracted from the Cycle 21 rise time. Note that a major maximum for Cycle 22 occurred in Jul-Aug of 1989.

Method 2: Cycle 22 Shape Will Be Similar to Cycle 21 Shape

The dashed line shows how similar Cycles 22 and 21 have been in the **shape** of their early rise phases. If this is taken as evidence that this similarity will continue (which now appears to be less likely), then we could hypothesize that the Cycle 21 rise time (42 months) will apply to Cycle 22, and that maximum will occur 42 months from Aug 1986 or Jan 1987 (see above); i.e., **between Feb and Jul 1990**. If, as suggested above, there was an error in the time of solar minimum in 1976 of 3 months, then the Cycle 21 rise time was 45 months, and Cycle 22 maximum would occur in **Jun 1990**. Note the possible resurgence in

*Actually a combination of two points containing data mostly from Jul to Aug 1976 (F5 = 0.8) and Aug to Sep 1976 (F5 = 0.9).

**Actually a combination of two points containing data mostly from Dec 1986 to Jan 1987 (F5 = 1.6) and Jan to Feb 1987 (F5 = 1.5). These values are slightly different from those quoted earlier due to different starting dates for the 27-day intervals.

activity that began in Mar 1990 (see Figure 7). Of course, if solar maximum was about to occur, we would not necessarily know it for 6.5 months afterwards, since the Cycle 21 rise time, on which these calculations are based, is calculated from weighted 13-month running means.

These two methods lead to widely disparate estimates for the time of solar maximum. Method 1 (Mar to May 1989) depends on Cycle 22 having *historically*-low values of the rise time of from 28-33 months. Since no values below 35 months have ever been observed, perhaps this estimate should be rejected out of hand. In addition, an early maximum would necessarily accept a value of maximum flux not much greater than that of Cycle 21, whereas other methods indicate historically-high values of all other parameters. If, in fact, solar maximum did occur in Aug 1989, the above information indicates a rise time of between 31 and 36 months, which would indeed be near an all-time record low!

Method 2 (Mar to Jul 1990) is more in step with other estimates (cf. NASA Working Group report), does not violate historical rise-time limits and allows for considerable increase from the current value of the flux. It now appears that another maximum will occur in the coming months. We must await the decision of Sol to see if it will be a primary or secondary maximum.

COMPARISON WITH OTHER OBSERVATIONS

Previous investigators such as Gentili de Giuseppe *et al.* (1966) and Sýkora (1980) found that in Cycles 18 & 19 the Fe XIV flux was double-peaked, with one peak occurring near the maximum of R and the second 2-3 years later. However, the results for Cycles 20 and 21 [Sýkora (1980), and Rusin *et al.* (1988)] show a multipeaked variation with surges of activity every 2-3 years, and some of the data do not show any clear single maximum, similar to our F5. Coronal processes show a much more continuous level of activity than does R.

Fleck and Keil (1990, in preparation) report a steep drop in early 1983 in some of the full-disk parameters (most noticeably their Ca K emission index [EI] and other Ca K parameters), followed by a sharp recovery or spike in late spring (cf. Figure 8, from Lean (1987)). I confirm in our F5 (Figure 9) the steep drop near the beginning of 1983, which marks the end of the high fluxes that occurred during the epoch of solar maximum. There is no indication in the coronal data of sustained recovery from that low level in 1983 but only a brief burst of activity in May of that year (Figure 10), similar to the X-Ray spike seen in the NOAA GOES data presented by Fleck and Keil (cf. Wagner, 1988).

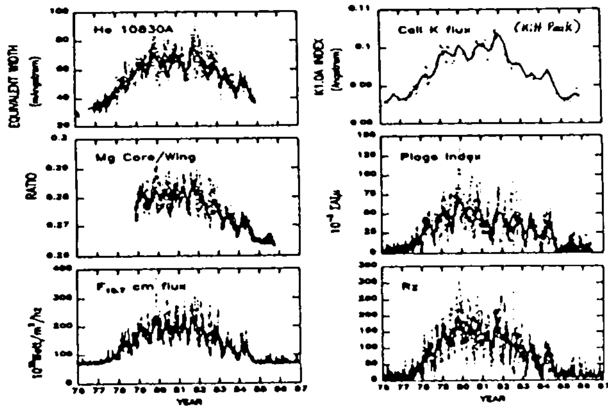

Fig. 8. Solar Cycle 21 as observed in several full-disk parameters (Lean, 1987).

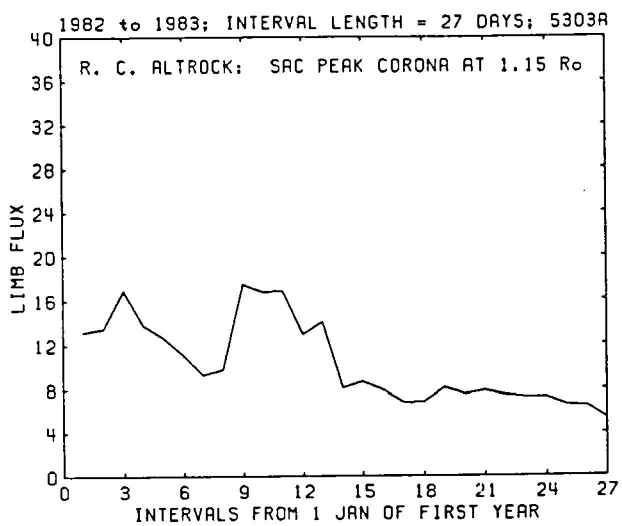

Fig. 9. 27-day-averaged F5 for 1982 and 1983.

Almost all of the data sets show a sharp rise to a plateau beginning in Jan 1984, and F5 also shows a 36% increase in the 27-day-average values during during the first half of 1984 (Figure 11). There is also a hint of the double maximum seen in many of the parameters, with F5 27-day-average values maximizing in Mar and May of that year. The large spike in F5 seen in Jan 1989 is matched by a similar peak in the Ca K EI that rises for the first time to "solar maximum" levels. In addition, the largest spike of Cycle 22 is seen in the GOES soft X-ray data at that time, a pattern similar to that of the Fe XIV data. However, the preceding sharp dip in F5 is not matched by any other parameter and may be due to instrumental problems occurring at that time in the Fe XIV filter. The overall rise from solar minimum in

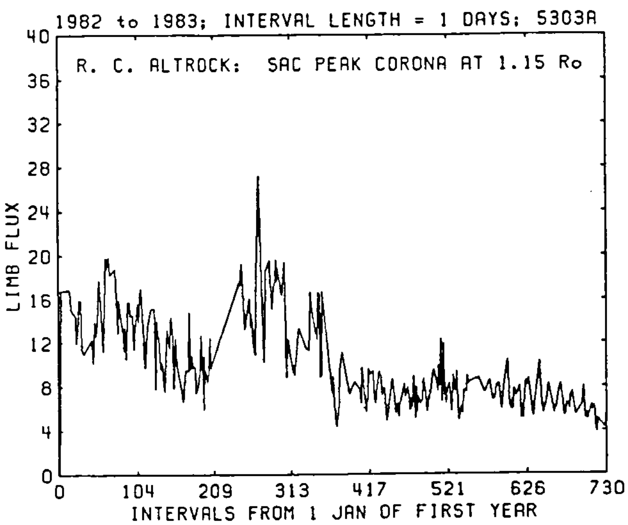

Fig. 10. Daily values of F5 for 1982 and 1983.

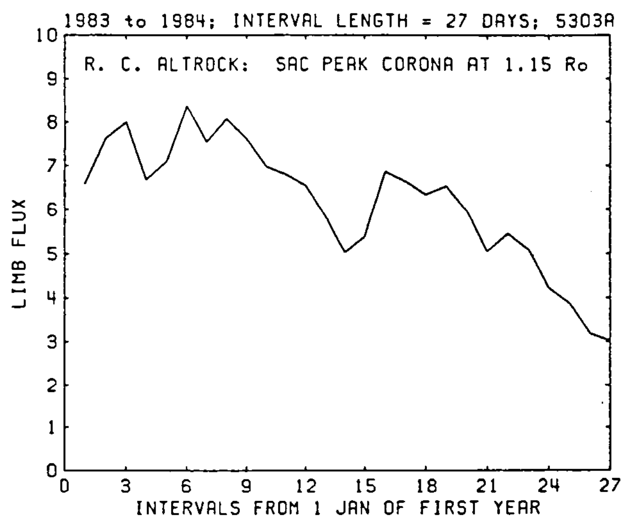

Fig. 11. 27-day-averaged F5 for 1983 and 1984.

1976 to solar maximum in late 1979 is 2184% in the 27-day-average values of F5, compared to an average rise of 19% in the Ca K EI. So far in Cycle 22, the increase from 1986 to 1989 in F5 has been 1564%, and in F6, 1371%.

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