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HIGH FLARE ACTIVITY IN THE LATE DECLINING PHASE OF CYCLE 23

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Abstract. In the declining phase of the current solar cycle (23), a large number of major flares were produced. In this cycle, the monthly sunspot number continuously remained below 100 since October 2002. However, during four epochs since then, flare activity became very high. Compared to this, each of cycles 21 and 22 produced only one epoch of high activity in the declining phase. In the declining phase of cycle 20, similarly to this cycle, there were four epochs of high flare activity. During 2003 and 2004, the distribution of flare sizes measured in GOES classes was much harder (*i.e.*, proportionately more energetic flares) than during the maximum years. Such pronounced hardening of the size distribution was not observed in the previous cycles. It is of theoretical interest to understand why some cycles are very active in the declining phase, and the high level of activity in the declining phase has practical implications for planning solar observations and forecasting space weather.

1. Introduction

The 11-year sunspot cycle provides us basic information about long-term variation of solar activity. Solar activity, including flare occurrence, seems to follow well the sunspot cycle to a first-order approximation. Solar flares occur frequently when the sunspot number R is high, and solar flares are scarce when R is low. Therefore, it is customary to plan to launch spacecraft for monitoring solar flares near sunspot maxima, as was the case for SMM (Solar Maximum Mission) and RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager).

However, when closely inspected, the solar flare activity variation with the sunspot cycle shows subtle differences from the variation of the sunspot number. Cross correlations of flare occurrence rates with the sunspot number show that flare occurrence lags behind the sunspot number (Temmer *et al.*, 2003). It has been also noticed that outstanding flares producing very energetic protons can occur even several years after solar maxima (Fritzova-Švestkova and Švestka, 1973; Švestka, 1995).

In this solar cycle, flare activity was very high during several epochs in the late declining phase. During a 12-day period from October 30 to November 10, 2004, fourteen major flares with X-ray class ≥M3.0 (including three X-class flares) were observed. (In this paper, flares with X-ray class ≥M3.0 are referred to as major flares.) This epoch of high solar activity is notable in the following respects. First, during the preceding 71 days (August 20 through October 29), the Sun was very quiet, producing only two major flares. Second, this high-activity epoch occurred very late in the declining phase – 55 months after the sunspot maximum in March 2000. Furthermore, during the six-day interval January 15 – 20, 2005, 10 major flares were produced. In addition to these epochs, flare activity was very high during three previous epochs in the declining phase of this solar cycle, while the monthly sunspot number continuously remained smaller than 100.

Such high activity in the declining phase was an unexpected boon to RHESSI, which was launched in February 2002. Therefore, it is important to understand the level of flare activity in the declining phase of solar cycles for practical purposes of planning solar observations and space weather forecast as well as theoretical understanding. Thus, in this paper, I study time profiles of the production rate of major flares for four recent solar cycles (cycles 20 – 23), paying attention to activity in late declining phases, when *R* remained continuously below 100.

For cycles 21 – 23 (1976–present), I use soft X-ray data obtained by a series of GOES (Geostationary Operational Environmental Satellite). For cycle 20, I use soft X-ray observations by Solrad 9 and lists of major flares compiled by Dodson and Hedeman. All the flare data used in this paper are available at the website www.ngdc.noaa.gov/stp/SOLAR.

2. Time Profiles of Flare Production Rate

2.1. Solar cycle 23

Figure 1 shows the 27-day running mean of daily rates of major flares for cycle 23. Four epochs of high solar activity, denoted by *a*, *b*, *c*, and *d*, occurred 3.2, 3.6, 4.4 and 4.6 years after the solar maximum in March 2000. The active regions producing major flares during these four epochs are listed in Table I. In addition to these, in the period from 2005 January 15 through 20, ten major flares were produced, five of which were X-class flares. Nine of the ten major flares were produced by AR 10720.

Although these four epochs of high activity occurred in the declining phase, when the monthly sunspot number was low, they are comparable in strength to high-activity epochs observed during the maximum phase of this solar cycle. Especially, epoch *b* produced the largest number of major flares and produced the highest X-ray class flare (X28 on November 4) and an X17 flare (October 28). During each of these epochs, two to four active regions that were widely separated from each other on the Sun produced major flares.

2.2. Solar cycles 21 and 22

Figure 2 shows the production rate of major flares for cycles 21 and 22. We can notice only one high-activity epoch during the declining phase of each solar cycle.

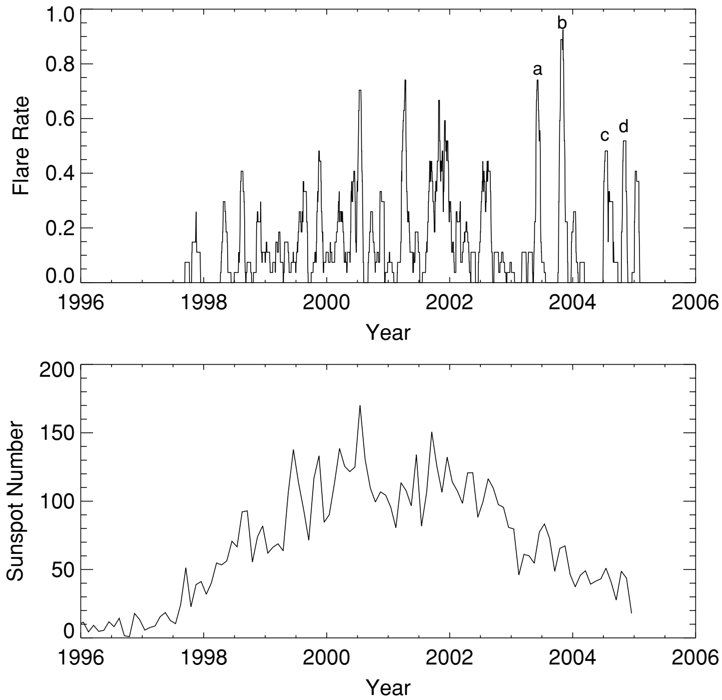

Figure 1. Flare rate and sunspot number as functions of time for cycle 23. The flare rate is a 27-day running mean of daily number of major flares (≥M3.0) until January 25, 2005. The monthly sunspot number is shown until December 2004.

The high-activity epoch in the declining phase of cycle 21 is from April 20 through May 22, 1984, and the high-activity epoch of cycle 22 is from August 20 through September 10, 1992. The active regions producing major flares during these epochs are shown in Table II.

AR 4471 and AR 4481 were the same active region (renamed for each disk passage), which was active during the two consecutive disk passages. Likewise, AR 4474 and AR 4492 were the same region, and so were AR 7260 and AR 7276.

2.3. Solar cycle 20

For cycle 20, GOES did not observe soft X-rays from the Sun, but Solrad 9 observed solar X-rays during a part of it – from March 1968 to February 1974. To complement the shortcoming of Solrad data, I also use lists of major flares by Dodson and Hedeman (1971, 1975, 1981), who compiled important flares, determining their CFIs (comprehensive flare indexes) relying on various ground-based observations. I regard flares with CFI > 6 as major flares for this study.

TABLE I
Four high-activity epochs in the declining phase of cycle 23.

Active region	Number of major flares	Hemisphere	CMP date
a. First epoch (May 27 – June 17, 2003): 20 major flares			
10365	5	S	May 25.7
10375	10	N	June 7.7
10380	1	S	June13.7
10386	2	N	June 22.0
Unidentified	2	–	–
b. Second epoch (October 19 – November 5, 2003): 24 major flares			
10484	4	N	Oct 23.9
10486	17	S	Oct 29.3
10488	3	N	Oct 28.7
c. Third epoch (July 13 – August 19, 2004): 20 major flares			
10646	4	N	July 15.7
10649	6	S	July 19.0
10652	3	N	July 23.2
10656	7	S	Aug 12.2
d. Fourth epoch (October 30 – November 10, 2004): 14 major flares			
10691	5	N	Oct 28.5
10696	9	N	Nov 6.1

Figure 3 shows time profiles of Solrad major flares (a), CFI major flares (b), and the sunspot number (c). In the top panel, we can identify three epochs of high flare activity in the declining phase, denoted by *a*, *b*, and *c*. In the middle panel, we see the same epochs as in the top panel, although epoch *b* is less conspicuous here. Additionally, we find epoch *d* in the middle panel. The four epochs were 3.0, 3.4, 4.1, and 5.3 years after the sunspot maximum.

The active regions producing major flares during these epochs are listed in Table III. During epoch *b*, the most prominent active region was AR 11976, which produced the famous γ-ray flares of August 4 and 7, 1972. Exceptionally, epoch *d* was due to only one super-active region, AR 13043. (For cycle 20, AR numbers refer to McMath region numbers, while for later cycles they refer to NOAA region numbers.) No one knows how many X-ray major flares ($\geq$M3.0) this active region produced because of lack of observation. However, in terms of the sum of H-α flare indexes for an individual region, it is second only to AR 11976 among the active regions in Table III. Therefore, there is no doubt that epoch *d* was a high-flare-activity interval. AR 12322, which produced 7 major flares during epoch *b*, was renamed as AR 12352 and produced 2 major flares during the next disk passage. AR 12336,

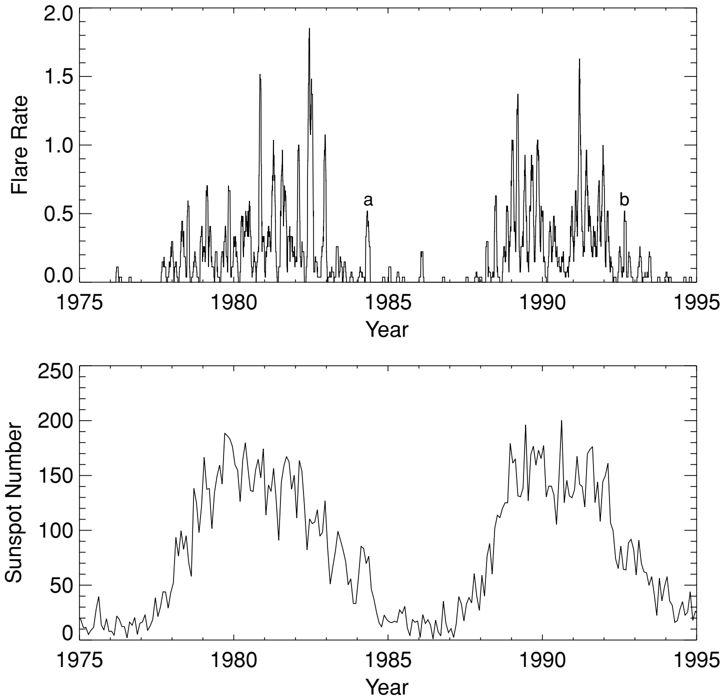

Figure 2. Same as Figure 1, but for cycles 21 and 22.

which produced 8 major flares during epoch *b*, produced 2 major flares during its preceding disk passage while identified as AR 12306.

3. The Size Distribution of Flares and Solar Cycle Phase

It is often mentioned that the fraction of energetic flares is larger in declining phases of solar cycles. Well-known energetic flares of cycle 21 – γ-ray flares of August 4 and 7, 1972 (Chupp *et al.*, 1973; Suri *et al.*, 1975); the two-ribbon flare of July 29, 1973 (Moore *et al.*, 1980) – were all observed during its declining phase. Fritzova-Švestkova and Švestka (1973) and Švestka (1995) reported occurrence of outstanding flares in declining phases of solar cycles.

Using SMM hard X-ray observations of solar flares, Bai (1993) studied how the size distribution varied as solar cycle 21 progressed. The negative spectral index for the size distribution of peak hard X-ray count rates is 1.78($\pm$0.03) for 1979, 1.80($\pm$0.03) for 1980, 1.72($\pm$0.03) for 1982, and 1.72($\pm$0.05) for 1983 and 1984. Indeed, the spectrum flattens slightly in the declining phase, which is nevertheless statistically significant.

Are the large numbers of energetic flares observed in 2003 and 2004 just refelcting the trend of flattening of the size distribution in the declining phase? In order

TABLE II
High-activity epochs in the declining phases of cycles 21 and 22.

Active region	Number of major flares	Hemisphere	CMP date
a. An epoch of Cycle 21 (April 20 – May 22, 1984): 21 major flares			
4471	1	N	April 15.4
4474	11	S	April 28.9
4481	2	N	May 11.7
4492	6	S	May 24.4
Unidentified	1	–	–
b. An epoch of cycle 22 (August 20 – September 10, 1992): 14 major flares			
7260	2	N	Aug 18.3
7270	9	S	Sep 3.5
7276	2	N	Sep 14.0
Unidentified	1	–	–

TABLE III
High-activity epochs in the declining phase of cycle 20.

Active region	Number of major flares	Hemisphere	CMP date
a. Epoch a of cycle 20 (February 8 – March 6, 1972): 17 major flares			
11734	3	S	Feb 16.6
11748	4	N	Feb 22.4
11751	2	S	Feb 25.4
11759	1	N	Feb 29.0
11769	5	S	Mar 9.5
Unidentified	2	–	–
b. Epoch b of cycle 20 (August 1 – August 19, 1972): 11 major flares			
11970	1	S	July 30.4
11974	1	S	Aug 1.1
11976	7	N	Aug 4.7
11985	1	N	Aug 14.7
12002	1	S	Aug 26.9
c. Epoch c of cycle 20 (April 26 – May 5, 1973): 17 major flares			
12322	7	N	Apr 24.2
12323	1	S	Apr 28.7
12336	8	S	May 7.4
Unidentified	1	–	–
d. Epoch d of cycle 20 (Jun 30 – July 9, 1974): 14 major flares			
13043	14	S	July 4.0

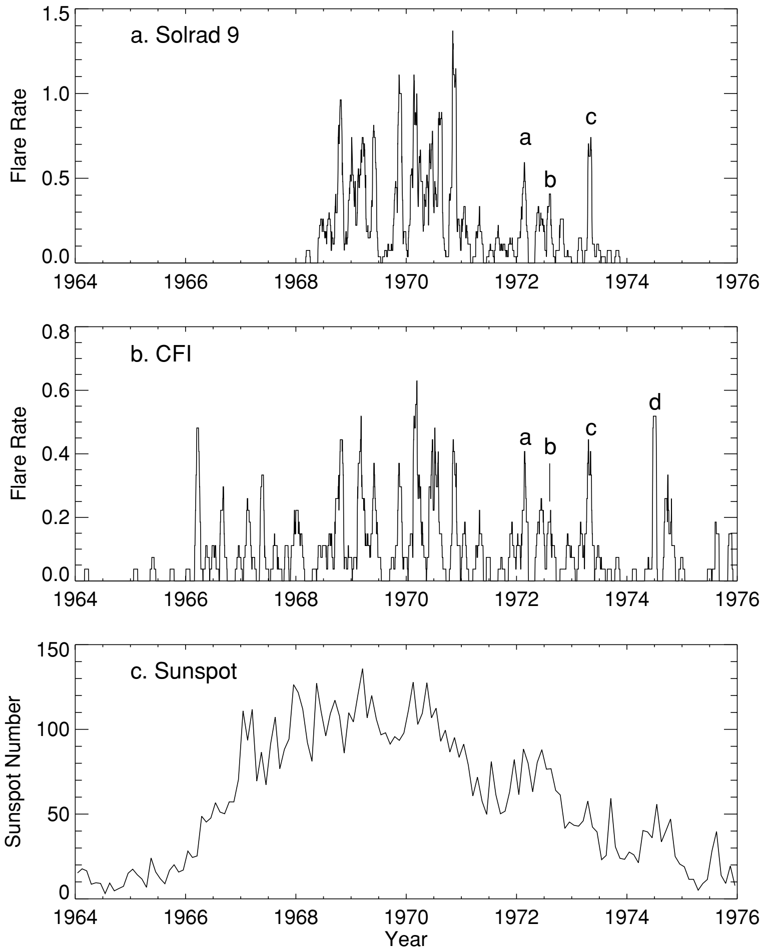

Figure 3. Flare rates and sunspot number as functions of time. (a) Major flares (≥M3.0) observed by Solrad 9, (b) major flares (CFI>6) from lists of Dodson and Hedeman, (c) sunspot number.

to answer this, let us see how annual numbers of flares in different size intervals vary with solar cycle phase. Figure 4a shows annual numbers of flares in four different size intervals. Figure 4b shows a hardness ratio, which is the ratio of the number of flares in the interval M3.0 – M9.9 to the number of flares in the interval C3.0 – C9.9 in GOES X-ray class. The hardness ratio is large for 1986, 1989, 2003, and 2004. However, the hardness for 1986 is not statistically significant, because the number of flares in the M3.0 – M9.9 interval is only 6 for this year. The large values of hardness ratio for 1989, 2003, and 2004 are, on the ohter hand, statistically significant. Except for this, we do not find any trend following solar cycle phase.

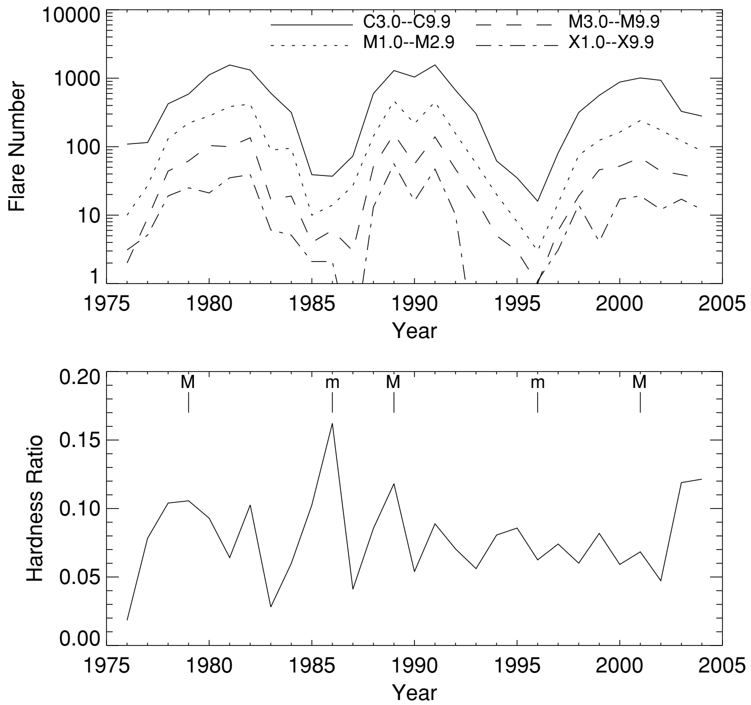

Figure 4. Annual number of flares in different size intervals and hardness ratio. In the lower panel, sunspot maximum years and minimum years are indicated by letters M and m, respectively.

4. Discussion

In this paper, I investigate epochs of high flare activity during declining phases of solar cycles. Similarly, Švestka (1995) reviewed general characteristics of solar activity during declining phases. Let us compare Švestka's results with this paper. Approaches and emphases are different. I paid attention to the declining phase when the monthly sunspot number remained continuously below 100, while Švestka studied activities about 2.7 years after the sunspot maximum. I identified intervals during which large numbers of major flares were produced, while Švestka was interested in outstanding flares.

Solar cycles 20 through 22 are studied by the both papers. Let us compare the results for these cycles. For cycle 20, Švestka identifies AR 11976 and AR 13043 as high activity centers of the declining phase. They were active during epoch *b* and epoch *d* of Table III. For cycle 21, Švestka identified the interval from 1982 June 3 to July 19 as a high-activity interval. This interval was indeed very active, but I do not discuss this interval because the sunspot number during this interval was higher than 100. Both papers agree in identifying AR 4474 of April 1984 as a high-activity center. For cycle 22, Švestka identified AR 7321 as a high-activity center, which appeared more than a month after epoch *b* of Figure 2. During the interval from 1992 October 23 through November 2, five major flares were produced, which are too few to qualify the interval as a high-activity interval. However, AR 7321 developed later during its disk passage, and it was arleady over the western limb by the time it produced an X9 flare on November 2. It must have produced many more major flares after passing over the limb.

Let us compare the four recent cycles studied here. For cycles 21 and 22, only one epoch of high flare activity is found in the declining phase of each cycle. After such an epoch, the solar activity remained very low until the rise phase of the next solar cycle. However, in the declining phase of the current cycle, four epochs of high flare activity have been observed. In cycle 20 also, four epochs of high flare activity were observed in the declining phase.

It seems premature to generalize from a study of only four cycles, but it is worth mentioning the following. The weaker two cycles (cycle 20 and cycle 23 are comparable in sunspot numbers) had multiple epochs of high flare activity in the late declining phase, when the monthly sunspot number continuously remained smaller than 100. On the other hand, the stronger cycles (21 and 22) had only one high-activity epoch in the late declining phase of each cycle.

Figure 5 shows yearly numbers of major flares for the recent three solar cycles. The dotted line shows percentages of major flares from super-active regions only. A super-active region is defined as an active region that produced four or more major flares during one disk passage (Bai, 1987). We find that, during solar maximum years of cycles 21 and 22, super-active regions produced about one half of major flares, except in 1990. In cycle 23, from 1998 through 2002, super-active regions produced about 30% of major flares. However, during 2003 and 2004, super-active regions produced more than 70% of major flares.

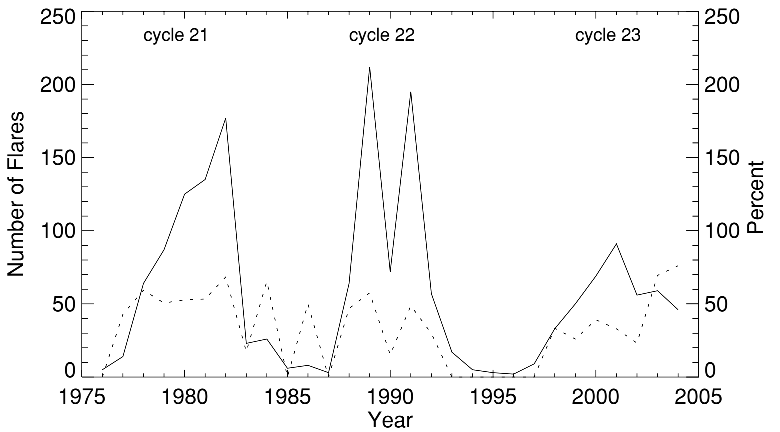

Figure 5. Annual number of major flares for cycles 21 through 23. The *solid line* indicates the annual number of major flares, and the *dotted line* indicates the percentage of major flares produced by super-active regions.

During 2003 and 2004, the Sun was usually devoid of big active regions. Then, suddenly, the Sun produced big active regions in several places, separated widely. (See SOHO MDI (Michelson Doppler Imager) magnetograms at `http://soi.stanford.edu/magnetic/index5.html.`) They became very prolific, giving rise to high-activity epochs. Therefore, we can conjecture that, once in a while in the declining phase, the Sun becomes more efficient for transporting magnetic fields from the base of the convection zone to the surface. For instance, giant convection cells at the base might have become more active during such epochs, and as a consequence magnetic ropes might have been carried upward more efficiently at upwelling boundaries.

Some active regions contributing to high-activity epochs produced major flares during two consecutive disk passages. Since it is unlikely that these active regions became dormant coincidentally with their location in the backside of the Sun, it follows that these active regions must have remained active more than one solar rotation.

According to Temmer *et al.* (2003), for cycles 19, 21, and 23, solar flare activity lags behind the solar cycle variation of sunspot number. For cycle 23, this paper covered data until February 2002. Now that we have seen high activity epochs in 2003 and 2004, we are sure that flare activity lagged behind the sunspot variation for cycle 23 (see Figure 1).

During epochs of high flare activity in the current cycle, many important CMEs were observed. For example, on October 28, 2003, a fast bright halo CME, which is nicknamed the "Mother of all halos," occurred in association with an X17 flare. The next day, a fast bright full halo CME also occurred in association with an X11 flare. Therefore, high activity in the declining phase of a solar cycle are of interest for space weather forecast.

5. Summary

Let us summarize flare activities in the declining phase.

First, during declining phases of solar cycles, more major flares occur than are expected from sunspot numbers. Similarly, more numerous outstanding flares occur than are expected (Švestka, 1995). Such high activities in declining phases seem to make the cycle variation of flare occurrences lag behind the sunspot number variation, which is reported by Temmer *et al.* (2003).

Second, four epochs of high flare activity were observed during the declining phase of the current solar cycle, the same as cycle 20. On the other hand, during the late declining phases of cycles 21 and 22, during which monthly sunspot number remained continuously below 100, only one epoch of high activity was observed for each cycle. It is worth noting that cycles 20 and 23 were weaker than cycles 21 and 22. It should be checked in the future whether the strength of a cycle and its number of high activity epochs in the declining phase are related.

Third, the size distributions of flares of 2003 and 2004 are much flatter than those for maximum years and those for all preceding years. Although the flare size distribution during the declining phase of cycle 21 was observed to be slightly flatter than that for maximum years (Bai, 1993), the flattening of the size distribution for 2003 and 2004 is much larger. This should be studied in more detail because the flare size distribution can provide a clue to flare mechanism(s).

Fourth, several active regions widely separated on the Sun produced major flares during high-activity epochs. This indicates that the mechanism for high-activity in the declining phase must be global in nature.

Fifth, some active regions contributing to high-activity epochs also produced major flares either during its preceding disk passage or during its next disk passage. Therefore, the mechanism for the high-activity epochs must be active longer than one solar rotation.

Because of many energetic CMEs and energetic proton events associated with high activity epochs in the declining phase, such epochs are important for the practical purpose of space weather forecast.

Acknowledgement

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