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2007 ApJ 663 L45

(http://iopscience.iop.org/1538-4357/663/1/L45)

THE ASTROPHYSICAL JOURNAL, 663:L45–L48, 2007 July 1

THE UNPREDICTABILITY OF THE MOST ENERGETIC SOLAR EVENTS

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Received 2007 March 7; accepted 2007 May 16; published 2007 June 15

ABSTRACT

Observations over the past two solar cycles show a highly irregular pattern of occurrence for major solar flares, γ-ray events, and solar energetic particle (SEP) fluences. Such phenomena do not appear to follow the direct indices of solar magnetic activity, such as the sunspot number. I show that this results from the non-Poisson occurrence for the most energetic events. This Letter also points out a particularly striking example of this irregularity in a comparison between the declining phases of the recent two solar cycles (1993–1995 and 2004–2006, respectively) and traces it through the radiated energies of the flares, the associated SEP fluences, and the sunspot areas. These factors suggest that processes in the solar interior involved with the supply of magnetic flux up to the surface of the Sun have strong correlations in space and time, leading to a complex occurrence pattern that is presently unpredictable on timescales longer than active region lifetimes (weeks) and not correlated well with the solar cycle itself.

Subject headings: Sun: flares — Sun: magnetic fields — Sun: particle emission — Sun: X-rays, gamma rays — sunspots

1. INTRODUCTION

It has long been known anecdotally that highly energetic solar events do not strictly follow the solar sunspot cycle (e.g., Garcia & Dryer 1987). The fact that we only have a few cycles of modern data has made it difficult to describe this discrepancy quantitatively, especially in view of the small numbers of the most energetic events. The fossil records typically do not have enough time resolution to overcome these problems (but see McCracken et al. 2001). These most energetic events include some of the most geoeffective ones, so there we have a clear practical reason for studying their occurrence patterns—we would like to predict the occurrence of a major event.

The most energetic events also represent the extreme limit of the mechanism that stores energy in the solar corona. In the consensus view, magnetic energy builds up gradually in the corona as a result of stresses imposed from below. The stressed coronal field then relaxes, by unknown processes, to produce a flare and/or coronal mass ejection (CME). The energy appears to arrive in the corona as the result of buoyant motions of current-carrying flux systems (e.g., Schrijver 2007) rather than by the twisting of the coronal field by photospheric surface flows, as often assumed in numerical simulations. The patterns therefore reflect the persistence of the flux-emergence process, which is known to display coherence in both space and time (e.g., Knaack & Stenflo 2005), and ultimately must be attributed to the solar dynamo and other processes in the solar interior (e.g., Ruzmaikin 1998).

Flare occurrence apparently follows a nonstationary Poisson distribution with time-varying mean rates (Biesecker 1994; Wheatland 2000; Moon et al. 2001) and a clearly power-law dependence on event "size," where this conceptually reflects total event energy but in practice often refers to an observational parameter such as peak X-ray luminosity (e.g., Drake 1971; Hudson 1991). Many studies have shown that flare occurrence follows a flat power-law relationship, $d(\log N)/d(\log E) = -\alpha$, with $\alpha < 2$. There are suggested weak dependences of the exponent on the phase in the solar cycle (Bai 1993; Wheatland & Litvinenko 2002) by the active region (Kucera et al. 1997) and from star to star (e.g., Shakhovskaya 1989). Such a flat distribution requires a high-energy cutoff to conserve energy, but there is no clear evidence for such a cutoff yet.

The more energetic the flare, the more likely the occurrence of a CME, although in a few cases an X-class flare will not have a CME association (e.g., de La Beaujardière et al. 1995). For weaker flares, associated CMEs occur much less frequently (e.g., Yashiro et al. 2006). The CME distribution must therefore deviate from the flare power law at low event energies, possibly not following a power law at all (Jackson & Howard 1993). Interestingly, solar energetic particle fluences do follow a power law, but it is a significantly flatter one than that of the flares (van Hollebeke et al. 1975; Gabriel & Feynman 1996; see also Hudson 1978). The occurrence of solar energetic particles (SEPs) might otherwise be expected to reflect the CME distribution, because CME-driven shocks are known to accelerate SEPs (e.g., Reames 1999; Cliver et al. 2004).

In this Letter we report a large specific variation in the X-class flare occurrence rate that we trace through similar patterns in SEP fluences and in sunspot areas. This juxtaposition is consistent with the interpretation of flare occurrence with Biesecker's variable-rate Poisson process, although the small numbers of the most energetic flares means that this interpretation is only weakly grounded in this context. We instead suggest an origin in correlations of solar interior magnetism on timescales longer than about one rotation period, whose existence will strongly limit flare prediction on these timescales until the interior dynamics is better understood.

2. X-CLASS FLARES

An X-class flare corresponds to a peak flux of 10^{-4} W m^{-2} in the *GOES* standard 2–8 Å passband. Such events lie at the upper end of the occurrence energy distribution function of all flares, and they may differ in their temporal occurrence because of the requirement for an upper energy cutoff—because of this, one cannot assume that the energy distribution continues to have the same power-law form as the flaring rate changes. Their small numbers (about 125 in the past solar cycle, from 1996 through 2006) make statistical analyses difficult, and in fact the more energetic of these events may saturate the detectors, which tends to diminish the quality of the statistics.

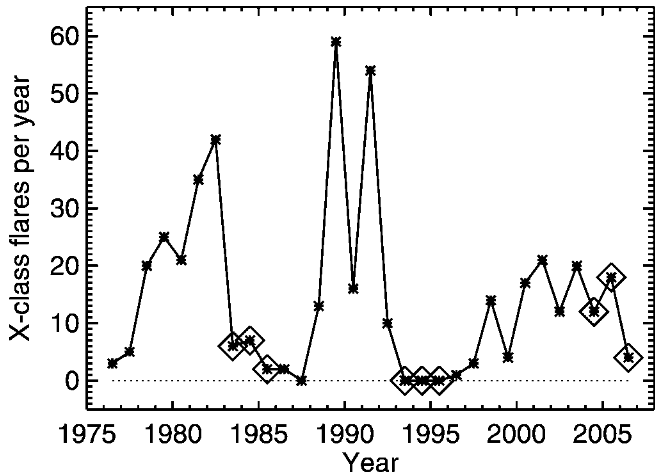

FIG. 1.—X-class flare numbers by year from 1975 September 1 through 2007 January 31. Points shown as diamonds are the years of the solar-cycle-declining phases, defined here as 1983–1985, 1993–1995, and 2004–2006. The corresponding numbers of X-class flares are 15, 0, and 34 respectively.

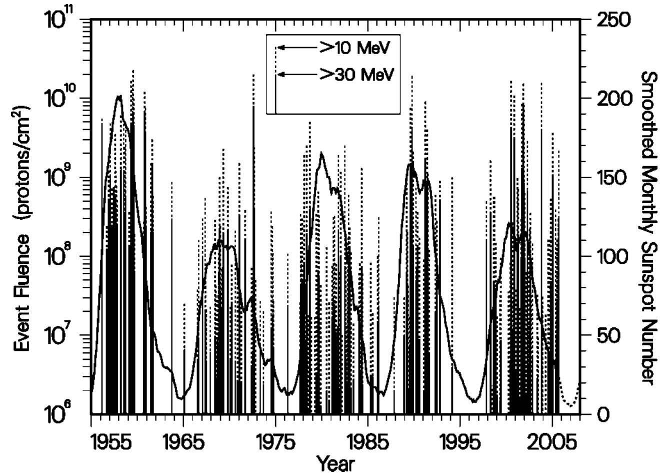

FIG. 2.—SEP event occurrences for 1954 to the present (excluding the events of 2006 December), shown as dotted vertical lines for >10 MeV threshold and solid vertical lines for >30 MeV (from Reedy 2006). The background curve is the sunspot number in monthly bins. Note the large fluences around 2005 and the negligible fluences one cycle earlier around 1994.

The declining phases of the past two solar cycles have shown a striking discrepancy in the occurrence of X-class flares. This got attention because of the *RHESSI* observations of γ-ray flares in 2003–2005 (e.g., Shih et al. 2006); such events typically correspond to the X-class flares, and *RHESSI* observed several remarkable examples (e.g., Share et al. 2004) in its inaugural years 2002 and 2003. The expectation for the years 2004–2006, if based on the previous cycle years of approximately 1993–1995, would have been *zero* further events—not a single X-class flare occurred during these 3 late years of the previous cycle, although one old-cycle event did occur in 1996 (Kosovichev & Zharkova 1998; Hudson et al. 1998). To our surprise, as many as 34 X-class flares occurred over 2004–2006, although not all observable as γ-ray events from *RHESSI* because of its orbital eclipse cycle. See Figure 1 for the data, all of which were obtained from Web resources maintained by NOAA.[1]

Figure 1 shows three cycles of X-class flare occurrence, highlighting the discrepant behavior in the decaying phases of cycles 21, 22, and 23. The difference in occurrence of energetic events between the latter two epochs is highly significant; for a guide to significance, we can use a Poisson distribution based on the number of unique active regions in the years 2004–2006 (11 unique regions, for an average of about three X-class flares per region). Computing the Poisson probability of one event in the earlier epoch (the 1996 flare) relative to the number of unique regions of the later epoch, we find a likelihood of <0.02%. This conservatively confirms the obvious inference from the figure, namely, that the X-class event numbers are highly discrepant and that the occurrence of such major energetic events has shown much greater variation than the sunspot number itself. Cycle 21, on the other hand, showed an intermediate number of events (15 X-class flares, from nine unique regions) and does not appear discrepant.

3. SOLAR ENERGETIC PARTICLES

The striking difference shown by the X-class flare occurrence between the past two cycle-declining phases also shows up strongly in the SEP fluences (Fig. 2; Reedy 2006). This would be expected because of the strong correlation between X-class flare occurrence and CME occurrence, as documented recently by Yashiro et al. (2006). The declining phases of the two recent cycles, comparing (for example) 1994 with 2005 in Figure 2, clearly differ significantly.

The identification of flare activity with SEP fluxes might seem inconsistent with the theory of particle acceleration by CME-driven shocks, rather than flares per se (e.g., Reames 1999; Cliver et al. 2004), and frequent assertions of the independence of CME and flare occurrence. This becomes understandable from the work of Yashiro et al. (2006), who confirm the well-known strong association of CMEs with the most energetic flares. The discrepancy in the numbers of the most energetic events between the two recent cycle-declining phases can thus be traced in flare, CME, and SEP occurrence patterns. We discuss the significance of this finding in § 5, but first we investigate whether or not this occurrence discrepancy can also be detected in sunspot area statistics.

4. SUNSPOT AREAS

The plot in Figure 3 shows data obtained from the tabulations of sunspot group areas by the Solar Optical Observing Network

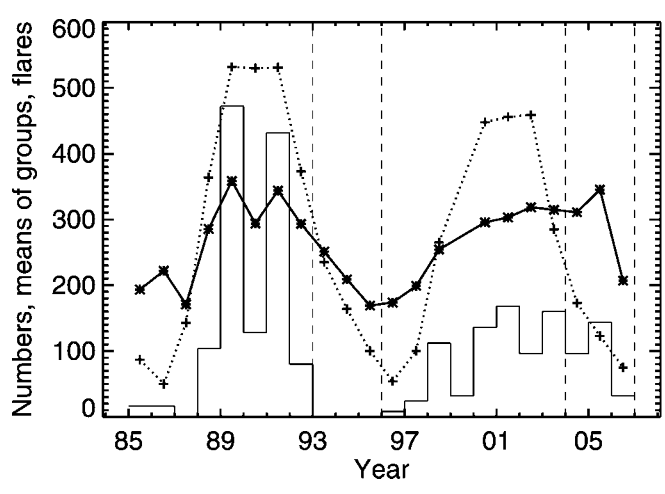

FIG. 3.—Sunspot and flare behavior during cycles 22 and 23. *Dotted line*, the annual numbers of sunspot groups; *solid line*, 2 × the mean peak areas of the groups (see text). *Histogram*, the numbers of X-class flares × 8. The vertical dashed lines mark the two declining-phase epochs studied in this Letter. Data from the SOON network via NOAA.

[1] See http://www.ngdc.noaa.gov/stp/SOLAR.

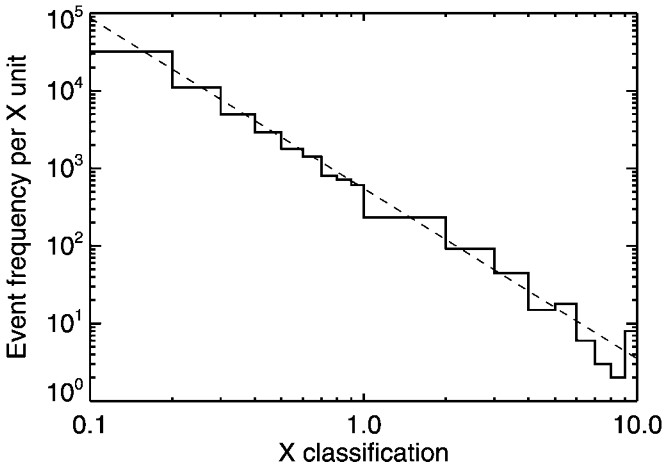

FIG. 4.—Distribution of *GOES* 1–8 Å peak fluxes for the interval 1975 September–2007 January for the M- and X-class events (discarding the 22 "superflare" occurrences above X10). The dashed lines shows a fit using the maximum likelihood method of Crawford et al. (1970), which does not require binning. The binning shown is 0.1 X units for the M flares and 1 X unit for the X flares (where X1 corresponds to 10^{-4} W m^{-2} peak soft X-ray flux). This fit predicts the observed number of superflares within errors, giving a lower limit on the break energy.

(SOON) stations. A large fraction of the tabulated data has been used, typically from three or more stations for each day, but with the rejection of a small number of outliers and also the measurements with quality values below 3 (the range is 1–5; see the NOAA Web site for details of the SOON sunspot data). The solid line in the plot shows the mean of the maxima of the daily areas for individual groups, in millionths of the hemisphere (the customary unit). This shows a time variation significantly distinct from that of the number of groups (*dotted line*) that roughly tracks the sunspot number. The larger values of mean areas during the decay phase of cycle 23 (2004–2006) show that the distribution function of sunspot group areas favored larger spots than during the corresponding interval in cycle 22 (1993–1995). This asymmetry coincides with the asymmetry noted above in X-class flare occurrence and in SEP production.

5. DISCUSSION

Major energetic solar events do not closely track the solar cycle as a source of the slow variation under the dominant Poisson statistics. Indeed, the "Bayesian blocks" of Wheatland (2000) or the timescales for Poisson behavior obtained by other methods (e.g., Gallagher et al. 2002) are considerably shorter than the mean waiting times for X-class events (on the order of one event per month over 1996–2006). We conclude that other physics dictates the occurrence patterns of the most energetic events, for which at most a few may occur in a given active region. The underlying cause of the Poisson behavior for the less energetic events should be found in the physics of energy buildup and release in the corona. The occurrence of the most energetic events presumably has more to do with the broadband coherence of solar magnetic activity on large scales in both space and time, as discussed by Knaack & Stenflo (2005) in terms of "intermittent oscillations" revealed by spherical-harmonic expansions of synoptic magnetogram data. Examples of broadband correlations would include the butterfly diagram and the presence of "active longitudes" where active regions may occur repeatedly. We can also note the remarkable eruption of three distinct active regions in 2003 October, each producing X-class flares, and with distinct active regions in both hemispheres. Such a sudden and widespread surge of activity is certainly remarkable, even though noted here only a posteriori.

Magnetic flux emergence leads directly to flare activity (e.g., Schrijver 2007), and the occurrence of multiple major flares in a given active region therefore points to a persistence in the pattern of flux emergence. This persistence seems to be required to explain the occurrence of homologous flares, since we believe that extracting the energy from stressed coronal magnetic fields requires their irreversible restructuring, for example, by magnetic reconnection. Nitta & Hudson (2001) show that this persistence can result in homologous CMEs in association with impulsive X-class flares. For reasons currently unknown, the strongest flux emergence, leading to the most energetic solar events, does not follow the relatively smooth pattern of flux emergence that defines the solar cycle and the occurrence patterns of less energetic events.

The striking variability in the occurrence of energetic events described in this Letter might correspond to a modulation of the event rate near the upper limit on flare energy. Such a cutoff is required by the nonconvergence of the flat occurrence power law of solar flares. The existence of a cutoff in particle fluences is already well established from the fossil records, which have the advantage of extending over longer periods of time and thus of capturing the rarer, extremely energetic events. The ^{14}C record suggests a maximum SEP fluence of some 10^{10} protons cm^{-2} (Lingenfelter & Hudson 1980), and fossil cosmic-ray records over longer timescales agree well with this limit (Reedy 1996). McCracken et al. (2001) set the cutoff at about 6×10^9 protons cm^{-2} (omnidirectional fluence) at >30 MeV based on nitrate concentrations in Greenland ice cores. This proxy has the advantage that it overlaps the historical record.

The SEP cutoff fluence corresponds roughly to the largest X-ray flare fluxes, of class X10 (Lingenfelter & Hudson 1980). Observing an analogous cutoff in the X-ray fluxes (or other measures of flare energy) is difficult, however, both because of the rarity of the most energetic events and because they tend to cause detector problems that make it difficult to obtain precise photometry (the *Geostationary Operational Environmental Satellite* [*GOES*] photometers themselves saturate at about this level). Such a cutoff in X-ray flare statistics, which best reflect total flare energy, has not yet been reported. Nita et al. (2002) actually do observe an upper cutoff in radio burst magnitudes, in a comprehensive study, but they also note calibration difficulties and other factors that may contribute to this. The SEP fluxes have a "streaming flux limit" (e.g., Reames 1999), so the agreement of the SEP cutoff with the presently observed maximum in the *GOES* event energies may be fortuitous.

Does any index of flare magnitude show a similar high-energy limit? The soft X-ray photometry from *GOES* provides the most stable long-term database of flare magnitudes, and we have analyzed it to answer this question. Figure 4 shows the distribution of M- and X-class flares for the period from 1975 September through 2007 January. This consists of 5637 M events, 424 X events, and 22 "superevents" above X10 (numbers inclusive of M1.0, X1.0, and X10.0). We do not show the superevents in the figure because of distortion due to saturation. The maximum likelihood method of Crawford et al. (1970), independent of binning, gives a fit over the M–X range of $dn/dS = 5520S^{-2.193 \pm 0.015}$ events per unit X-class interval, the differential distribution. This distribution predicts 24.6 superevents, whereas 22 were actually observed. Within errors, there is thus no downward break. The fit over the M–X range given here is slightly steeper than expected, probably because of the lack of background subtraction in the reported event magnitudes. The flare energy upper limit must therefore be significantly above X10—as noted by Schaefer et al. (2000), solar superevents, were any to have occurred, ought to have been detected by solar astronomers within the historical era.

Resolving this question—at what point does the flare energy distribution steepen?—would provide a important clue for students of the generation of solar magnetic flux and its delivery to the photosphere. Kucera et al. (1997) interestingly suggest that a cutoff may be observable directly in event distributions for smaller active regions, at lower event energies. Thus, the hypothetical cutoff in X-ray flare magnitudes might reflect the downturn in active region areas expected from the lognormal distribution noted for sunspot areas (Bogdan et al. 1988). The result regarding mean areas (Fig. 3) conflicts with the stability of the spot area distribution noted by Bogdan et al., but this may reflect the differing timescales studied. The existence of the needed cutoff in the distribution has been anticipated by Mullan (1975), who suggested relating the maximum energy of a stellar flare with the scale lengths present in the convection zone of the star.

6. CONCLUSIONS

We have shown, based on the decay phases of solar cycles 22 and 23, an unexpected example of large-amplitude variations in the occurrence of the most energetic solar events. We could also trace this pattern in SEP fluxes and in sunspot group areas. These most energetic events (*GOES* X1 or greater) do not follow the usual Poisson statistics with mean rates that govern lesser flares with shorter waiting times. The waiting times for the most energetic events indeed often exceed the active region lifetimes or the solar rotation period. Their statistics therefore reflect physics unrelated to coronal energy buildup and the mean flaring rate for a given active region. We suggest that solar interior dynamics dictates the pattern of occurrence of the most energetic events, rather than the coronal development.

This dramatic variability reduces the predictability of major hazards in space (e.g., Smith & Scalo 2007), since it is clear that a variable-rate Poisson distribution following the solar cycle as defined by a smooth sunspot number will not suffice. Worse yet, the flatness of the particle fluence distribution—which has an index of 1.2–1.4 (van Hollebeke et al. 1975; Gabriel & Feynman 1996), flatter still than the flare energy distribution at about 1.8 (e.g., Hudson 1991)—means that individual events will dominate the total X-ray and γ-ray fluences. At present, such events are basically unpredictable on timescales longer than a few days.

This work was supported by NASA grant NAG5-12878. I especially thank Bob Lin, Bob Reedy, and Albert Shih for their help during the preparation of this Letter. I also thank Ed Cliver for a reading of the preliminary version and Mike Wheatland for correspondence.

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