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STATISTICAL STUDIES OF THE SOLAR γ-RAY FLARES

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Flares are probably the most commonly known phenomena that release a large amount of energy from the Sun in forms of photons and charged particles. While it is believed that the solar flares result from the sudden release of the coronal energy through violent MHD activities, most investigations in the past decades have been focused on how an individual flare should occur in such a short time. Recently, a new avenue, based on statistical studies, has been opened for investigations of the solar flares [1,2,3]. The rationale behind the new approach arises from the recognitions that the solar corona is a driven-dissipative system, and that the MHD activities in the solar corona are highly nonlinear. Incidentally, these two components are found essential for the so-called "self-organized critical phenomena". Typical examples of the "self-organized critical phenomena" include the collapse of sandpiles and the avalanches.

The scenario of the self-organized criticality is that nonlinear, driven-dissipative systems tend to have internal regulating mechanisms that place the systems on the boundaries of marginal stability in some phase space, where fluctuations of all sizes are just excited. This self-regulating state is reminiscent of that in the critical phenomenon in equilibrium statistical mechanics. As a consequence of the critical state, the fluctuations exhibit power-law distributions.

The ISEE 3 space-craft has collected the soft-x-ray solar-flare data for years, and the data have been analyzed recently showing that the peak-x-ray luminosity exhibits an unchallengeable power-law frequency distribution [1,2], $f(L_x) \sim L_x^{-\gamma}$, where $\gamma \approx 1.8$. Such distribution has also been reproduced in theoretical models in the framework of self-organized criticality [1,2,3], reinforcing this idea applied to the solar flares.

The γ-ray electrons are a few orders of magnitude more energetic than the soft-x-ray electrons. It is not unreasonable to expect that the γ-ray may not obey the same power-law distribution as the soft-x-ray does since the γ-ray electrons may only be produced in sizable flares that are more energetic than the soft-x-ray flares.

(i) Peak-Luminosity Frequency Distribution:

With this expectation in mind, we analyzed the BATSE γ-ray solar flare data. The particular 2B catalog of the BATSE data that we choose extend from April 1991 through April 1993 and contain 3800 flares. Surprisingly, we find that the peak-γ-ray luminosity L_p of the flares, within each year as well as in the full two years, also obeys the same power-law distribution $\propto L_p^{-\gamma}$. The power-law distribution of the full data extends more than 5 orders of magnitude in number, with a best-fit power index γ about 1.7. It is noted that the solar activities are much higher during 1991-1992 than during 1992-1993, and yet the power indices do not change even noticeably over the entire duration of observations. This result is consistent with the soft-x-ray observations. Moreover, we also note that the power index γ for the γ-ray more or less agrees with that for the soft-x-ray. These features suggest that the γ-ray and x-ray electrons are of probably the same origins. That is, even a weak flare can produce the same ratio of γ-ray electrons to soft-x-ray electrons as a strong flare does. This finding may shed light to the electron acceleration mechanisms during magnetic reconnection.

(ii) Time Interval Frequency Distribution:

A complimentary study looking into how the flare sizes should distribute is to examine the time interval between successive flare events. Assuming the energy injection rates are the same over time, the time interval, or the build-up time for the coming flare, should be proportional to the size of that flare. We therefore analyze the time interval distribution, and find that the distributions also largely obey power-law: $f(\Delta t) \sim \Delta t^{-\beta}$. However, the power index decreases from $\beta = 2.2$ in 1991-1992 to $\beta = 1.6$ in 1992-1993. The full data is dominated by the active phase 1991-1992 data and therefore also shows a power-law distribution with an index $\beta = 2$.

The flattening of the power-law distributions for the energy-storage time must be related to the fact that the energy injection rate decreases from the active phase to the quiet phase. However, quantitatively how such changes can be determined within the framework of self-organized criticality remains to be an open question.

(iii) Flare Auto-Correlation Functions:

Since the duration of the flares is short compared with the interval between sucessive flares, one may apply the method of the galaxy-galaxy correlations for the occurence of flares in the time domain. The purpose of this exercise is easy to understand. The distributions explored in the previous sections are nothing more than the histograms of certain characteristics in the flares, which, among the hierachy of statistical properties, are the lowest level statistics. The next level is the pair correlation, and the next the triple correlation, etc. The higher level the statistics is, the more subtle properties it may reveal, such as the flare clustering.

In what follows, we examines the pair-auto-correlation function and the triple-auto-correlation function, respectively. We define the pair correlation function as: $C_2(\tau) \equiv \int_0^T n(t)n(t+\tau)dt/T$ and the triple correlation function as: $C_3(\tau) \equiv \int_0^T n(t)n(t-\tau)n(t+\tau)dt/T$, where n is the number density of the flares and T is the total integration time. To retain the energetic information, we divide the data into two peak-luminosity bands. When fitted by power laws, the pair correlation functions have the form: $C_2(\tau) \sim \tau^{-\alpha}$, where $\alpha \approx 0.14$ for both luminosity bands. They are rather flat correlation functions, indicative of power spectra $P(\omega) \sim \omega^{-0.86}$, very close to a scale-invariant $1/f$ spectrum. In the log-log plots, we discover that there is another quasi-periodic component superposing on the power-law correlation. We substract the actual data from the underlying best-fit power law, and Fourier transform the residued component with respect to $log(\tau)$. The result exhibits a rather distinct peak, suggesting that the pair correlation contains a peculiar component periodic in $log(\tau)$, with a period about $log(\tau_{day}) = 1.35$, where τ_{day} is the time delay in unit of a day. It is not clear how physically such a peculiar component should arise.

For the flare triple correlations, we find that the three curves have the same forms: $C_3(\tau) \sim \tau^{-\xi}$, where $\xi \approx 0.32$. Again, the modulation periodic in $log(\tau)$ is also very distinct in C_3.

In sum, we have confirmed that the γ-ray solar flares show similar statistical properties as the x-ray solar flares. This fact reveals that the eletron acceleration mechanisms should be the same for both the γ-ray and x-ray electrons, regardless of the strengths of the flares. In addition, as the energy injection rate is higher in the more active phase than in the quieter phase, the power-law distributions of the energy-storage time also change accordingly, in that the distribution appears steeper in the more active phase. This result is somewhat in contradiction to the intuition, and it may reveal some subtle informations regarding how the magnetic energy is stored in the corona. So far, no explanation can be given. Finally, we also find power law forms in the flare two-point and three-point auto-correlation functions, with the two-point correlation function appearing very flat, indicative of an $1/f$ power spectrum. Superposing on the power-law auto-correlation functions is another component periodic in $log(t)$. Again, this component has so far no plausible explanation.

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