The Log-normal Distributions of Coronal Mass Ejection-related Solar Flares and the Flare/CME Model of Gamma-ray Bursts

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Abstract

It is known that gamma-ray bursts (GRBs) are highly time-variable and the statistical distribution of physical variables show log-normal. The solar flares are also highly time-variable phenomena, but the physical quantities of them show power-law distribution. GRBs are believed to be the emission from the relativistic outflow from the central engine. On the other hand, the outflow from the Sun is known as coronal mass ejections (CMEs). We analyze the distributions of some quantities of CMEs and the solar flares related to CMEs (CME-related solar flares) to compare with the distributions of GRBs. We found the distributions of X-ray peak fluxes of CME-related solar flares and the speed of CMEs are very similar to log-normal distribution. Hence the distributions of GRBs are similar to those of CME-related solar flares and CMEs, and the ejection mechanisms of outflow from the central engine of GRBs and the Sun might be similar, that is, magnetic reconnection. We propose the new model of the central engine of GRBs by the analogy of solar flares and CMEs.

1. Introduction

The gamma-ray bursts (GRBs) are very energetic and highly time-variable phenomena. The statistics of physical quantities such as peak fluence, total duration, peak interval, pulse duration, and break energy show log-normal distributions (McBreen et al. 1994 [7], Li & Fenimore 1996 [6], Nakar & Piran 2002 [8], Preece et al. 2000 [11]). On the other hand, it is well known that solar flares are also highly time-variable. But the statistical distributions of physical quantities of flares such as peak count rate, total duration, waiting time show power-law (Dennis 1985 [3], Pearce et al. 1993 [10], Crosby et al. 1993 [2]). What is the origin of these differences of the distributions? It will be due to the difference of the photon-emitting region; GRBs are suggested to be the emissions from relativistic flow ejected from the central engine, while the emissions associated with solar flares come from the low corona of the Sun. Hence, when we compare GRBs and solar flares, we must take into account the mass ejections

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from the Sun rather than flare itself. The mass ejection from the Sun is known as coronal mass ejections (CMEs); CMEs are the plasmoids ejected from the Sun to the interplanetary space. It is believed that solar flares are caused by magnetic reconnections and plasmoids are generated by the reconnection; when the plasmoids gain large energy, they can escape from the magnetosphere of the Sun, and be observed as CMEs. Thus, we analyze the statistical distributions of the CME and CME-related solar flares, and compare them with those of GRBs.

2. Data analysis

We take 254 samples of CME-related solar flares, and 4925 samples of CMEs from Oct 19 1996 to Dec 26 2001. The selection rule of CME-related solar flares as is follows: at first, we prepare the solar flare data of SGD (Solar Geophysical Data) and CME data of the SOHO/LASCO CME CATALOG; next, we compare the leaving time of a CME from the solar surface with the starting time and the peak time of X-ray fluxes of solar flares. If the leaving time of the CME is between the starting time and the peak time of a flare, we identify the CME is associated with the flare. By this rule, we pick up CME-related solar flares for data analysis.

3. Results

The statistical distribution of the X-ray peak fluxes of solar flares and the speed of CMEs show the distribution very similar to log-normal distribution (Fig.1); we checked that the distribution of them cannot be fitted to Gaussian distribution. Thus the statistical distribution of physical quantities of GRBs and those of the CME-related solar flares and CMEs are very similar.

The log-normal distribution is the distribution that has characteristic value, whereas power-law distribution has no characteristic value. The probability density function of log-normal distribution is written as follows (Aitchison & Brown 1957 [1]):

$$f(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\log x-\mu)^2}{2\sigma^2}\right] & (x > 0), \\ 0 & (x \leq 0), \end{cases} \tag{1}$$

where x is physical variable, and μ, σ^2 are the sample mean and variance of $logx$, respectively. The log-normal distribution is generally explained by statistical effects of the production of physical variable by mathematical aspect, and Ioka & Nakamura (2002 [5]) shows the log-normal distributions of GRBs can be explained by this manner. But we think physical meaning exists in log-normal distribution; as for solar flares, the distributions of physical variables of solar flares are power-law, whereas those of the CME-related solar flares and CMEs are log-normal.

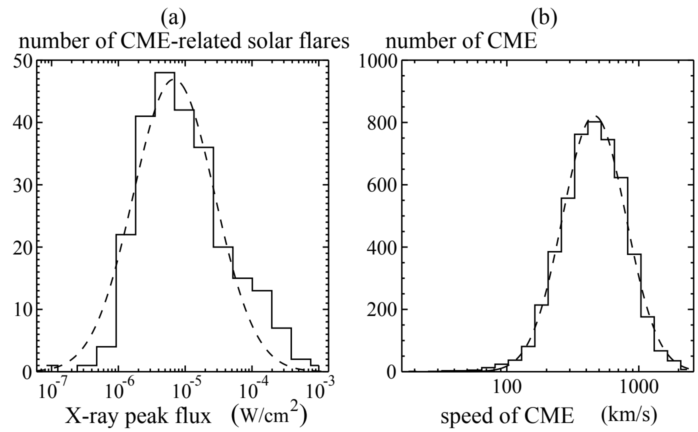

Fig. 1. (a) The distribution of the X-ray peak fluxes of CME-related solar flares. Horizontal axis is X-ray peak flux in logarithmic scale in unit of W/cm^2, longitudinal axis is the number of CME-related solar flares. The dashed curve is the best-fitted log-normal distribution. (b) The distribution of the speed of CMEs. Horizontal axis is the speed of CME in logarithmic scale in unit of km/s, longitudinal axis is the number of CMEs in linear scale. The dashed curve is the best-fitted log-normal distribution.

The difference among them is probably due to energy of flares; CMEs must have energy enough to escape from the Sun. Otherwise they will fall down to the Sun and cannot be observed as CMEs; then the characteristic values exist as the threshold in the statistical distribution of CME-related solar flares and CMEs.

4. Discussion

The similarity of the distribution of GRBs and CME-related solar flares and CMEs suggests that the distribution of the phenomena associated with mass ejection show log-normal distribution. There is another observation supporting this suggestion: X-ray emission from the Cyg X-1. Negoro & Mineshige (2002 [9]) found that the distributions of X-ray intensity and the time intervals of X-ray peaks from Cyg X-1 whose intensity is larger than a certain value, which is thought to be associated with jet from Cyg X-1, show log-normal.

Now we suggest the flare/CME model of GRBs based on this idea (Fig. 2). The central engine of GRBs are supposed to be driven by the collapse of a massive star (collapsar) or the merging of NS-NS or BH-NS binary, and the system of a stellar mass black hole and an accretion disk will be formed. The accretion disk will be highly magnetized because a black hole cannot support large magnetic field; hence magnetic reconnection will occur in the accretion disk, and plasmoids will be generated. If a large flare occurs, plasmoids will gain large energy enough to escape from the magnetosphere of the disk, and will become relativistic shells.

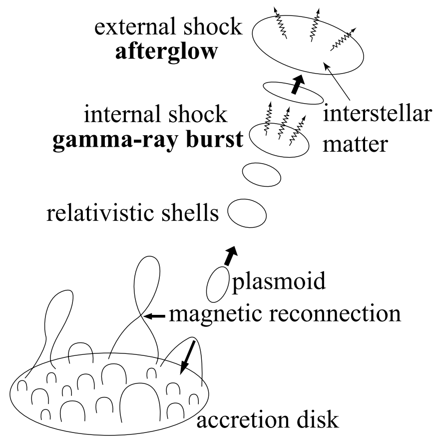

Fig. 2. The flare/CME model of gamma-ray bursts.

Flares will occur repeatedly, and plasmoids will be ejected many times. If a faster shell overcomes a slower shell, an internal shock will occur. When the shell collides with interstellar matter, the external shock will be formed and afterglow will be emitted. In our model, relativistic shells are comparable to CME from the Sun; in fact, the collision of CMEs are found by radio observation (Gopalswamy et al. 2001 [4]).

5. References

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