Log-Normal Distributions in Cygnus X-1: Possible Physical Link with Gamma-Ray Bursts and Blazars

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Abstract

Prompted by recent discoveries of log-normal distributions in gamma-ray/X-ray temporal variabilities of gamma-ray bursts (GRBs) and blazars, we re-examine the X-ray variability of Cygnus X-1 in the hard/low state using Ginga data in 1990. It was previously reported that the distributions of the time intervals between X-ray shots (flares) deviated from the Poisson distributions at short time intervals: the occurrence of shots tended to be suppressed for several seconds before and/or after a shot event. Detailed analyses show that this deviation is larger for shots with larger peaks, and that the time-interval distributions for large shots approach log-normal distributions with a peak at the interval of 7–8 s. Furthermore, we also show that the peak-intensity distribution for the shots is consistent with the log-normal distribution, though no typical peak intensity can be seen. This might indicate the presence of a physical link connecting the physics of black hole accretion flow and that of jet/GRB formation.

Key words: accretion, accretion disks — methods: statistical — galaxies: jets — gamma rays: bursts — X-rays: individual (Cyg X-1)

1. Introduction

Gamma-ray bursts (GRBs) may be the most enigmatic objects in present-day astronomy. Among their peculiar properties, highly aperiodic time variability is undoubtedly one important aspect. Among various timing analyses, we pay special attention to one by Li and Fenimore (1996), who found log-normal distributions for the peak fluence and peak time intervals of GRBs (for careful and detailed analyses, see Nakar, Piran 2002; Quilligan et al. 2002). Although its physical meaning is not obvious, it is expected that this feature may contain an important clue to understanding the central engine of GRBs.

Apparently similar, highly aperiodic intensity fluctuations are known in X-rays from Galactic black hole candidates (GBHCs) in the hard/low state, though, in the other states, similar, highly aperiodic variations have not been observed, except for rather periodic flares known as quasi-periodic oscillations (e.g., van der Klis 1995). One may thus ask if the variability properties of GBHCs in the hard state share common characters with GRBs. An affirmative answer is actually anticipated in a sense, since the central engines of GRBs are often discussed in terms of accretion models (e.g., Narayan et al. 1992, 2001). The basic idea underlying these models is that, whatever the origin might be (black hole–neutron star mergers, black hole–stellar core mergers, and so on), the final configuration may likely be a stellar-mass black hole surrounded by a massive accretion disk or torus with a mass ranging between 0.01–1.0 $M_{\odot}$. If so, it is natural to expect some similarities to exist in gamma-ray and X-ray variabilities of GRBs and GBHCs. This expectation becomes even more strengthened by the recent discovery of log-normal distributions in the blazar variability by D. Yonetoku and T. Murakami (in preparation).

However, negative results have already been reported based on Ginga observations of the prime GBHC, Cygnus X-1 (Negoro et al. 1995, hereafter N95). The time intervals between adjacent flare-like events (called X-ray shots), $\Delta t$, basically follow exponential functions, but a broken exponential function. In this Letter, we put forward this discovery by performing new analyses of shots with large peaks using the same Ginga data of Cyg X-1 with N95, and discuss its physical meaning.
2. Data and Peak Detection Algorithm

We reanalyzed the Ginga LAC data of Cyg X-1 in the hard state on 1990 May 9–11. The minimum time resolution and the energy band of the data used were 7.8 (1/128) ms and 1.2–58.4 keV binned into 12 energy channels. The net exposure time was 16.22 ks (N95).

The properties of time variations of Cyg X-1 are basically different from those of GRBs, though both exhibit flare-like events, so-called shots and bursts, respectively. In addition to a big difference in the duration between extreme transient outbursts (lasting for less than $\sim 100$ s in GRBs) and the hard state (lasting for more than 1 month in BHCs), the short-term variations on the timescales of less than 10 s are also different. It is now clear that the variability of Cyg X-1 consists of multi-components: shots with the typical peak duration of 0.1–0.2 s, and spikes with much shorter duration and smaller peaks (Negoro et al. 2001). Furthermore, the shot peak intensities are rather smoothly distributed down to smaller ones, although the minimum ends are not clear due to the statistical count fluctuations (N95; Focke 1998). These and the statistical fluctuations (worse S/N ratios) prevent us from defining a ‘reliable’ peak for small shots and an ‘apparent’ bottom between adjacent shots.

Thus, we do not adopt the Li and Fenimore’s (1996) peak detection algorithm, but the same detection algorithm as N95. This leads to interesting results, as shown later. We changed, however, the algorithm to calculate the local mean number of counts, $\langle p \rangle$, in order to select the shot peaks as free as possible from detection criteria: we calculate $\langle p \rangle$, not from the numbers of counts at intervals of 32 s (N95), but from those in a bin to be checked and neighboring bins in $T_m$ (including the checked bin) on its either side (Focke 1998). Namely, $\langle p \rangle$ in an $i$-th bin is estimated as $\langle p \rangle(i) = \sum_{j=i-T_m/t_b+1}^{i+T_m/t_b-1} x_j$, where $t_b$ is the bin width, and $x_j$ is the number of X-ray counts in a $j$-th bin. This estimation gives a more definite local mean for each bin than the previous one, and does not yield discontinuity at every 32 s intervals, as before. We have confirmed, however, that this change essentially has little effect on this and previous results. We calculate $\langle p \rangle$ for each bin, and select peaks using following criteria: the peak number of counts $p$ of the shot should be larger than 1.5–3 times $\langle p \rangle$, and should have the maximum number of counts within a certain duration $T_p$ on either side.

We note that the parameter $T_m$ has an influence on the peak interval distributions. However, this dependence is not recognized in distributions for shots with $p \gtrsim 2.2 \langle p \rangle$, to which we pay attention here. $T_m$ is set to be 64 s, much longer than the duration which we are interested in and shorter than the timescale of the long-term variations. $T_p$, on the other hand, affects the results of the peak intensity distribution, and is set to 0.25 s from the typical shot duration obtained from the mean profile of the shots (N95). All of the data are binned on $(t_b = 31.25 \text{ ms})$ intervals in order to avoid large statistical count fluctuations. This also does not affect the following results qualitatively. Thus, $\langle p \rangle$ is estimated from 127.96875 s ($=2T_m-t_b$) data with a checked bin being at the center.

3. Distributions of Peak Intervals and Intensities

A log-normal function in this paper is expressed as
Poisson distribution at longer intervals of $\Delta t \geq 10^2$. These enhancements make the shot occurrence rates, excluded in the distributions, and other artificial effects not due to data gaps, by which intervals are completely gradually, but around $p \simeq 2.3(p)$ ($\simeq 336$ c/31.25 ms), mainly due to a sudden drop at $\Delta t = 2-6$ s. For instance, the occurrence rate at $\Delta t = 2.25-3.25$ s for shots with $p \geq 2.35(p)$ is about half of what is expected from the Poisson distribution at longer intervals of $\Delta t \geq 10.25$ s.

On the other hand, we have confirmed that enhancements at $\Delta t \sim 50$ s and $\Delta t \sim 70$ s in figure 1 are real, and not due to data gaps, by which intervals are completely excluded in the distributions, and other artificial effects. These enhancements make the shot occurrence rates, $\lambda$, defined as frequency $\propto \exp(-\lambda t)$, smaller, and this and poor statistics make suppression at $\Delta t = 2-6$ s in the top and middle panels in figure 1 less visible, compared with N95.

We may caution that it is not yet clear if the distributions are really log-normals rather than anything else because of the large error bars. We also point out, however, that the same might be true for the GRB cases. The difference between a broken exponential function and a log-normal function is not so clear at $\Delta t > \mu$, as shown in figure 1. It might be worth reinvestigating the peak interval distributions in previous GRB timing studies, while taking account of the suppression at short intervals.

Figure 2 depicts the dependence of the log-normal peak positions, $\mu$, on the selected peak intensities. A significant shift of the peak position, $\mu$, by the magnitude of the shots is not recognized. Fits to histograms binned into 2 s give $\mu = 7.5_{-2.3}^{+1.2}$ for $p \geq 2.25(p)$ at $\Delta t \geq 6$ s, $\mu = 7.5_{-1.2}^{+1.2}$ for $p \geq 2.35(p)$ at $\Delta t \geq 2$ s, $\mu = 6.9_{-2.3}^{+2.3}$ for $p \geq 2.5(p)$ at $\Delta t \geq 2$ s, and $\mu = 9.8_{-3.4}^{+3.4}$ for $p \geq 2.6(p)$ at $\Delta t \geq 2$ s. This suggests the existence of a particular time interval in this system.

3.2. Peak Intensity Distribution

The number of a peak-bin count, $p$, is approximately proportional to the total number of counts of the shot, i.e., “peak fluence”, since the shot profile is almost independent of the peak intensity (Negoro et al. 1994). To investigate the peak intensity distribution, we only used the May 9 and 11 data with similar local mean numbers of counts, $\langle \bar{p} \rangle \simeq 150$ c/31.25 ms. We, however, did not exclude data with any $\langle p \rangle$ different from N95, because of the change in the estimation of $\langle p \rangle$. This does not result in any qualitative difference in the following results.

We found that the peak intensity distribution is well consistent with a log-normal distribution, though no typical peak intensity can be seen (points with 1 $\sigma$ errors and solid line in figure 3). Of course, this is not a surprising
matter because the shape of the right side of a log-normal function is similar to an exponential function, as already noted. A fit to the data at $p > 240$ c/31.25 ms, where the data are almost completely accumulated, with a log-normal function gives $\mu = 140 \pm 14$ c/31.25 ms$^2$. Note that this peak intensity at the maximal frequency is almost the same level as the mean count rate $\sim 150$ c/31.25 ms. The shape of the peak intensity distribution depends slightly on $T_p$ (N95), but the distribution is always consistent with a log-normal function with $\mu = 100–200$ c/31.25 ms. Thus, the existence of the peak is still a matter to be confirmed.

In the previous subsection, we have shown that large shots give rise to the log-normal distributions for the peak intervals. Inversely, do shots with long intervals as producing a log-normal distribution for time intervals have a log-normal distribution for peak intensity? To investigate this problem, we only selected shots with $p \geq 2.0(p)$ (open circles), of which peak intervals are widely distributed up to $\sim 40$ s (cf., those for shots with $p \geq 1.5(p)$ are only up to $\sim 15$ s; see the top panel of figure 1 in N95). The data show that all distributions for shots with long preceding and/or following intervals, say $\Delta t > 5$ s or 10 s (closed squares), are more consistent with an exponential distribution (dashed line) than a log-normal distribution having a typical peak intensity at a high count rate (dash-dotted line for the case of $\mu \sim 320$ c/31.25 ms). Thus, a tendency to support the above hypothesis is not recognized.

4. Discussion

In the present study we re-examined the temporal variability of Cyg X-1 and found for the first time a similarity to the variability of GRBs. The similarity and differences should contain important physics to probe the central engine of GRBs.

The most intriguing difference is that the Cyg X-1 shots, including small ones, have smooth (exponential) peak-interval and peak-intensity distributions, and GRBs and blazar flares, on the other hand, have log-normal distributions, indicating the presence of a typical timescale and size of energy. Note that a smooth (power-law) peak-intensity distribution is known to exist in solar flares (Dennis 1985), and is also found in 3D MHD flow simulation data (Kawaguchi et al. 2000; Agol et al. 2001). Such a power-law distribution is claimed to be ubiquitous in nature (Bak 1996), and is often discussed in terms of the dynamics of diffusion systems with interacting degrees of freedom (self-organized criticality, see Bak et al. 1988; Mineshige et al. 1994; arguments about the exponential and power-law distributions, see Takeuchi et al. 1995). It can be conjectured that MHD turbulence created by various MHD processes in accretion disks exhibit spatial fractal patterns which could be responsible for the smooth distributions of flare amplitudes (Kawaguchi et al. 2000).

On the other hand, the typical peak interval duration, 7–8 s, found in the (log-normal) peak interval distributions for large shots, seems to correspond to the timescales of filling/refilling energy in the innermost part of the accretion flow before/after the shot occurrence (e.g., N95). What happens if a large amount of (sudden) accretion takes place in the inner part of the accretion disk? VLBI observations of the extragalactic jets (Junor et al. 1999) and recent MHD jet simulations (Kudoh et al. 2002) indicate that jets originate from a compact region with a size of several tens to hundreds of Schwarzschild radii. It is of great importance to note that radio flares are observed only after large X-ray flares in the Galactic microquasar, GRS 1915–105 (Mirabel et al. 1998). Furthermore, recent discovery of short-term temporal correlation between X-rays and optical in the BHC, XTE J1118+480, strongly suggests that the outflow (or jet) follows the shot (Kanbach et al. 2001).

It may be that jets can be produced only when large enough disturbances have been added to the innermost part of the accretion flow.

To summarize, we newly discovered a similar behavior in Cyg X-1 to that of GRBs and blazars, if we only selected large shots from the variability light curves of Cyg X-1. There could also be large- and small-amplitude variations in accretion disks at the centers of GRBs, as in GBHCs, but only large variations (which satisfy a certain criterion) can produce observable bursts through jets in GRBs.

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