Estimation of Luminosity Function of GRB observed by MAXI

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Abstract

The Luminosity Function (LF) of gamma-ray bursts (GRBs) is defined as the number of bursts per unit luminosity interval. By estimating the LF, we can understand the distribution of GRBs as a function of luminosity and redshift. Although various studies have estimated the LF of GRBs, the results have been uncertain across different authors. In particular, estimations in the low energy range haven't been made yet. The Monitor of All-sky X-ray Image (MAXI) is one of the X-ray instruments sensitive to the low energy in the range of 2 to 20 keV, capable of detecting such dark GRBs. The LF is conventionally plotted using observed data with known redshifts z. However, MAXI has only a limited number of GRBs with known z, making direct estimation challenging. To deal with this limitation, we conducted a Monte Carlo simulation to generate a large number of artificial GRB samples. Our results indicate that we can estimate the LF in the low luminosity range, which MAXI has the potential to detect Low-Luminosity GRBs below $10^{49.5}$ erg s^{-1}.

1. Introduction

MAXI's observation

Observation period: 8/15/2009 – (observed 157 GRBs)

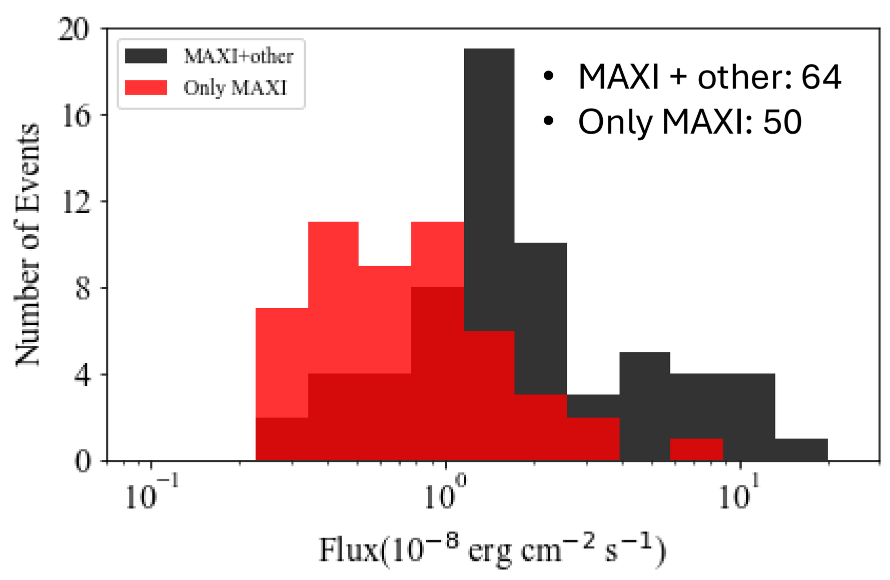
- MAXI + other detectors with simultaneously: 82 events
- Only MAXI: 75 events

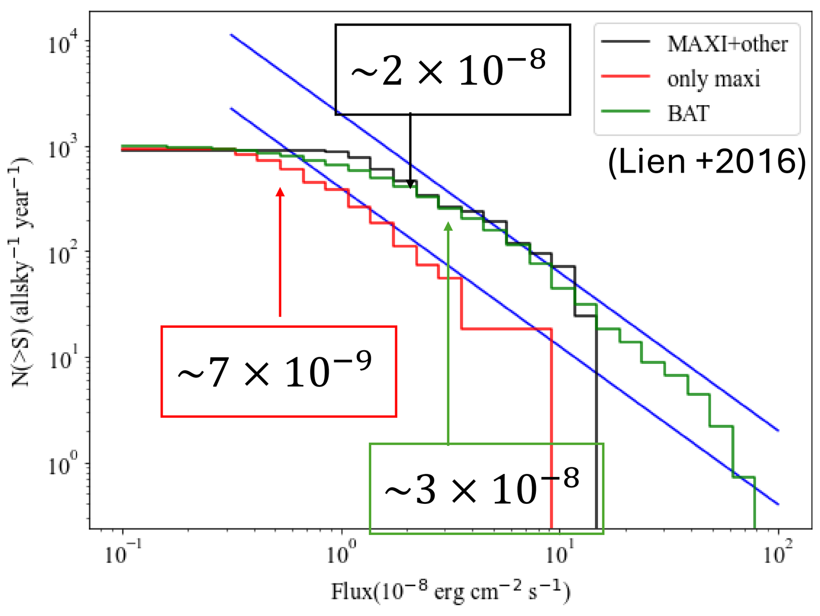
Results of spectral analysis for MAXI GRBs (analyzed 114 events)

- detect the low flux ($< 10^{-8}$ erg cm^{-2} s^{-1}) events (46% out of analyzed events)
- Only MAXI events indicate nearby and Low-Luminosity GRB

➡ MAXI may be able to observe the rare GRBs that other detectors cannot detect

We want to understand about luminosity distribution of MAXI GRBs



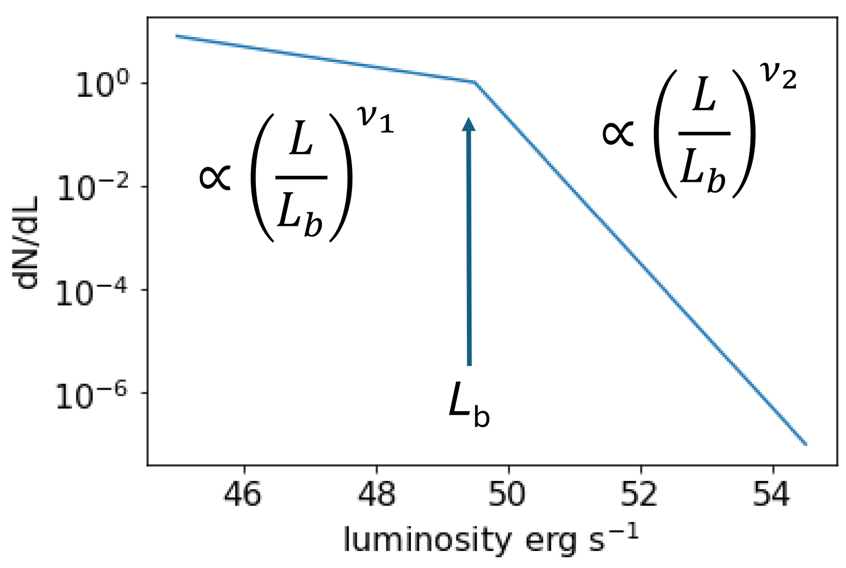


2. Luminosity Function (LF)

defined as the number of bursts per unit luminosity interval

$$\frac{dN}{dL} = \begin{cases} \left(\frac{L}{L_b}\right)^{\nu_1}, & L \le L_b \\ \left(\frac{L}{L_b}\right)^{\nu_2}, & L > L_b \end{cases}$$

L_b: luminosity at the break of the power law



Estimating the LF for GRB

- understand the distribution of GRBs as a function of luminosity and redshift z.
- infer the GRB rate R_{GRB} (Gpc^{-3}yr^{-1})

3. Methods

A LF for GRB is conventionally plotted using observed data with known z.
MAXI has a limited number of GRBs with known z.
➡ It is challenging to estimate directly.

To deal with this limitation,
we conducted a Monte Carlo simulation to generate many artificial GRB sample.

- Determine the LF form (parameters: ν_1, ν_2, L_b)
- Assume the R_{GRB}
- Generate luminosity and z samples
- Determine the spectrum (Band function)
- Calculate the flux (2 – 20 keV)
- Create the logN-logS
- Compare observed samples and simulation samples

- LF form (Wanderman & Piran 2010)
$\nu_1 = -0.2, \nu_2 = -1.4, L_b = 10^{49.5}$ erg s^{-1}

- GRB rate (Porciani & Madau 2001)
$$R_{GRB}(z) = 23\rho_0 \frac{e^{3.4z}}{e^{3.4z} + 22.0} (\text{Gpc}^{-3}\text{yr}^{-1})$$

- Spectral model (Band +1993)
$$\Phi(E) = \begin{cases} A\left(\frac{E}{100\text{ keV}}\right)^{\alpha} exp\left(-\frac{(2+\alpha)E}{E_{peak}}\right), & E \le \frac{\alpha-\beta}{2+\alpha}E_{peak} \\ A\left(\frac{(\alpha-\beta)E_{peak}}{(2+\alpha)100\text{ keV}}\right)^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\text{ keV}}\right)^{\beta}, & E > \frac{\alpha-\beta}{2+\alpha}E_{peak} \end{cases}$$

- $E_{peak} - L_{iso}$ correlation(Nava +2012)
$$E_{peak} = 10^{-22.98} L_{iso}{}^{0.49}$$

3. Methods (continue)

Performing a Monte Carlo simulation, we created z and luminosity samples.

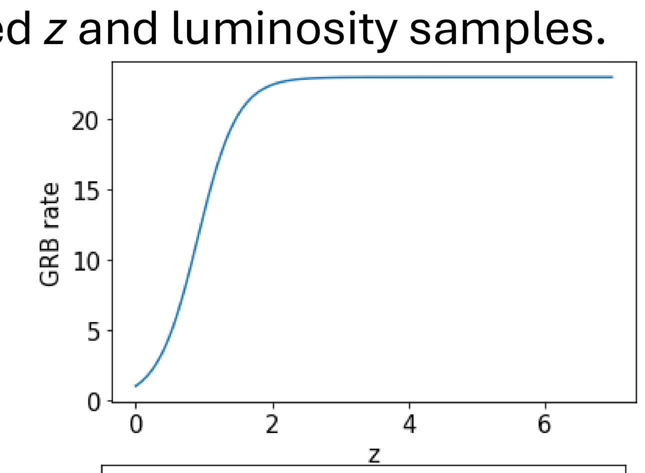
- z sample

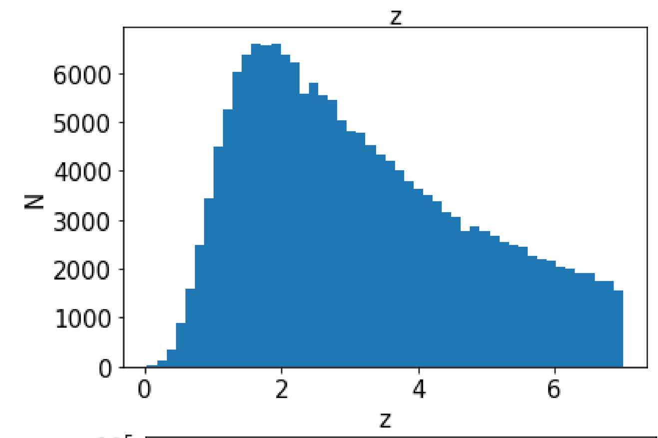
$$dN = \frac{R_{GRB}(z)}{1+z}\frac{dV}{dz}dz$$

dV/dz: variation of the volume of the universe as a function of the z (Zitouni +2021)

$$R_{GRB}(z) = 23\rho_0 \frac{e^{3.4z}}{e^{3.4z}+22.0} (\text{Gpc}^{-3}\text{yr}^{-1})$$

(Porciani & Madau 2001) $\rho_0 = 1$

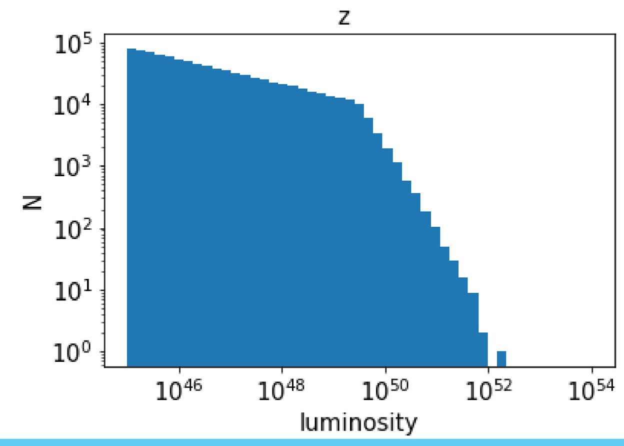




- Luminosity sample

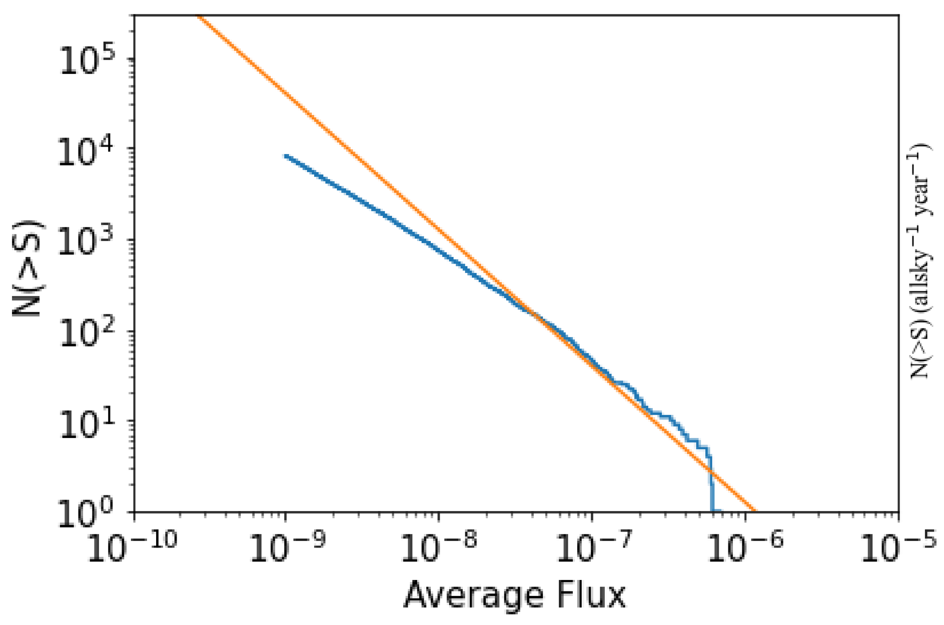
$$\frac{dN}{dL} = \begin{cases} \left(\frac{L}{L_b}\right)^{\nu_1}, & L \le L_b \\ \left(\frac{L}{L_b}\right)^{\nu_2}, & L > L_b \end{cases}$$

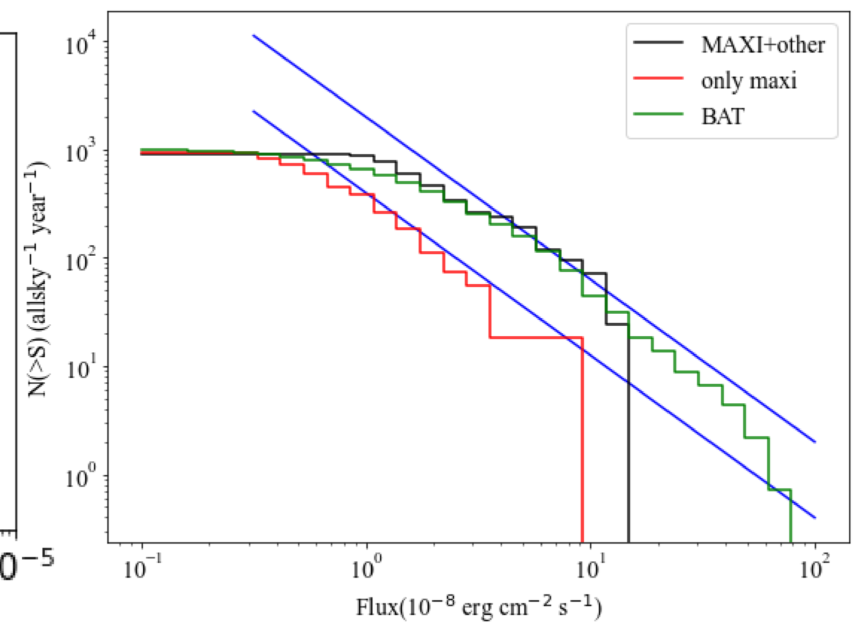
$$\nu_1 = -0.2, \nu_2 = -1.4, L_b = 10^{49.5} \text{ erg s}^{-1}$$



4. Results

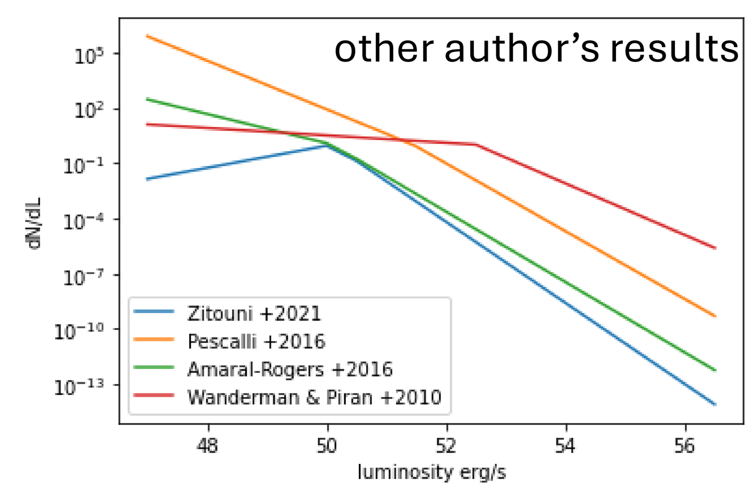
Detection limit of MAXI: Flux $> 10^{-9}$ erg cm^{-2} s^{-1}
Energy range: 2 – 20 keV





For L_b=$10^{49.5}$, the simulation results are consistent with the observation results.
For $L_b > 10^{49.5}$, they are not consistent.

MAXI GRBs would be distributed in the low-luminosity region compared to results from other authors (e.g., Swift, Fermi).



- Luminosity evolution

Several authors have reported that luminosity is proportional to z.

$$L = L_0(1+z)^k$$

For application to LF, the function is shown as

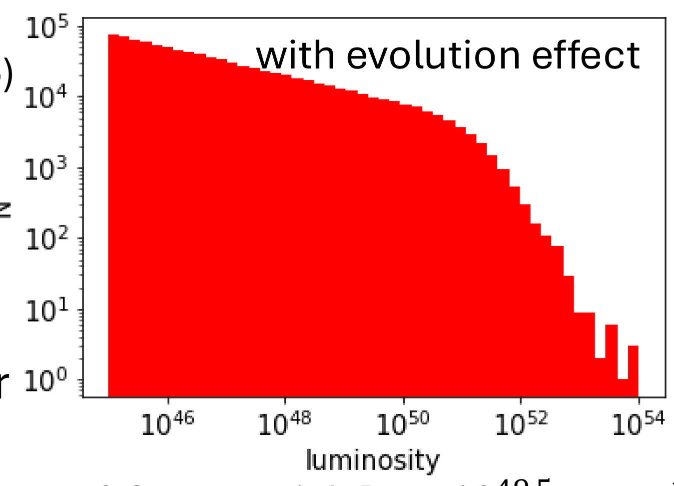
$$L_b = L_0(1+z)^k$$

L_0: intercept, k: slope
$k = 2.5$ (Pescalli +2016)

➡ GRBs are distributed with high-luminosity at high z.

We also performed the simulation with luminosity evolution .

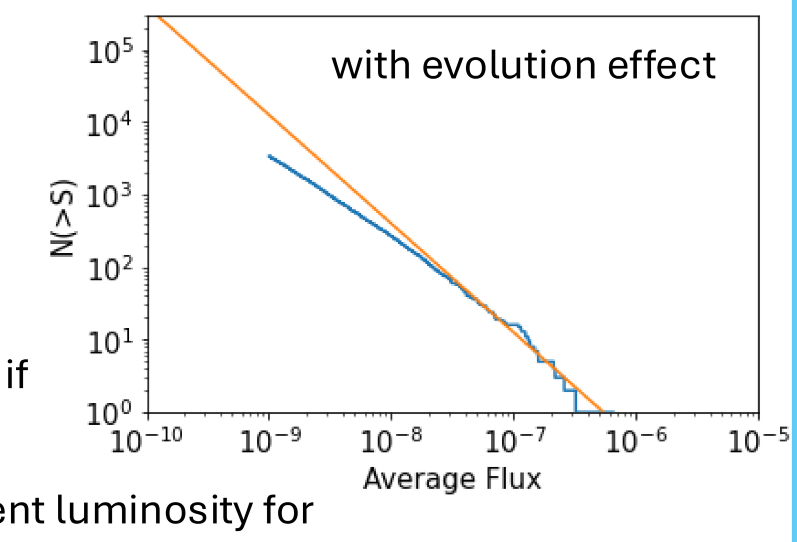
Even with evolution, L_b and L_0 are about an order of magnitude smaller than in other studies.



$\nu_1 = -0.2, \nu_2 = -1.4, L_0 = 10^{49.5}$ erg s^{-1}
average $L_b = 10^{51}, k = 2.5$

➡ MAXI GRBs possibly include more low-luminosity GRBs than those detected by other detectors.

➡ MAXI have capable of detecting low-luminosity GRBs.



If the ratio of high-luminosity samples is larger, the simulation results are not consistent with the observations.
We need to take luminosity evolution into account if MAXI detects high-luminosity at high z.

(Without evolution, high z GRBs don't have sufficient luminosity for MAXI's detection limit, thus they are excluded from the logN-logS due to its energy range and detection limit.)