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How Fast are Gamma-ray Bursts?

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Background and Research Goal

Gamma-ray bursts (GRBs) are some of the most powerful explosions in the universe, formed by the merger of two neutron stars or through the core-collapse of a massive star. They outshine all other gamma-ray sources since the big bang and can be divided into short and long bursts. Short bursts last less than 2 seconds while long bursts last more than 2 seconds. They are characterized by relativistic jets that are launched at the poles and can have black holes that reside in the center.
The goal of this research is to use the minimum variability timescale to determine methods to calculate the radius of gamma-ray emission and the maximum allowed peak energy for GRBs. Additionally, the goal is to estimate a redshift for GRBs that have no recorded redshift, and use this to approximate a luminosity distance for GRBs.

Research Summary

Using the Fermi Gamma-ray Space Telescope data, I determined the physical parameters of the outflow of various gamma-ray bursts. To do this, I calculated the shortest variations in the GRB light curves, the minimum variability timescale (MVT). After obtaining this timescale I estimated the Lorentz factor, and I was able to calculate the radius of the gamma-ray emission for each GRB. The analyzed GRBs included long and short bursts, as well as strong and weak ones. Using a GRBs fluence, peak energy, and isotropic energy, I used the Amati relation to create a redshift probability distribution that produced the unknown redshift for select GRBs. The redshift with the highest predicted probability was used in order to calculate the luminosity distance of the GRBs. Finally, I derived the highest peak energies allowed in GRB– given a Kerr black hole central engine.

Methods

This project utilized Fermi Gamma-ray Space Telescope data, obtained from NASA's High Energy Astrophysics Science Archive Research Center (HEASARC).

Using several Python scripts, I was created light curves of each GRB using the time-tagged event (TTE) type data, analyze the minimum variability timescale (MVT) for each burst for different energy ranges (10-50, 10-300, 10-1000 keV), and calculate the radius of the gamma-ray emission for each GRB. I took careful note of the following: the time at which the GRB triggered the detectors and the location - there are 12 detectors that monitor different locations in the sky. Figure 1 shows an example of an MVT versus lightcurve plot of a GRB, which illustrates anticorrelation between the flux and the MVT. For each GRB, I used the lowest MVT from all energy levels along with findings from Sonbas et al. in order to calculate the Lorentz factor (Γ). Using equation (1) I solve for the Lorentz factor (Γ):

$$MVT = 1.04(\Gamma/\Gamma_{knee})^{-4.05} \qquad (1)$$

From Sonbas et al., Γ_{knee}= 225. Then, using the equation (2) I calculated the radius of gamma-ray emission for each GRB (See Table 1 in Results).

$$R = 2\Gamma^2 c(MVT) \qquad (2)$$

Next, I used the Amati Relation to calculate the luminosity distance of several GRB that did not have a recorded redshift (z). I wrote a Python script that takes inputs for fluence, peak energy, and spectral shape from NASA's Fermi GBM Burst Catalog for each GRB and create a plot of the redshift band against the Amati Relation line. An example of this is shown in Figure 2. In order to create redshift probability distribution I wrote a function that would compute the perpendicular distance from each point to the Amati relation line, the higher the probability the closer the point is to the line. In the probability distribution, the redshift point with the highest probability was used to determine the luminosity distance of the GRB. An example of a redshift probability distribution is shown in Figure 3. Finally, I conducted the cosmological calculation for luminosity distance for each GRB using the astropy.cosmology Python package. The results for the redshift and luminosity distance for the various GRB are displayed in Table 2.

Deriving the highest peak energy ($E_{peak)}$ involved using the following two equations from Mészáros et al.:

$$kT_0 = (k/m_e c^2)(L_0/4\pi r_0^2 c\Gamma_0^2 a_{rad})^{1/4} \qquad (3) \qquad r_0 = f_1(a) 6GM_{bh}/c^2 \qquad (4)$$

Where a_{rad} is the radiation constant, and $f_1(a) = 2 - a + 2(1-a)^{1/2}$ is a function for the rotational parameter, a, which defines the innermost stable circular orbit radius of the jet of the GRB. We assumed a central engine black hole mass of 2 and 10 for theoretical purposes and once we determined a temperature (T_0) we used the relation $E_{peak} = 3.9kT_0$ to establish the peak energy allowed for each black hole central engine. Next, given that the maximum known E_{peak} for a GRB ~15 MeV, we determined the possible mass of the black hole in the center of the GRB. The results for this portion of the project is shown in Table 3 and a plot of E_{peak} versus the rotational parameter is illustrated in Figure 4.

Results

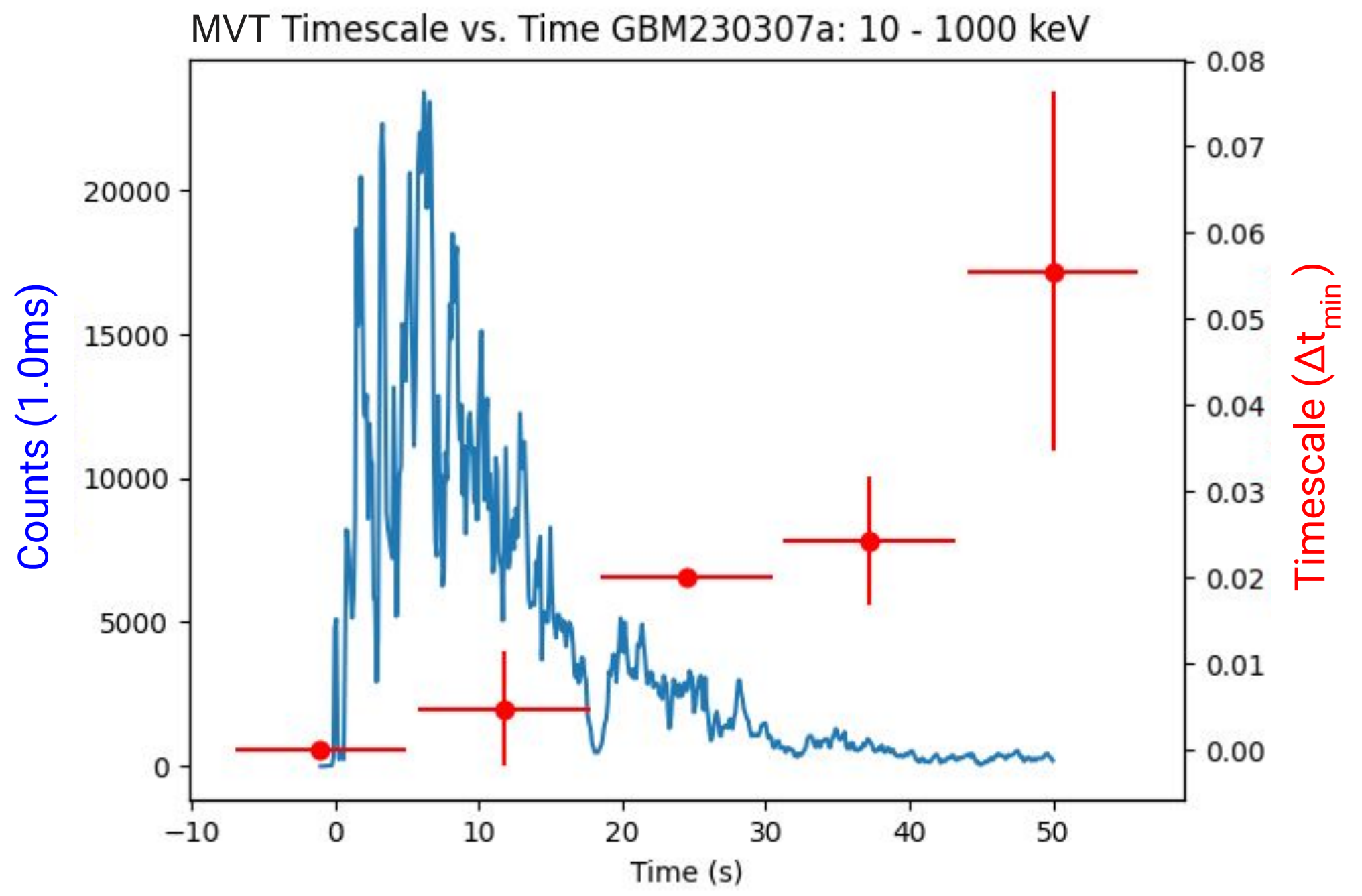

Figure 1: Minimum variability timescale versus time (Red) plotted against Flux versus time (blue) for GRB 230307a with energy range 10-1000 keV

GRB	MVT (s)*	Lorentz Factor (Γ)	R_0 (cm)
230307a	0.0048	849	2.08E+14
090510a	0.0025	997	1.49E+14
190114c	0.0143	648	3.61E+14
190829a	0.0703	437	8.08E+14
090902b	0.008	748	2.69E+14

Table 1: The calculated minimum variability timescale(MVT), Lorentz factor, and gamma-ray emission radius in centimeters and meters for select GRBs.

*MVT is shortest MVT for all energy levels
**Theoretical result
***15 MeV is the highest recorded E_peak for any GRB.
^Calculated Using Standard Cosmology

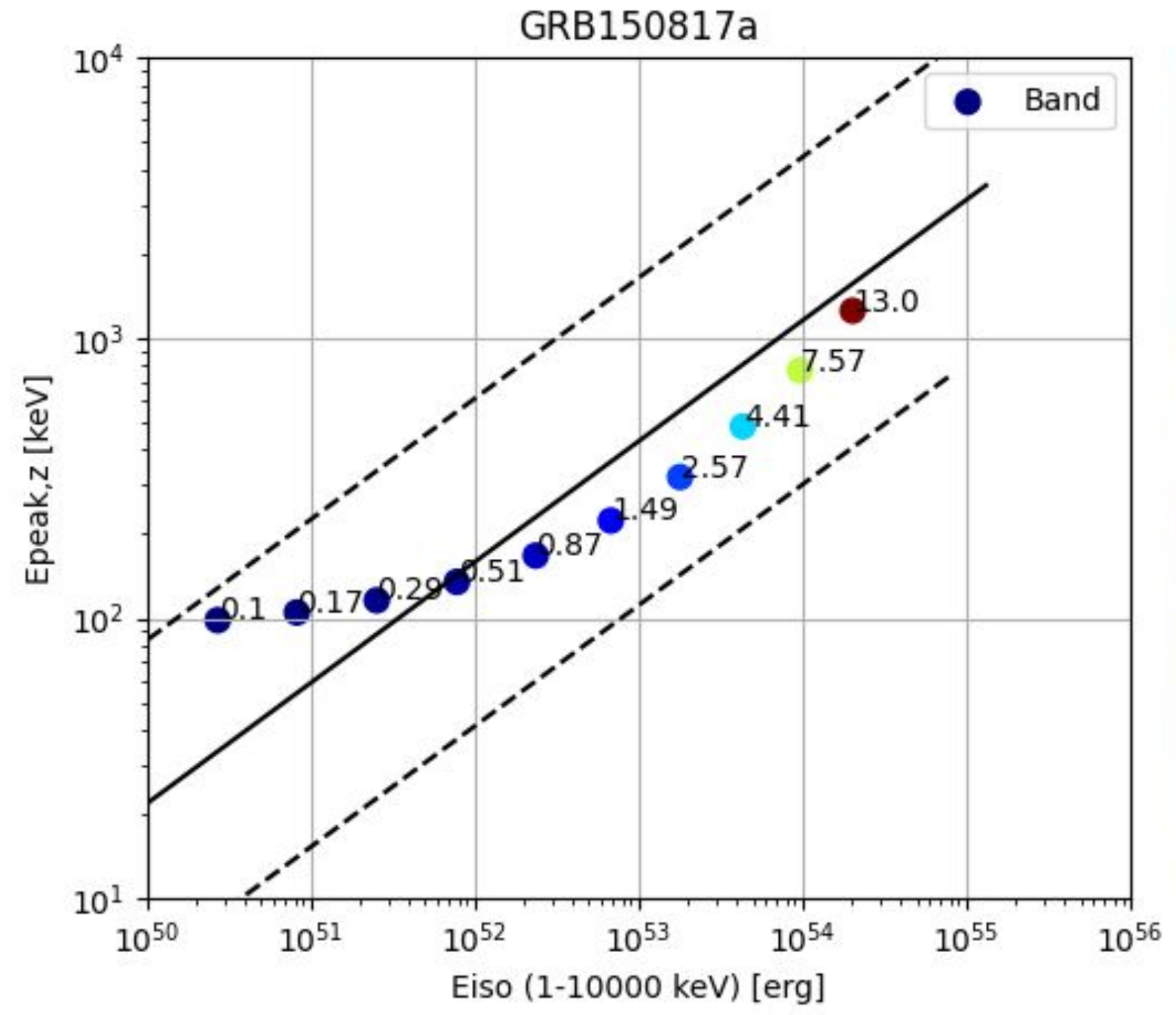

Figure 2: The isotropic energy versus the peak energy of GRB 150817a. The — line indicates the Amati Relation line with one-sigma error lines (- -). The redshift (z) band along with values are denoted by points on the plot.

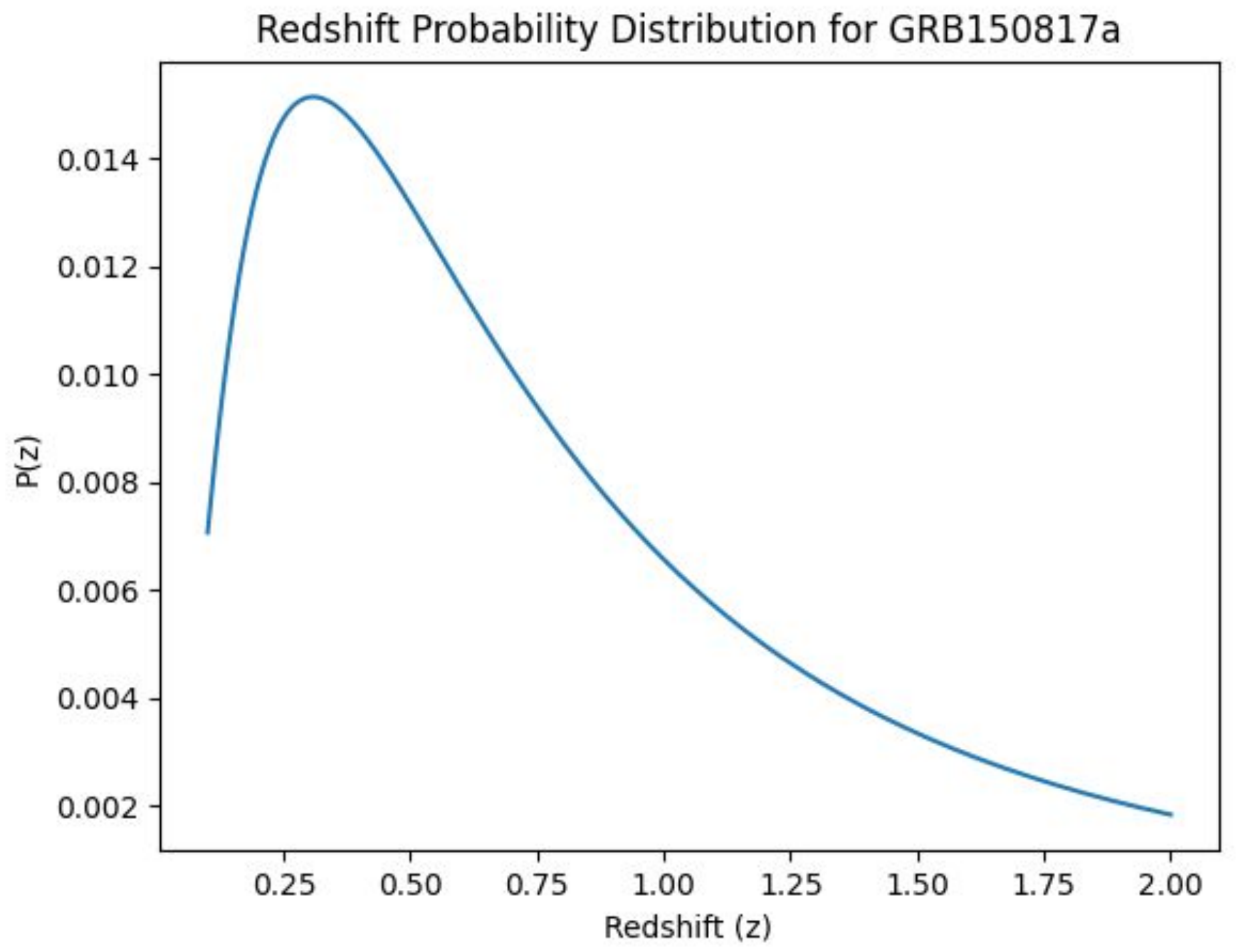

Figure 3: Redshift probability plot for GRB 150817a. You can observe a probability of ~1.5% for z = 0.306.

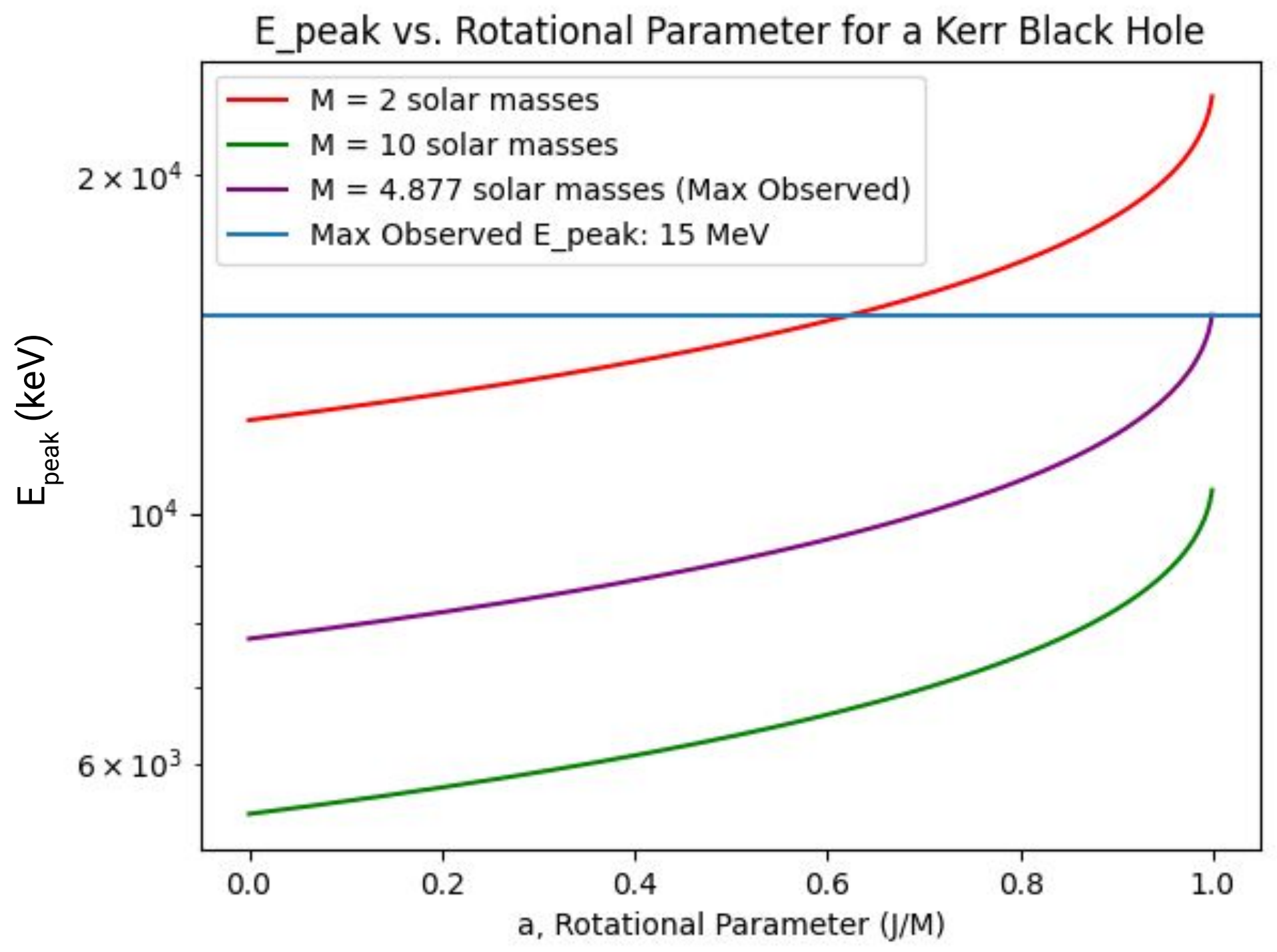

Figure 4: Rotational parameter (a) versus peak energy (keV) for GRBs with a black holes of solar mass 2, 10, and ~4.877.

Black Hole Mass (Solar Mass)	E_{peak} (MeV)
2	23.4**
10	10.5
4.877	15***

Table 3: Peak energies allowed for black hole central engines of GRBs, based upon its solar mass.

GRB	Estimated Redshift	Distance (cm)^
100620a	0.138 ± 0.241	2.01E+27
160819a	1.424 ± 0.278	3.16E+28
090428a	5.636 ± 0.309	1.66E+29
150817a	0.306 ± 0.241	4.90E+27

Table 2: Max probability redshifts (z) and luminosity distance (cm) for select GRBs.

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