A possible origin of the high-energy and very-high-energy gamma-ray bursts

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Keywords: gamma-ray bursts, very-high-energy gamma-ray bursts, antimatter, mass-energy equation, cosmic microwave background

Abstract

As highly intensive and brief pulses of light, gamma-ray bursts (GRBs) are the most energetic explosive phenomena in the Universe. A few mechanisms could explain the production of some GRB emissions, however, the physical origin of GRBs especially the high-energy (more than one GeV) and very-high-energy (above 100 GeV) ones still remains largely unknown. Based on our previously revealed quantitative relation between the speed of light in vacuum *c* and the temperature T of cosmic microwave background (CMB), we propose that the mass-energy relation at the redshift *z* space-time in the Universe should be $E=mc^2(1+z)^2$. Then, the mass-loss events such as the annihilation of matter and antimatter at high-redshift space-time will produce more energetic gamma-rays than our present space-time. Finally, we confirmed that this theoretical model is highly compatible with both the observed data and the data generated by a empirical formula $E_{iso} \propto (1+z)^{1.80^{+0.36}_{-0.63}}$. These results suggest that the events of mass-energy transition such as matter and antimatter collision at distant space-time in the Universe could be a possible physical origin of GRBs including the high-energy and the very-high-energy ones.

1. Background

Gamma-ray bursts (GRBs) are short but the brightest and most energetic flashes of γ-rays in the Universe. Since its first report in 1973[1], decades of studies have detected thousands of GRB events each year, however, the physical mechanism that could produce GRBs still remains one of the biggest secrets in the field[2]. Up to now, a number of physical models such as neutron star model, extragalactic model, Galactic model, and 'collapsar' model have been proposed to explain the origin of GRBs[2]. For example, enormous bursts and flares of γ-rays may be occasionally produced by Magnetars[3-5], which are highly magnetized young neutron stars. It was reported that GRBs may be produced in the most relativistic jets[6]. Moreover, the long GRBs may be formed in the core collapse of massive stars and the short GRBs may derive from the merger of two compact objects[7]. In addition, in distorted and largescale magnetic fields advected from central black holes, synchrotron radiation of electrons may also produce prompt GRB emission[8]. Moreover, peculiar origins also exist, for example white dwarf - neutron star merger with a post-merger magnetar engine[9]. The above physical mechanism could interpret normal GRBs with energies in KeV-MeV range, however, the physical progenitor of high-energy (more than one GeV) and very-high-energy (above 100 GeV) GRBs remain largely unknown[10].

We previously revealed a quantitative relation (Eq.1) of the speed of light in vacuum with the temperature of cosmic microwave background (CMB) [11] through investigating relations of fine-structure constant and CMB[12].

$$c_T = \frac{T}{T_0} c_0 \qquad (1)$$

Where c_T is the speed of light in the Universe with CMB temperature T, c_0 is the speed of light in the Universe with CMB temperature T_0 (the present space-time). Hence, the speed of light in the Universe at high redshift z space-time would be much greater than the present space-time. Based on the Einstein's mass-energy equation, the same mass-loss event would produce much more energetic photons in the distant Universe than the present space-time.

2. A physical model explains the origin of the high-energy and very-high-energy GRBs

Given the above observations, here we propose a physical model to explain the origin of the high-energy and very-high-energy GRBs. It is known that the redshift z can be described as a function of the CMB temperature T at z space-time and T_0, as shown in Eq.2.

$$1 + z = \frac{T}{T_0} \qquad (2)$$

Then, Eq.1 can be re-described as

$$c_T = (1 + z)c_0 \qquad (3)$$

Then, the mass-energy equation at the redshift z space-time in the Universe will be

$$E = mc_T^2 = mc_0^2(1 + z)^2 \qquad (4)$$

From this equation, it is clear that the same event of mass-loss at high z space-time will release more energetic photons than those at the present space-time in the Universe.

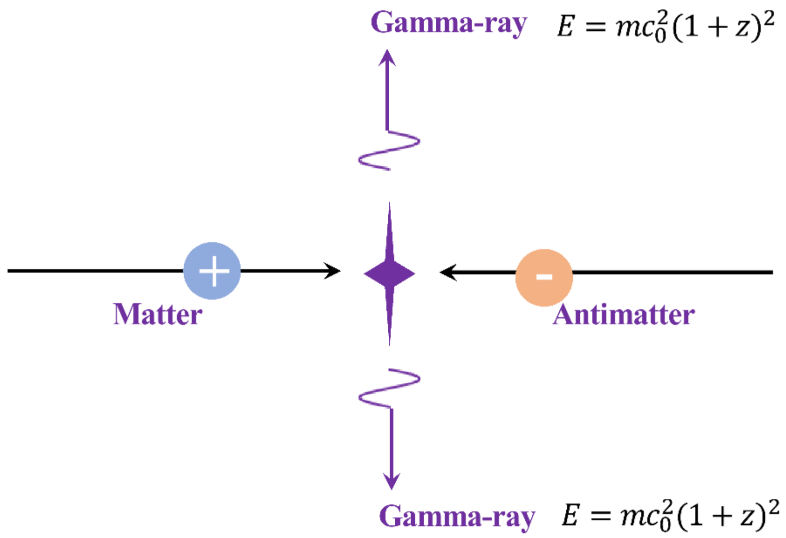

Figure 1. A physical model for the origin of the high-energy and very-high-energy γ-ray.

As shown in Figure 1, one extraordinary mass-energy transition event is the annihilation of matter and antimatter. At high redshift z space-time, the energy of the photons produced by the annihilation of matter and antimatter is described by Equation 4 and will much higher than that released in the present space-time in the Universe. Moreover, according to Equation 4, it is not difficult to simulate the relation of redshift z with the energy of each photon produced by the proton-antiproton collision and that by the electron-positron collision. It is known one proton-antiproton collision will produce two photons with 0.938 GeV of energy at present space-time, then Equation 4 tell us that the energy (GeV) of each photon produced by one proton-antiproton collision at the space-time of redshift z will be

$$E_z = 0.938(1 + z)^2 \qquad (5)$$

Similarly, the energy (GeV) of each photon produced by one electron-positron collision will be

$$E_z = 0.000511\ \ (1 + z)^2 \qquad (6)$$

The theoretical energy-z relation curves (z from 0 to 100) of the photons produced by proton-antiproton collision (purple solid curve) and electron-positron collision (red dotted curve) are shown as Figure 2.

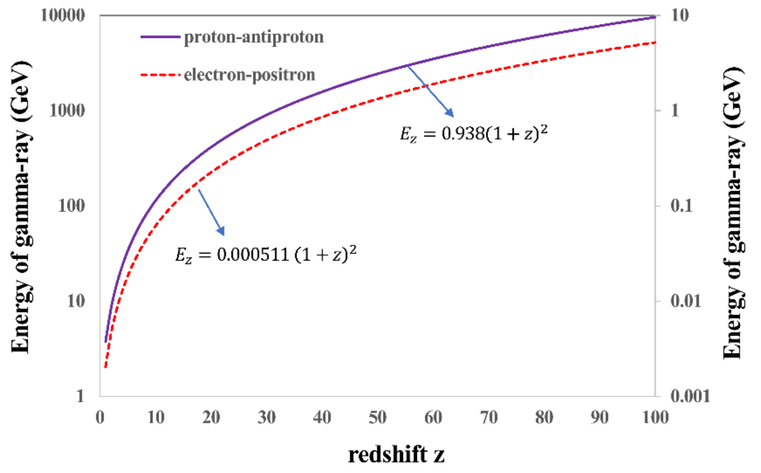

Figure 2. The theoretical energy-z relation curves (z from 0 to 100) of the γ-photons produced by proton-antiproton collision (purple solid curve) and electron-positron collision (red dotted curve).

3. The physical model is compatible with observational data

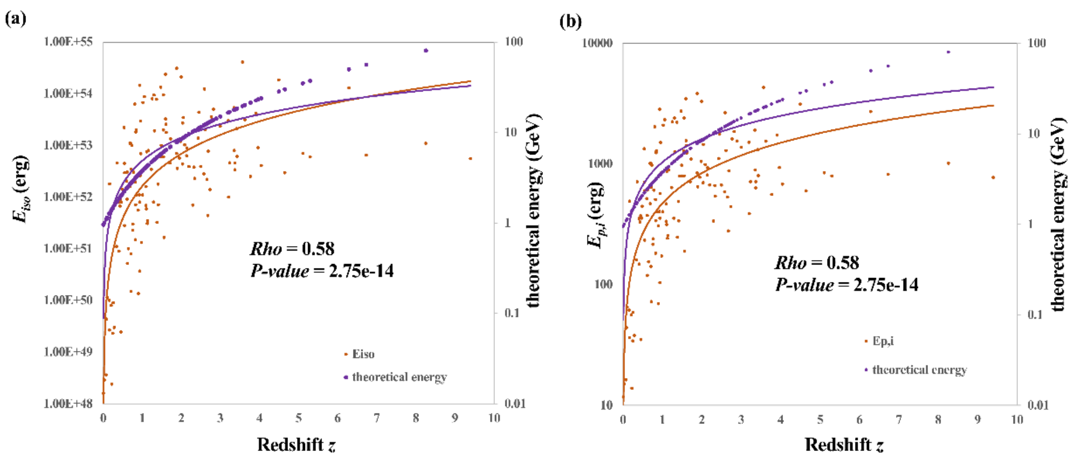

Figure 3. The theoretical energy-z curve (the purple dots and lines) is compatible with E_{iso} - z curve (a) and with $E_{p,i}$ - z curve (b) of the gamma-ray burst on the data in the grbcatag Catalog.

To validate the proposed physical model, we first used the GRBs data in the grbcatag Catalog (https://heasarc.gsfc.nasa.gov/). We curated the GRBs with the redshift and the isotropic-equivalent energy release (E_{iso}) as well. Using the redshift data, we calculated the corresponding energy (GeV) of one proton-antiproton collision based on the proposed physical model. As a result, we found that the theoretical redshift-energy curve is highly compatible with that from the observed data (Figure 3a, *Rho*=0.58, *p-value*=2.75e-14, Spearman's correlation). Given the consistent relation between E_{iso} and the cosmological rest-frame nuFnu spectrum peak energy ($E_{p,i}$), it is not surprise that we got very similar result when using $E_{p,i}$ data (Figure 3b).

We next validate the proposed model using the estimated collimation-corrected energy released in gamma-rays $E_{\gamma}=E_{iso}(1-\cos\theta_{jet})$ from *Tsvektova* et al.'s study[13], where θ_{jet} is the jet opening angle. As a result, we confirmed that the theoretical redshift-energy curve is also highly compatible with that from the observed data (Figure 4, *Rho*= 0.56, *p-value*=0.001).

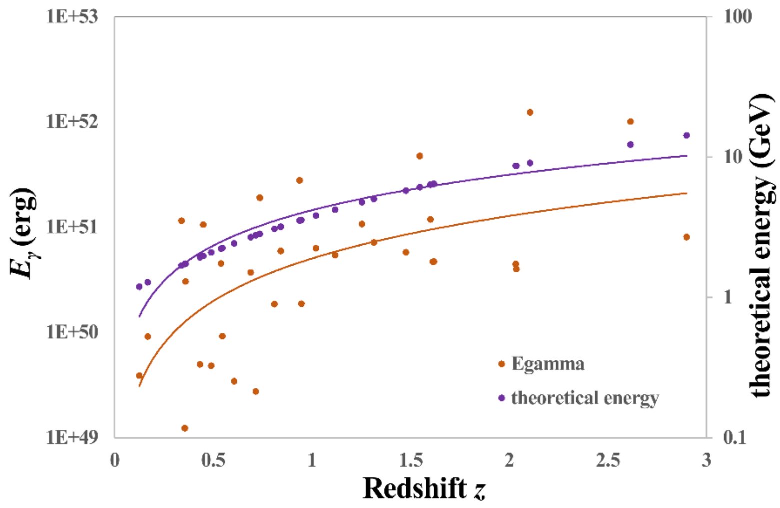

Figure 4. The theoretical energy-z curve is highly compatible with E_{γ} - z curve on the observed data from *Tsvektova* et al.'s study[13].

4. The theoretical model is compatible with one empirical formula

We noted that *Wu* et al. [14] previously proposed the following empirical formula (Eq.7) to describe the relation of E_{iso} with redshift z, which seems quite similar with the physical equations (Eq.4-6) proposed in this study.

$$E_{iso} \propto (1+z)^{1.80^{+0.36}_{-0.63}} \qquad (7)$$

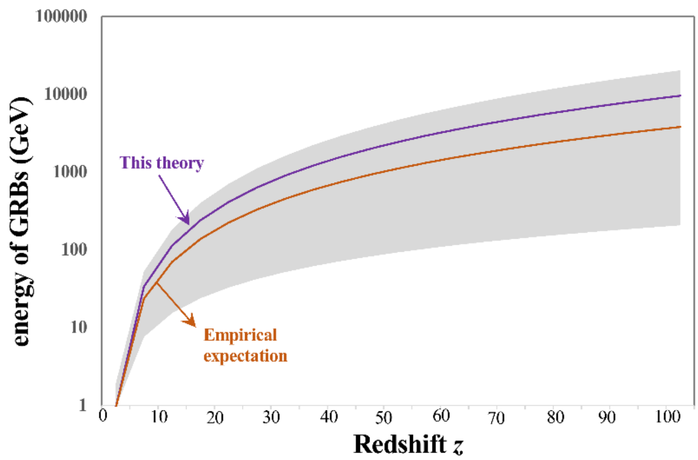

Figure 5. The theoretical energy-z curve (purple line) of the proposed physical model is highly compatible with the expected energy-z curve (orange line) generated using the *Wu* et al.'s empirical formula[14]. The gray region indicates the range between the upper limit and the lower limit of the empirical formula.

Using the energy (0.938 GeV) produced by one proton-antiproton collision as a factor, we simulated the energy – redshift curve (z from 0 to 100). As shown in Figure 5, the theoretical energy-z curve (purple line) is highly compatible with the expected energy-z curve (orange line) which is generated based on the *Wu* et al.'s empirical formula. The gray region means the range between the upper limit and the lower limit of the empirical formula. This result and the results from validation by observed data together indicate that the proposed physical model explains the observed GRBs very well, which further suggest that the mass-loss (e.g. matter and antimatter collision) in a high redshift z space-time could be one progenitor of GRBs including the high-energy and the very-high-energy ones.

5. Conclusion and Discussion

In summary, we proposed a quantitative equation connecting energy and mass at a distant space-time in the Universe. Then, at high-redshift space-time will produce more energetic photons than our present space-time. Then, we further proposed that the mass-loss events such as the annihilation of matter and antimatter could be one possible physical origin of GRBs including the high-energy and very-high-energy ones. Moreover, we confirmed this physical model by comparing its theoretical prediction with the observed data and the data generated using one previous empirical formula. It should be noted, the energy of GRBs would decrease to be $E/(1+z)$ at our space-time due to the effect of cosmological redshift. In addition, the proposed model explain the observed data very well, suggested one progenitor of GRBs could be the mass-energy transition event in high redshift space-time. This further suggest that the speed of light in different space-time may be really variable with its CMB temperature and the redshift. Of course, the proposed new theory should be tested in more data in the future.

It was considered that synchrotron emission of ultrarelativistic electrons and inverse Compton emission and could be two possible explanations for the high-energy and very-high-energy GRBs[10]. However, it seems unbelievable for electrons in these two events is capable of releasing such high energy, for example above one or 100 GeV.

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