The dark energy measurement in the early universe with Gamma-Ray Bursts

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Abstract

We calibrated the peak energy-peak luminosity relation of GRBs (so called E_p–L_p ; Yonetoku relation) using 52 events with the redshift $z < 1.755$ without assuming any cosmological models. The luminosity distances to GRBs are estimated from those of large amount of Type Ia supernovae with $z < 1.755$. This calibrated E_p–L_p relation can be used as a new cosmic distance ladder toward higher redshifts. We determined the luminosity distances of 36 GRBs in $1.8 < z < 8.3$ using the calibrated relation and plotted the likelihood contour in $(\Omega_m, \Omega_\Lambda)$ plane. We obtained $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$ for a flat universe. We can say that our universe in $1.8 < z < 8.3$ is compatible with the cosmological model derived for $z < 1.8$. This suggests that the time variation of the dark energy may be small or zero up to $z \sim 8$.

Key words: Gamma-Ray: Bursts — Cosmology: Dark Energy — Distance Ladder

1. Introduction

When we measure the energy density of dark matter and dark energy, we need the relation between the luminosity distance and the redshift – a history of cosmic expansion at each epoch. For example, we can measure the distance toward the nearby star using annual parallax. Then, we enable to estimate the absolute luminosity of those stars. Heltzshprung and Russell found the strong correlation between color temperature and the absolute magnitude for main sequence stars within the small distance scale measured by the annual parallax. If, the HR diagram is acceptable for all main sequence stars, we can estimate the absolute luminosity from the spectrum, and also estimate the distance of more remote stars. The several empirical relations, the period-luminosity relation of Cepheid variables, the rotation-luminosity relation of spiral galaxies, and standard candle of type Ia supernovae, etc., are calibrated with one of closer objects (relations). This concept is usually called as "the cosmic distance ladder", and they are firmly connected by astrophysics and free from any theoretical cosmology.

Using the Type Ia supernovae as the cosmic distance ladder, the existence of the dark energy is strongly suggested by Phillips (1993), Schmidt et al.(1998), Riess et al.(1998), Perlmutter et al.(1999). Thanks to the latest large number of observations of Type Ia supernovae, the data with $z \le 1.755$ favor the cosmological parameters of $(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$ for a flat cosmology (Riess et al. 2007), which is usually called as the concordance cosmological model. However the most distant Type Ia supernova ever observed is at $z = 1.755$, so that we need either further Type Ia supernovae or other distance indicators to know the property of the dark energy beyond $z > 1.8$, while the anisotropy of the cosmic microwave background (CMB) gives us the information at $z = 1089$ (Spergel et al. 2007).

One of the possible tools is Gamma-ray burst (GRB). The maximum redshift ever recorded is $z = 8.3$ which is higher than one of Type Ia supernovae. Since GRBs are known as the most violent and brightest explosion in the universe, they might be a possible good distance indicator beyond $z > 1.8$. In this paper, we extend the cosmic distance ladder toward $z = 8.3$ using GRBs, and measure the amount of dark energy and dark matter in the early universe.

2. Calibrated E_p–luminosity Relation

The prompt gamma-ray spectrum can be usually described as the spectral model of the exponentially connected broken power-law function suggested by Band et al.(1993):

$$N(E) = \begin{cases} A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp(-\frac{E}{E_0}) \\ \qquad \text{for } E \le (\alpha-\beta)E_0, \\ A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta} \left(\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right)^{\alpha-\beta} \exp(\beta-\alpha) \\ \qquad \text{for } E > (\alpha-\beta)E_0. \end{cases} \tag{1}$$

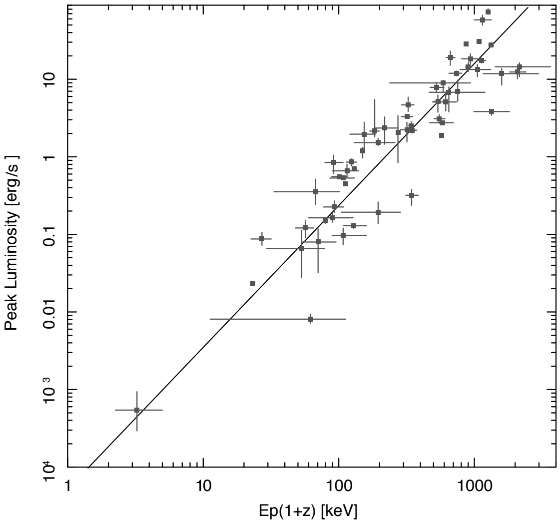

Fig. 1. The E_p–L_p relation (Yonetoku relation) of 52 GRBs with $z < 1.755$. The solid line is the best fit curve of $L_p/(10^{52}\mathrm{erg/s}) = 1.31 \times 10^{-4}[E_p(1+z)/1\mathrm{keV}]^{1.7}$.

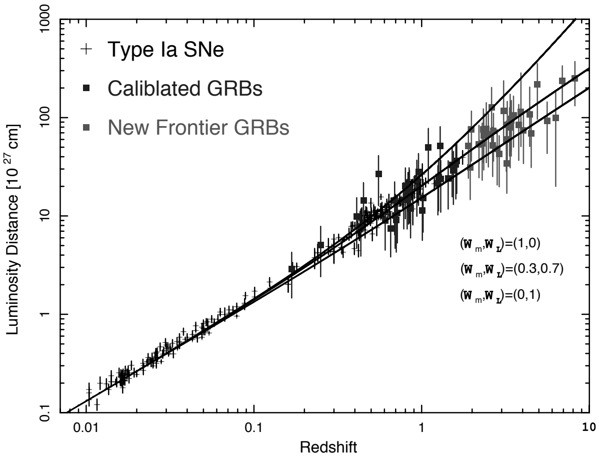

Fig. 2. The first Hubble diagram toward $z = 8.3$ measured by the calibrated E_p–L_p relation. The blue and the red points are the luminosity distance of $z \leq 1.755$ and $z > 1.755$, respectively. The data of Type Ia supernovae are also plotted as the black cross points. The uncertainty bar of each point includes the systematic dispersion around the best fit line of figure 1.

Here $N(E)$ is in units of photon $\mathrm{cm^{-2}s^{-1}keV^{-1}}$. This function has four parameters, the low-energy photon index α, the high-energy photon index β, the spectral break energy E_0 and the normalization. The peak energy can be derived as $E_p = (2+\alpha)E_0$, which corresponds to the energy at the maximum flux in the νF_ν spectra.

In our past study, we found a strong correlation between the peak energy (E_p) and the peak luminosity (L_p) (Yonetoku et al. 2004). This E_p–L_p relation (Yonetoku relation) may be useful for another cosmic distance ladder beyond the redshift range of type Ia SNe.

Then, for 52 samples, we calibrated the E_p–L_p relation using the luminosity distance from Type Ia SN observation without any assumption of theoretical cosmology. Figure 1 is the calibrated E_p–L_p relation. The correlation coefficient is 0.95 and the chance probability is about 10^{-17}. The best fit function is

$$\left(\frac{L_p}{10^{52}\mathrm{erg/s}}\right) = (1.31 \pm 0.67) \times 10^{-4}\left(\frac{E_p}{1\ \mathrm{keV}}\right)^{1.7\pm0.1} \quad (2)$$

In this equation, the error is expressed as the statistical uncertainty. However the data distribution has a larger deviation around the best fit line compared with the expected Gaussian distribution. We estimated this systematic deviation in the normalization as 9.6×10^{-5}.

3. Hubble Diagram and Cosmological Parameters

At present, there are more than 100 GRBs with known redshift, but the E_p has not been measured for all GRBs. Then, we apply the calibrated E_p–L_p relation to 36 GRBs in $1.8 < z < 8.3$ to determine the luminosity distance as a function of z as

$$d_L(z^i) = 10^{24}\mathrm{cm}\sqrt{\frac{1.31}{4\pi f^i_{p,obs}}}[E^i_{p,obs}(1+z^i)]^{1.7/2}. \quad (3)$$

Figure 2 is the first Hubble diagram until $z = 8.3$ measured by GRBs. Black, blue, red point is the type Ia SNe, the calibrated GRBs, and the new frontier of the Hubble diagram, respectively. Here, we would like to emphasize that this Hubble diagram is created by pure observational results. The GRB points have large error compared with type Ia SNe. This is because the systematic uncertainty of the E_p–L_p relation. But we can recognize the strong trend increasing the luminosity distance as a function of the redshift.

Then adopting the theoretical Λ-CDM model to the observed Habble diagram, we estimate the cosmological parameters. We used the Λ-CDM equations as

$$d_L^{th}(z, \Omega_m, \Omega_\Lambda) = (1+z)\begin{cases} \frac{c}{H_0\sqrt{\Omega_k}}\sin(\sqrt{\Omega_k}F(z)) \\ \frac{c}{H_0\sqrt{-\Omega_k}}\sinh(\sqrt{-\Omega_k}F(z)) \\ \frac{c}{H_0}F(z) \end{cases}$$

$\Omega_k > 0$, $\Omega_k < 0$ and $\Omega_k = 0$, respectively. Here,

$$F(z) = \int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda - \Omega_k(1+z)^2}}.$$

Three solid lines in figure 2 are examples of theoretical lines for several couples of Ω_m and Ω_Λ, respectively.

We calculated the confidence contour for two parameters of Ω_m and Ω_Λ. We define a likelihood function as

$$\Delta\chi^2 = \sum_{i=1}^{30} \left(\frac{\log d_L(z^i) - \log d_L^{th}(z^i, \Omega_m, \Omega_\Lambda)}{\Delta d_L(z^i)}\right)^2 - \chi^2_{best}. (4)$$

Here χ^2_{best} means the chi-square value for the best fit parameter set of Ω_m and Ω_Λ. In figure 3, we show the contour of the likelihood $\Delta\chi^2$ for the luminosity distances of 36 GRBs in $1.8 < z < 8.3$. Compared with the case of Type Ia supernovae, the shape of the probability contour stands vertical since the luminosity distance strongly depends on Ω_m rather than Ω_Λ for higher redshift samples. This is clear from the functional form of $F(z)$. Without any prior the most likelihood value is $(\Omega_m, \Omega_\Lambda) = (0.25^{+0.27}_{-0.14}, 1.25^{+0.10}_{-1.25})$ while for a flat cosmology prior that is $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$ with $1\ \sigma$ uncertainty. This is consistent with the concordance cosmology.

4. Discussion

In this paper, we extended the cosmic distance ladder toward $z = 8.3$ using GRBs calibrated by Type Ia supernovae. We also argued the cosmological parameters in $1.8 < z < 8.3$. Since our region of $1.8 < z < 8.3$ has not been explored yet, this is the first report to estimate the cosmological parameters up to $z = 8.3$.

The calibrated E_p–L_p relation has a large dispersion in the normalization. Therefore, currently, the measurement of the luminosity distance is not so accurate compared with the other distance indicators such as Type Ia supernova. It may be difficult to discuss the detailed time history of the cosmological parameters yet. However, if this deviation is the intrinsic property of GRBs, we will be able to discover the hidden physical quantities, or distinguish a possible sub-class from entire population of GRBs like Type Ia supernova. These improvements in the cosmic distance ladder will lead us to explore the deep space with better accuracy in near future. It will be possible to combine our data with (1) Type Ia supernova, (2) CMB, (3) Baryon Acoustic Oscillation (4) the large scale structure measurement and (5)weak gravitational lensing, to constrain the equation of state of the dark energy.

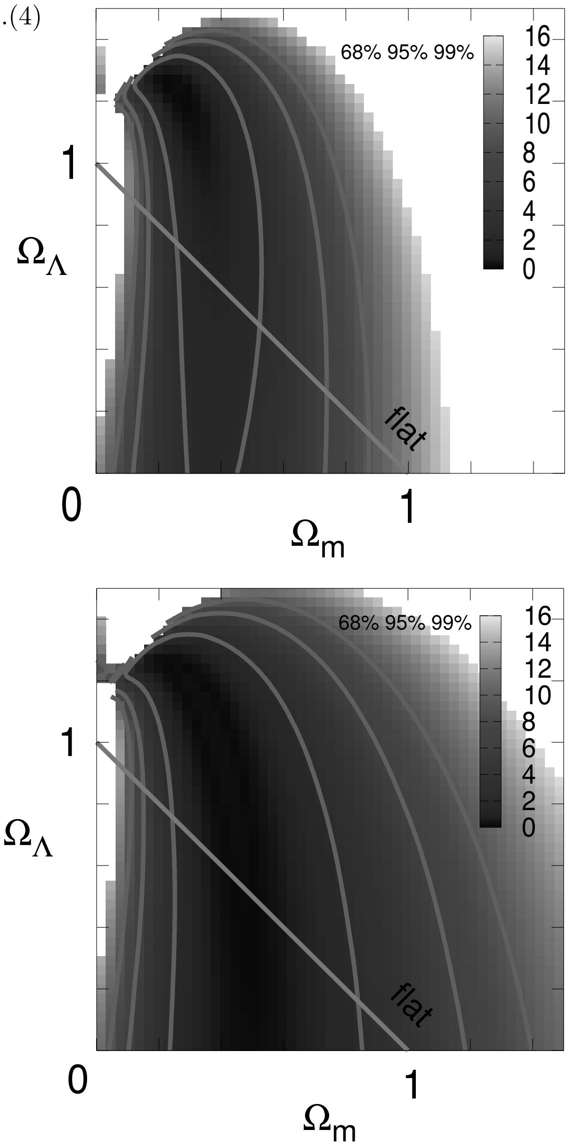

Fig. 3. The contour of the likelihood $\Delta\chi^2$ for the luminosity distances of 36 GRBs in $1.8 < z < 8.3$ (upper) and 18 GRBs in $3.0 < z < 8.3$. The significance levels of 68%, 95% and 99% are also shown on the same panels. Compared with the case of Type Ia supernovae, the shape of the contour stands vertical since the luminosity distance strongly depends on Ω_m at the high redshift. The most likelihood value of cosmological parameters are, for $1.8 < z < 8.3$, $(\Omega_m, \Omega_\Lambda) = (0.25^{+0.27}_{-0.14}, 1.25^{+0.10}_{-1.25})$ while for a flat cosmology prior they are $(\Omega_m, \Omega_\Lambda) = (0.37^{+0.14}_{-0.11}, 0.63^{+0.11}_{-0.14})$. For $3.0 < z < 8.3$, $(\Omega_m, \Omega_\Lambda) = (0.33^{+0.52}_{-0.26}, 1.14^{+0.21}_{-1.14})$ while for a flat cosmology prior they are $(\Omega_m, \Omega_\Lambda) = (0.49^{+0.33}_{-0.24}, 0.53^{+0.22}_{-0.37})$.

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