Probing dark energy with gamma-ray bursts

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We propose a new method to use gamma-ray bursts (GRBs) as an alternative probe of the dark energy. By calibrating luminosity-variability and luminosity-lag time relations at low redshift where distance-redshift relations have been already determined from type Ia supernovae (SNIa), GRBs at high redshift can be used as a distance indicator. We investigate the potential impact of future GRB data on determining the current matter density \( \Omega_m \) and the dark energy equation of state \( w \) which is assumed to be constant. We show that a combined analysis of a data set expected from the Swift and the current SNIa data results in excellent determination of both \( \Omega_m \) and \( w \).

Accelerating universe, which is strongly suggested by the distance measurements of type Ia supernova (SNIa) [1–3], is one of the most interesting and challenging problems in modern cosmology. Recent observation of the cosmic microwave background (CMB) anisotropy [4] revealed that the universe is almost flat and confirmed the need for the energy component which accelerates our universe.

The cosmological constant, or “dark energy” in general, is often introduced to account for this cosmic acceleration. Dark energy is the unknown energy component which has effective negative pressure \( p = w \rho \) \((w < 0)\). The case with \( w = -1 \) corresponds to the cosmological constant. Since the value of \( w \), which is a function of redshift \( z \) in general, is closely related to the nature of dark energy, it is of great importance to determine the value of \( w \) observationally. Until now, a number of methods are proposed to probe the dark energy equation of state \([5–13]\). However, currently \( w \) has not been determined quite well even if one assumes that \( w \) is constant \([14,15]\). In particular, the current distance measurements of SNIa poorly determines the value of \( w \) because of the degeneracy between \( w \) and the dark-energy density \([1–3]\). Moreover, the use of CMB anisotropy, which is known to be one of the most powerful and clean probe of cosmological parameters, introduces an additional degeneracy between the Hubble constant and dark-energy parameters \([15]\). That is one of the reason why future SNIa search, such as the proposed SNAP satellite \([16]\), has been vigorously studied as a probe of the dark energy \([17–19]\).

In this Letter, we propose another method using gamma-ray bursts (GRBs) as a distance indicator.

Recent studies have suggested the possibilities that GRBs can be standard candles through the relations between absolute “isotropic-equivalent” luminosity \( L \) and other observed quantities. Two of them, which we use in this Letter, are variability \( \langle V \rangle \) \([20,21]\) and spectral lag \( \langle \tau_{\text{lag}} \rangle \) \([22,23]\). The variability is a specific measure of the “spikiness” of the light curve. The spectral lag is the time between peaks as recorded at high and low photon energies. These two quantities are related to the luminosity as \( L \propto V^{\alpha_v} \) and \( L \propto V^{\alpha_{\text{lag}}} \), respectively. Furthermore, a \( V/\tau_{\text{lag}} \) relation, which must exist if the \( L/V \) and \( L/\tau_{\text{lag}} \) relations are true, has been confirmed with an independent sample of 112 BATSE bursts \([24]\). There are also some theoretical explanations for these relations \([25,26]\).

Once these relations are established by observations, then one can use these relations to derive the absolute luminosity of GRBs and to estimate the luminosity distance to the GRBs \([27]\).

Up to now, only \( \sim 10 \) GRBs have the enough information \((z, V, \tau_{\text{lag}})\) to establish the above relations. However, the Swift satellite \([28]\), planned for launch in 2003, is expected to detect \( \sim 1000 \) GRBs, about half of which will be observed with known redshifts, during 3 years of observations. This huge number of GRBs allows us to probe the expansion history of the universe more deeply than SNIa \([27]\). In this Letter, we simulate the data which is expected to be obtained by the Swift and investigate the ability to probe the dark energy independently with other methods such as CMB anisotropy. Throughout the Letter, we assume a flat universe \( \Omega_m + \Omega_X = 1 \), where \( \Omega_m \) is the present matter density and \( \Omega_X \) is the present dark-energy density.

Here we must be careful to avoid circular logic. The original studies of the \( L/V \) and \( L/\tau_{\text{lag}} \) relations assumed a particular set of cosmological parameters (the Hubble constant \( H_0 \), \( w \), \( \Omega_m \) and the flatness of the universe) to derive the relations. Without any assumptions about the cosmological parameters, we cannot determine \( L/V \) and \( L/\tau_{\text{lag}} \) relations which are used to obtain the absolute luminosity of GRBs. Thus we assume that a form of the luminosity distance as a function of the redshift at \( z < 1 \) has already been well determined by the current SNIa observations. This is approximately that of the \( \Lambda \)-dominated universe \((w = -1, \Omega_X = 0.7 \text{ and } \Omega_m = 0.3)\). The errors associated with the form of the luminosity distance at \( z < 1 \) is reflected in the systematic errors in the derived absolute luminosities of the low-\( z \) (\( z < 1 \)) GRBs. We calibrate these two relations by using only low-\( z \)
GRBs, and obtain the absolute luminosities of high-z (z > 1) GRBs using these relations. After that, the procedure is the same as that using SNIa: fitting parameters such as w and Ω_m so as to reproduce the magnitude as a function of the redshift. The apparent magnitude m and redshift z are related by the luminosity distance as:

\[ m = M + 25 + 5 \log d_L(z), \]  

where M is an absolute magnitude and

\[ d_L(z) = \frac{(1+z)c}{H_0} \int_0^z dz' \times [\Omega_m (1+z')^3 + (1-\Omega_m)(1+z')^{3+3w}]^{-\frac{1}{2}} \]  

is the luminosity distance in units of Mpc.

For concreteness, we simulate a future data set similar to one expected from the Swift. The sample comprises 500 GRBs, which is consistent with the expected number of GRBs with measured redshifts. Their redshifts and luminosities are distributed according to the GRB rate history and the luminosity function based on the model of the star formation rate 2 (SF2) in [29], which is roughly constant at z ≥ 2. This model is consistent with the current observations of UV luminosity density of the galaxy population. The energy spectrum of the GRB is assumed to be a single power-law with index −2.25. The observed luminosities are calculated assuming a background cosmology with H_0 = 65 km s^{-1} Mpc^{-1}, Ω_m = 0.3, Ω_X = 0.7 and w = −1. The flux limit of the Swift, f > 0.04 photons cm^{-2} s^{-1}, is applied to check whether a produced GRB will be observed or not. The errors in redshifts are tentatively neglected because of the lack of information on the redshift measurement by Swift, while we will show later that inclusion of the errors in redshifts does not change our result so much. We assume the log-normal distribution of the luminosity errors of 0.02 in logarithmic units of base 10. Other errors below are also assumed to be the log-normal distribution. Fig. 1 shows the redshift distribution of the simulated GRBs. The average redshift of these GRBs is about 3. Although very high-z GRBs might be subject to some possible biases, they are practically not influential on the analyses below, because the number of such high-z GRBs is not so large.

Next the observed variability and spectral lag are given to each GRB according to the following L/V and L/τ_{lag} relations,

\[ L = 3 \times 10^{56} (V(1+z))^3 \text{erg/s}, \]  

(3)

\[ L = 10^{50} \left( \frac{\tau_{lag}(1+z)}{1\text{s}} \right)^{-1} \text{erg/s}, \]  

(4)
with the intrinsic scatter as well as the measurement uncertainties. For both the \(L/V\) and \(L/\tau_{\text{lag}}\) relations, we assume both the intrinsic scatter and measurement error to be 0.1 in logarithmic units. The indices and proportional constants of these relations are different among various studies. The values we use are typical of them [20–23]. The measurement errors are almost the same as those of the current observations. The simulated data are plotted in Fig. 2 and 3 with the assumed relations (3) and (4), respectively. Although the \(L/\tau_{\text{lag}}\) relation might steepen to \(L \propto \tau_{\text{lag}}^{-3}\) at \(\tau_{\text{lag}} \gtrsim 0.1\)s [23], our assumption of single power-law for the \(L/\tau_{\text{lag}}\) relation is enough because GRB events with such large \(\tau_{\text{lag}}\) will be very rare for the luminosity function adopted here. In fact the indices that we adopted need not be the true values since they are to be determined from the \textit{Swift} observation. Thus what we require are that there are some one-to-one relations between the observable quantities \((V \text{ and } \tau_{\text{lag}})\) and the absolute luminosity \(L\) and that the relations are independent on \(z\) for \(0 < z \lesssim 3\). Although evolution of the relations is not likely as is stated in [27], it will be tested if the luminosity distance up to \(z \lesssim 1.7\) is obtained from the \textit{SNAP} observation.

Then the absolute luminosities of the low-\(z\) GRBs are calculated by the luminosity distance-redshift relation which has been determined by the current SNIa observations. Its uncertainties lead to the uncertainties of the absolute luminosities of \(\sim 0.2\) in logarithmic units. Then the \(L/V\) and \(L/\tau_{\text{lag}}\) relations are derived by the low-\(z\) GRBs. As a result, we recover the the \(L/V\) and \(L/\tau_{\text{lag}}\) relations of the form \(L \propto V^{2.13}\) and \(L \propto \tau_{\text{lag}}^{-0.99}\) from the simulated low-\(z\) GRBs. Two independent absolute luminosities of high-\(z\) GRBs are obtained by these relations, and are combined as weighted averages to produce combined absolute luminosities. Fig. 4 shows the binned magnitude difference \(\Delta m\) between several representative cosmological models and the fiducial model (\(\Omega_m = 0.3, w = -1\)), along with the simulated data.

Finally we perform \(\chi^2\) constraints to see to what extent we can constrain dark energy properties from the observation of GRBs. Here we assume the dark energy to have a time-independent equation of state \(w = p/\rho = \text{const.}\) We do not put a prior \(w \geq -1\) because it may bias our final result [14] and because several theoretical models which predict \(w < -1\) do exist [30,31]. Further a flat universe with \(H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}\) is assumed. We calculate \(\chi^2\) as

\[
\chi^2 = \sum_i \frac{(m_i - M_i - 25 - 5 \log d_L(z_i, \Omega_m, w))^2}{\delta m_i^2},
\]

where \(N_{\text{GRB}}\) is the number of GRBs, \(m_i\) is the observed apparent magnitude, \(M_i\) is the absolute magnitude estimated from \(L/V\) and \(L/\tau_{\text{lag}}\) relations, and \(\delta m_i\) is the error of the magnitude. SNIa data fit and the combined fit of GRB and SNIa data are also performed. For the SNIa data, we use the data of the SCP (primary data set C) [2], the High-Z Search Team [3] and Calán-Tololo survey [32] for the SNIa analysis. Fig. 5 shows the best-fit 1\(\sigma\) and 3\(\sigma\) confidence regions in the \(\Omega_m - w\) plane by the simulated GRB data, the current SNIa data and the combined analysis. Since average redshifts are significantly different between SNIa (\(\sim 0.5\)) and GRB (\(\sim 3\)), the combined fit results in the excellent determination of both \(\Omega_m\) and \(w\). Our simulation demonstrates that \(\Omega_m\) and \(w\) can be determined within \(\sim 20\%\) accuracy from the combined analysis of only two types of observation: SNIa and GRBs. Note that constraints from both SNIa and GRBs are quite insensitive to other (cosmological) parameters, such as the Hubble constant, the spectral index of primordial power spectrum, and the normalization of rms mass fluctuations, which are also very important in using other methods, e.g., CMB anisotropy or cluster abundance.

![FIG. 4. Magnitude difference \(\Delta m\) between several cosmological models and the fiducial model (\(\Omega_m = 0.3, w = -1\)), along with the simulated binned data. Three solid curves are for (\(\Omega_m, w\)) = (0.2, -1), (0.3, -1) and (0.4, -1), and two dashed curves are for (\(\Omega_m, w\)) = (0.3, -1.5) and (0.3, -0.5).](image)

![FIG. 5. Best fit 1\(\sigma\) and 3\(\sigma\) confidence regions in the \(\Omega_m - w\) plane by the simulated GRB data (dotted), the current SNIa data (dashed) and the combined analysis (solid). The cross shows the assumed model (\(\Omega_m, w\)) = (0.3, -1). A flat universe is assumed.](image)
Besides the fiducial simulation, we perform two additional pessimistic simulations: one with 300 GRBs instead of fiducial 500 GRBs, and another with redshift error of 0.2 in logarithmic units which is neglected in Fig. 5. The best fit 1$\sigma$ confidence regions for these two pessimistic simulations as well as the fiducial simulation are shown in Fig. 6. Although the two pessimistic simulations result in larger 1$\sigma$ regions, $\Omega_m$ and $w$ are still determined well. Therefore, we conclude that search for distant GRBs can be a promising way to probe the dark energy density and dark energy equation of state separately.

![Figure 6](image)

**FIG. 6.** Best fit 1$\sigma$ confidence regions of the combined analysis for two additional pessimistic simulations as well as the fiducial simulation. Solid, dotted and dashed curves correspond to the result of the fiducial simulation, one with 300 GRBs, and one with redshift error of 0.2 in logarithmic units, respectively. The cross shows the assumed model ($\Omega_m, w) = (0.3, -1)$.

In summary, we have investigated a potential impact of future GRB searches on probing the cosmological parameters such as the matter density fraction of the universe $\Omega_m$ and the equation of state of dark energy $w$. Our result is that a combined analysis of a data set expected from the *Swift* and the current SNIa data results in the excellent determination of these parameters.

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