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Measuring cosmology with Gamma-Ray Bursts(*)

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Summary. — Gamma-Ray Bursts (GRBs) are becoming more and more standardizable candles. Different methods have been proposed to measure cosmology with the relation between the γ-ray energy E_γ of a GRB jet and the peak energy E_p of the νF_ν spectrum in the burst frame. We compare the procedures and results of these methods. Using the present sample of 17 GRBs, we obtain a constraint on the mass density $\Omega_M = 0.22^{+0.42}_{-0.07}$ (1σ) for a flat ΛCDM universe with the median circumburst density $n \simeq 3.0\,\mathrm{cm}^{-3}$. Theoretical investigations of the $E_\gamma \propto E_p^a$ relation reach $a \sim 1.5$. A larger sample in the *Swift* era is expected to provide further constraints on the GRB cosmography.

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1. – Introduction

Type-Ia supernovae (SNe Ia) have revolutionized cosmology in the past several years. Early observations on them at redshift $z < 1$ strongly suggest that the expansion of the universe at the present time is accelerating [9, 8]. Since then, the nature of dark energy (with negative pressure) that drives cosmic acceleration has been one of the greatest mysteries in modern cosmology. Recent observations of 16 higher-redshift (up to $z \simeq 1.7$) SNe Ia present conclusive evidence that the universe had once been decelerating [10]. These newly-discovered objects, together with previous reported SNe Ia, have been used to provide further constraints on both the expansion history of the universe and the equation of state of a dark energy component [10].

GRBs are the brightest electromagnetic explosions in the universe. It has been widely believed that they should be detectable out to very high redshifts [7, 2, 1]. γ-ray photons with energy from tens of keV to MeV, if produced at high redshifts, suffer from no extinction before they are detected. These advantages over SNe Ia would make GRBs an attractive probe of the universe. Schaefer [12] advocated a new cosmographic method

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(hereafter method I), different from the "Classical Hubble Diagram" method in SNe Ia [9], by considering two luminosity indicators for nine GRBs with known redshifts, and gave the constraint $\Omega_M < 0.35$ (1σ; Λ-models) for a flat universe. The newly reported relation between the γ-ray energy E_γ of a GRB jet and the peak energy E_p of the νF_ν spectrum in the burst frame, *i.e.* $(E_\gamma/10^{50}\text{ergs}) = C(E'_p/100\text{keV})^a$, where a and C are dimensionless parameters, makes GRBs more standardized candles (Ghirlanda relation; Ghirlanda *et al.* [5]). Physical explanations of this relation are involved to the standard synchrotron mechanism in relativistic shocks or the emission from off-axis relativistic jets, together with the afterglow jet model. According to the explanations, $a \sim 1.5$ might be intrinsic. Dai *et al.* [3] first used the Ghirlanda relation to measure cosmology, proposing another cosmographic method (hereafter method II) for 12 GRBs with known redshifts. Following Schaefer's method, Ghirlanda *et al.* [6] and Friedman and Bloom [4] also used the Ghirlanda relation to investigate the same issue. Detailed procedures of the two methods are shown in sect. **2**. Here we summarize the results of Xu *et al.* [13] (sample updated continuously).

2. – Method analysis

According the popular relativistic jet model of GRBs and afterglows, the jet's afterglow light curve is expected to present a break when the bulk Lorentz factor of the ejecta drops below the inverse of the jet's half-opening angle, *i.e.*, $\gamma \simeq \theta^{-1}$ [11]. Therefore, together with the assumptions of the initial fireball emitting a constant fraction η_γ of its kinetic energy into the prompt γ-rays and a constant circumburst density n, the jet's half-opening angle is given by $\theta = 0.161[t_{j,d}/(1+z)]^{3/8}(n_0\eta_\gamma/E_{\text{iso},52})^{1/8}$, where $E_{\text{iso},52} = E_{\text{iso}}/10^{52}\text{ergs}$, $t_{j,d} = t_j/1\,\text{day}$, $n_0 = n/1\,\text{cm}^{-3}$. For simplicity, the value of η_γ is taken as 0.2 throughout this paper. The "bolometric" isotropic-equivalent γ-ray energy of a GRB is $E_{\text{iso}} = 4\pi d_L^2 S_\gamma k/(1+z)$, where S_γ is the fluence (in units of $\text{erg}\,\text{cm}^{-2}$) received in an observed bandpass and the quantity k is a multiplicative correction of order unity relating the observed bandpass to a standard rest-frame bandpass (1–10^4 keV). The energy release of a GRB jet is thus calculated by $E_\gamma = E_{\text{iso}}(1-\cos\theta)$.

The Ghirlanda relation is

$$(E_\gamma/10^{50}\text{ergs}) = C(E'_p/100\,\text{keV})^a, \tag{1}$$

where a and C have no covariance. From the above equations, we obtain the apparent luminosity distance with the small angle approximation (*i.e.*, $\theta \ll 1$) as

$$d_L = 7.69\frac{(1+z)C^{2/3}[E_p^{\text{obs}}(1+z)/100\,\text{keV}]^{2a/3}}{(kS_\gamma t_{j,d})^{1/2}(n_0\eta_\gamma)^{1/6}}\text{Mpc} \tag{2}$$

with the uncertainty σ_{d_L} given by Xu *et al.* [13]. The apparent DM of a burst thus reads $\mu_{\text{obs}} = 5\log d_L + 25$ with the uncertainty of $\sigma_{\mu_{\text{obs}}} = 2.17\sigma_{d_L}/d_L$.

The theoretical luminosity distance in Λ-models is given by

$$\begin{aligned} d_L = {} & c(1+z)H_0^{-1}|\Omega_k|^{-1/2}\text{sinn}\,\{|\Omega_k|^{1/2} \\ & \times \int_0^z \mathrm{d}z[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\}, \end{aligned} \tag{3}$$

where $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$, and "sinn" is sinh for $\Omega_k > 0$ and sin for $\Omega_k < 0$. For $\Omega_k = 0$, this equation degenerates to be $c(1+z)H_0^{-1}$ times the integral.

The likelihood for Ω_M and Ω_Λ can be determined from a χ^2 statistic, which is

$$(4) \qquad \chi^2(\Omega_M, \Omega_\Lambda, a, C|h) = \sum_k \left[\frac{\mu_{\rm th}(z_k; \Omega_M, \Omega_\Lambda|h) - \mu_{\rm obs}(z_k; \Omega_M, \Omega_\Lambda, a, C|h)}{\sigma_{\mu_{\rm obs}(z_k;\, \Omega_M, \Omega_\Lambda, a, C, \sigma_a/a, \sigma_C/C)}} \right]^2,$$

where h is taken as 0.71. If the Ghirlanda relation is calibrated by low-z bursts, $\mu_{\rm obs}$ and $\sigma_{\mu_{\rm obs}}$ then are independent of Ω_M and Ω_Λ, and h should be marginalized, which is the same as in SNe Ia [9].

The procedures of the two methods are summarized as follows:

Method I

The procedure of this method is to: 1) fix $\Omega_i \equiv (\Omega_M, \Omega_\Lambda)_i$, 2) derive $\mu_{\rm th}$ and E_γ for each burst for that cosmology, 3) fit the E_γ-E_p relation to yield a set of $(a, C)_i$ and $(\sigma_a/a,\ \sigma_C/C)_i$, 4) use the $(a, C)_i$ and $(\sigma_a/a,\ \sigma_C/C)_i$ to derive $\mu_{\rm obs}$ and $\sigma_{\mu_{\rm obs}}$ for each burst, 5) calculate χ_i^2 by comparing $\mu_{\rm th}$ with $\mu_{\rm obs}$, and then convert it to the probability by $P(\Omega_i) \propto \exp[-\chi_i^2/2]$ [9], 6) repeat steps 1–5 to obtain the probabilities in all the cosmic models. Because one first fits the Ghirlanda relation for cosmology Ω_i and then obtains the probability in that cosmic model, Method I is described by

$$(5) \qquad P(\Omega_i) = P(\Omega_i|\Omega_i) \qquad (i = 1, \mathrm{N}).$$

Method II

The procedure of this method is to: 1) fix Ω_i, 2) derive $\mu_{\rm th}$ and E_γ for each burst for that cosmology, 3) fit the $E_\gamma - E_p$ relation to yield a set of $(a, C)_i$ and $(\sigma_a/a,\ \sigma_C/C)_i$, 4) use the $(a, C)_i$ and $(\sigma_a/a,\ \sigma_C/C)_i$ to derive $\mu_{\rm obs}$ and $\sigma_{\mu_{\rm obs}}$ for each burst, 5) repeat steps 1–4 (*i.e.* $i = 1, N$) to obtain all the values of $\mu_{\rm obs}$ and $\sigma_{\mu_{\rm obs}}$ for each burst for each cosmology; 6) re-fix Ω_j, 7) calculate $\chi^2(\Omega_j|\Omega_i)$ by comparing $\mu_{\rm th}(\Omega_j)$ with $\mu_{\rm obs}(\Omega_i)$, and then convert it to a conditional probability by $P(\Omega_j|\Omega_i) \propto \exp[-\chi^2(\Omega_j|\Omega_i)/2]$, 8) repeat step 7 from $i = 1$ to $i = N$ to obtain the probability for cosmology Ω_j by $P(\Omega_j) \propto \sum \exp[-\chi^2(\Omega_j|\Omega_i)/2]$, 9) repeat steps 6–8 to obtain the probabilities in all the cosmic models. Method II is described by

$$(6) \qquad P(\Omega_j) = \sum_i P(\Omega_j|\Omega_i) \quad (j, i = 1, \mathrm{N}).$$

3. – Cosmological constraints

With method I, we obtain constraints from 17 GRBs on the Ω_M-Ω_Λ parameters, shown in fig. 1a (blue contours). The dataset is consistent with the cosmic model of $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$, yielding a $\chi^2_{dof} = 17.74/15 \approx 1.18$. We measure $\Omega_M = 0.16^{+0.42}_{-0.14}$ (1σ) for a flat universe.

With method II, constraints from 17 GRBs in the Ω_M-Ω_Λ plane are also shown in fig. 1a (red contours). We see that, method II gives a bit more stringent constraints than method I. In the $(0.27, 0.73)$ model, the data give a $\chi^2_{dof} = 17.65/15 \approx 1.18$. We find $\Omega_M = 0.22^{+0.42}_{-0.07}$ (1σ) for a flat universe.

As comparison, we present how well the 17 GRBs could constrain the Ω_M-Ω_Λ parameters if the Ghirlanda relation was calibrated by low-z bursts (dashed contours in fig. 1a;

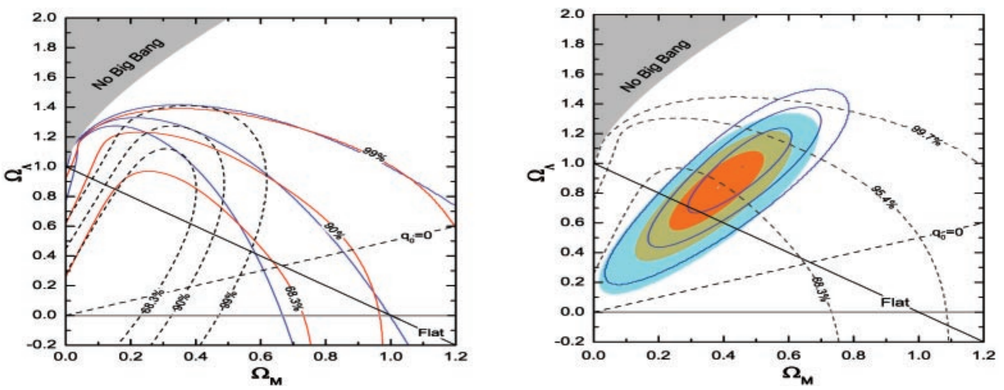

Fig. 1. – a) Left panel: Joint confidence intervals (68.3%, 90% and 99%) for $(\Omega_M, \Omega_\Lambda)$ from the 17 GRBs with method I (blue contours), method II (red contours), and assumption of $a = 1.5$ and $C = 1.0$ (dashed contours). b) Right panel: Confidence intervals (68.3%, 95.4% and 99.7%) in the Ω_M-Ω_Λ plane from the 17 GRBs with method II (dashed contours), from the SN gold sample (blue contours) and from the SN+GRB data (color regions). The upper and lower dots indicate the best-fits from the SN sample and the SN+GRB sample.

for illustrative purpose only). The parameters a, C, σ_a/a and σ_C/C are *empirically* taken as 1.5, 1.0, 0.05 and 0.10, respectively (see [13]). As can be seen, realization of low-z calibration would make GRBs place much more stringent constraints.

A combination of SNe Ia and GRBs will give new constraints on cosmology, although the results are dominated by alone SNe. The results are shown in fig. 1b. The SN, SN+GRB data are consistent with the cosmic concordance model of $\Omega_M = 0.27$, respectively, yielding $\chi^2_{dof} = 178.17/155 \approx 1.15$ and $\chi^2_{dof} = 199.15/(157 + 17 - 2) \approx 1.16$. However, the confidence region at 1σ level moves closer to the $(0.27, 0.73)$ cosmic model and thus more consistent with the conclusions from WMAP observations.

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