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A redshift determination of the host galaxy (*)

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Summary. — Using the Suprime-Cam on the Subaru telescope, we carried out deep multi band (V, R, I, z') imaging for the host galaxy of GRB980329, which is one of well studied "optically dark" gamma-ray bursts. The host galaxy was detected clearly in all bands. Combining these measurements with published near-infrared data, we determined the photometric redshift of the galaxy as $z = 3.56$ (3.21–3.79 at 90 range). The implied V-band extinction is rather low, typically ~ 1 mag. At $z = 3.56$, the isotropic 40–700 keV total energy of GRB980329 is calculated as $(2.1 \pm 0.4) \times 10^{54}$ erg. Assuming that this GRB was emitted by a pair of jets with a total energy of 10^{51} ergs, their opening angle is calculated as $\theta_j = 2.1$. The present results disfavor the high-redshift hypothesis and the high extinction scenario of optically dark bursts.

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PACS 98.70.Rz – γ-ray source; γ-ray bursts.
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1. – Introduction

In recent years, *Beppo-SAX* and *HETE-2* have been providing quick position information of a number of gamma-ray bursts (GRBs) with a typical position accuracy of $\sim 10'$, and lead to rapid follow-up observations in the optical and near infrared frequencies. Nevertheless, about half of the promptly localized GRBs are associated by very faint (> 23 mag after 1 day from the burst [1] or no optical afterglows [2]. Such events

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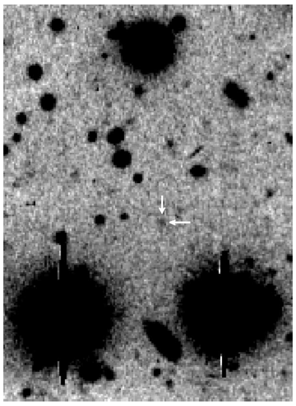

Fig. 1. – The V-band image of the GRB980329 field taken with the Subaru Suprime-Cam. The host galaxy of the GRB is indicated by arrows near the image center.

are grossly termed "optically dark GRBs". To be more precise, here we define a GRB "optically dark" if its optical afterglow is fainter than 23 mag 1 day after the burst. Typical optically dark GRBs include GRB030115 and GRB021211. The afterglow of GRB030115 was extremely red; although a near-infrared counterpart with $K \sim 19$ was detected 1 day after the burst, no optical afterglow brighter than 20 mag was detected even at 0.1 day. In the case of GRB021211, the afterglow showed a rapid decay until around 0.1 day, fading to > 22 mag by the next day.

There are three possible explanations for optically dark GRB. 1) They have such high redshifts ($z > 5$) that optical afterglows suffer strong Lyman absorption [3]. 2) The optical afterglow is extinguished by dust in the vicinity of GRB or in the star-forming region in which the GRB occurs [4,5]. 3) Some optical afterglows show rapid decay from very early phase [6,7]. However, the faintness of the optical afterglows that is the defining characteristic of the optically dark GRBs has hampered their redshift determinations. As a result, fundamental quantities of optically dark GRBs, such as their distances, total energies, and occurrence rates, have remained unknown; this in turn has made it difficult to choose among the three alternative explanations.

GRB980329, detected by the *BeppoSAX* satellite on March 1998, 29.16 UT [8], is one of the optically dark GRBs observed extensively from the X-ray to radio range, respectively. The optical afterglow exhibited the two characteristics of optically dark GRBs: an optical faintness with $R = 24$ mag and a very red ($R-K \sim 5$ mag) color, measured 1 and 3.6 day after the burst, respectively [10]. Although a redshift of ~ 5 was suggested on the basis of a break in the spectral energy distribution (SED) between R and I bands of its afterglow [9], the estimate was based on photometric measurements at different epochs, and was hence subject to uncertainties in the correction for the decay. In November 1998, the host galaxy was detected in the near infrared at a K-band magnitude of ~ 22 by Yost *et al.* (2002) [11] using the Hubble Space Telescope (HST) and the Keck observatory.

2. – Observations

Using the Suprime-Cam on the 8.2 m Subaru telescope at Mauna Kea Observatories, we carried out V-, R-, I-, z'-band observations of the GRB980329 field on January 12, 2002. All the observations were done under photometric conditions, with the seeing between $0.5''$ and $0.8''$ (fig. 1). The total exposure times were 5400 s for the V-, Rc- and Ic-band, and 4500 s for the z'-band.

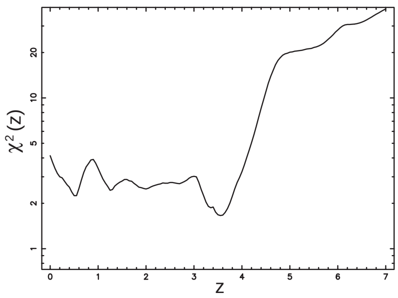

Fig. 2. – The reduced chi-squared of the model fit to the multi-band photometric data of the host galaxy, shown as a function of the assumed redshift.

3. – Data analysis and results

We estimated the redshift of the host galaxy using the HYPERZ code of Bolzonella *et al.* [12] (2000). For each trial redshift z, the code calculates a synthetic model SED as a linear combination of starburst SED template, using the stellar evolutionary code (GISSEL98) [13] by Bruzual and Charlot (1993). The synthetic SED is compared with our V, Rc, Ic, and z'-band results, as well as the public H and K-band data (Yost *et al.* 2002) [11].

We first searched for the $\chi^2(z)$ minimum with a step of $z = 0.05$, and then refined the search with $z = 0.005$. As a result of this procedure, we have obtained the χ^2 curve as shown in fig. 2 Thus, a clear minimum is found at $z = 3.56$ (χ^2/d.o.f = 1.65), with the 90% error range being 3.21–3.79. In particular, any redshift higher than ~ 4.3 is securely ruled out. Thus, our V-band flux point plays a crucial role, because the drop from the R-band to the V-band can be successfully interpreted as the redshifted Lyman α absorption.

4. – Discussion

4˙1. *High-z?* – Even assuming the highest allowed redshift ($z = 4.25$), the Lyα line and continuum absorption is expected to affect the R-band flux of the afterglow only by 0.08 mag; in calculating this, we fixed the spectral index at $\beta = 1.4 \pm 0.4$ which has been computed from the X-ray afterglow (in't Zand *et al.* [8]), and employed the optical depth calculated by Yoshii *et al.* [14] Since the expected R-band absorption is not high enough to explain the darkness of the afterglow, the high-z scenario for optically dark GRBs is inappropriate at least in the particular case of GRB980329.

4˙2. *Extinction ?* – The V-band extinction implied by our best-fit synthetic SED is only $A_v \sim 0.6$ mag. This result is supported by SCUBA observations of several dark GRB: the sub-mm results suggest that optically dark GRBs do not have particularly dusty environments [15].

4˙3. *Jet opening angle.* – Since the true gamma-ray energy released, E_γ, is given by $E_\gamma = f_\mathrm{b} \times E_\mathrm{iso}$, where $f_\mathrm{b} = (1 - \cos\theta_\mathrm{j}) \cong \theta_\mathrm{j}^2/2$, θ_j is the jet opening half-angle and E_iso is the isotropic burst energy, we can estimate θ_j if E_γ is given. According to Bloom *et al.* (2003) [16], we may assume $E_\gamma = 1.3 \times 10^{51}$ ergs in the 20–2000 keV band. Then, the observed 40–700 keV fluence of GRB980329 ($6.5 \pm 0.5 \times 10^{-5}$ ergs cm^{-2}; Amati *et al.* (2002) [17]), after cosmological K-correction (Bloom, Frail, and Sari (2001) [18]), yields $E_\mathrm{iso} = (2.1 \pm 0.4) \times 10^{54}$ ergs in the 20–2000 keV band at the redshift we have determined.

In our K-correction, we assume that the gamma-ray spectrum has the same form as the Band *et al.*(1993) [19] spectrum, with the spectral parameters reported by Amati *et al.* [17]. Hence the jet opening angle of GRB980329 is calculated as $\theta_j = 2^{\circ}.1$.

4.4. *Jet break time.* – The opening angle of the conical blast wave is related to the jet break time t_j in the lightcurve as (Sari *et al.* (1999) [20])

$$t_j = (0.057)^{-\frac{8}{3}} (\theta_j)^{\frac{3}{8}} \left(\frac{1+z}{2}\right) \left(\frac{E_{\rm iso}(\gamma)}{10^{53}}\right)^{\frac{1}{3}} \left(\frac{\eta_\gamma}{0.2}\right)^{-\frac{1}{3}} \left(\frac{n}{0.1}\right)^{-\frac{1}{3}}, \tag{1}$$

where η_γ is the efficiency of the fireball in converting the energy in the ejecta into gamma-rays, and n is the mean circumburst density in cm^{-3}. When a GRB has a narrow jet opening angle and/or higher density, the jet break time is reduced. Substituting $\theta_j = 2^{\circ}.1$ into eq. (2), we obtain $t_j = 0.31$ day for $\eta_\gamma = 0.2$ and $n = 20\,\mathrm{cm}^{-3}$ reported by Yost *et al.* (2002) [11]. This value of t_j is consistent with the report by Yost *et al.* (2002) [11], based on the afterglow analysis, that the jet break occurred within 1 day of the burst. Note that, the density of GRB980329 is higher than that of typical GRB which have bright afterglow and narrow jet opening angle such as GRB990510 ($\theta_j = 3.36^{\circ}$, $n = 0.29\,\mathrm{cm}^{-3}$) and GRB010222 ($\theta_j = 3.13^{\circ}$, $n = 1.7\,\mathrm{cm}^{-3}$) (Bloom *et al.* 2003) [16]. This result implies the afterglow has large decay index (~ 2) from early phase such as optically dark GRB021211 (Crew *et al.* 2003 [6]) and GRB020124 (Berger *et al.* 2002 [7]).

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