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THE STUDY OF GAMMA-RAY BURSTS AND THEIR HOST GALAXIES IN THE GTC ERA

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RESUMEN

Siguiendo la rápida localización de las breves explosiones cósmicas de rayos gamma (GRB) por satélites científicos, se espera que la instrumentación prevista para el GTC permitirá estudiar la variabilidad, obtener espectros de media resolución y caracterizar el entorno del GRB, pudiendo incluso confirmar si existe una contribución en el espectro debido a una supernova subyacente. Tanto la espectroscopía de las galaxias anfitrionas como la imagen en banda estrecha por medio de los filtros sintonizables permitirá contrastar si las ubicaciones de los GRBs coinciden con regiones de formación estelar en las galaxias anfitrionas. Asímismo la instrumentación de que dispondrá GTC será muy eficiente en lo que respecta a la detección de la clase de GRB de corta duración que hasta ahora no se han podido detectar en el óptico o IR cercano.

ABSTRACT

GTC imaging/spectroscopy of GRB afterglows localized by various satellites will be a very powerful tool for the study of the high redshift Universe. The scientific aim is the rapid identification of the optical counterparts to the gamma-ray events, and the study of their variability, their spectra, and their environments. This will take advantage of the enormous collecting power of the GTC, which will allow us to achieve breakthroughs in the GRB field, such as checking whether a supernova-like contribution is present in the host spectrum at late times. Host spectroscopy and tunable-filter imaging are also foreseen in order to characterize the host galaxy and determine whether the GRB locations lie on top of star forming regions in the parent galaxies. Moreover, the GTC instrumentation is likely to be very efficient in detecting intrinsically absorbed afterglows, as well as the so-called short/hard GRBs undectected to date in the optical.

Key Words: **COSMOLOGY: EARLY UNIVERSE – GAMMA RAYS: BURSTS**

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1. INTRODUCTION

Gamma-ray bursts (GRBs) have remained a puzzle for many astrophysicists since their discovery in 1967 (Klebesadel, Strong, & Olson 1973). With the advent of the X–ray satellites *BeppoSAX* and *Rossi-XTE*, it has been possible to carry out deep multiwavelength observations of the counterparts associated with the long duration GRBs class just within a few hours of occurrence, thanks to the observation of the fading X-ray emission that follows the more energetic gamma-ray photons once the GRB event has ended. The fact that this emission (the afterglow) extends to longer wavelengths, has led to the discovery of optical/IR/radio counterparts starting in 1997, greatly improving our understanding of these sources. But nothing is known about the short/hard duration class, which comprises about one third of all the events. Now it is proven that long duration GRBs originate at cosmological distances with energy releases of 10^{51}–10^{54} erg. The central engine that powers these extraordinary events is thought to be a rotating massive star with a Fe core that collapses forming a Kerr black hole (BH) and a 0.1–1 $M_\odot$ torus. The matter is accreted at a very high rate and the energy can be extracted either from the accretion of disk material by the BH or from the rotational energy of the BH via the Blandford–Znajek process. The energy released in this process is $\sim10^{54}$ erg and "dirty fireball", is produced reaching a luminosity $\sim$1000 times larger that than of a normal SN. This would happen every $\sim10^6$ yr in a given galaxy. A review of the observational characteristics can be found in Fishman & Meegan (1995) and Piran (2000).

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2. OPTICAL/IR AFTERGLOW OF LONG GRBS

BeppoSAX made it possible to detect the first X-ray afterglow following GRB 970228, whose precise localization ($1'$) (Costa et al. 1997) led to the discovery of the first optical transient (or optical afterglow, OA) associated with a GRB (van Paradijs et al. 1997). The light-curve exhibited a power-law (PL) decay $F \propto t^{-\alpha}$ with $\alpha = 1.1$, thus confirming

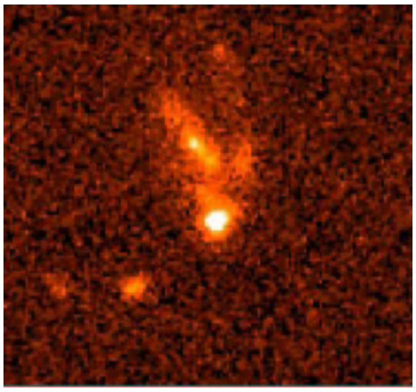

Fig. 1. *HST* observation of GRB 990123 17 at T_0 + 17 d. The optical afterglow (bright point source) reached $V = 8.9$. The underlying object ($V = 24.5$) is a complex galaxy system at $z = 1.599$. Image from Fruchter et al. (2001).

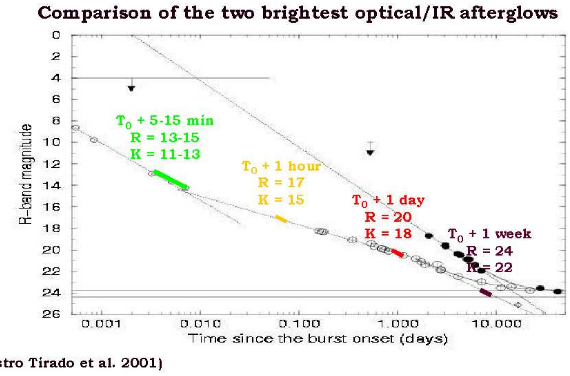

Fig. 2. The two brightest optical GRB afterglows detected so far: GRB 990123 (empty circles) and GRB 991208 (filled circles). The dotted lines are the constant contribution of the two host galaxies, $R \sim 23.9$ and 24.3, respectively. The dashed lines are the pure OA contributions to the total fluxes. The solid lines (only shown here after $T > 5$ d) are the combined fluxes (OA plus underlying galaxy in each case). The upper limits are for GRB 991208. Adapted from Castro-Tirado et al. (2001).

the prediction of the relativistic blast-wave model (Sari et al. 1998). PL declines were measured for $\sim$35 OAs in 1997–2002, yielding values in the range $0.8 < \alpha < 2.3$ with $\langle\alpha\rangle = 1.35$ (Figure 1).

For GRB 970508, a "plateau" ($\alpha = 0$) was observed between T_0 + 3 hr and T_0 + 1 d. The optical light curve reached a peak in two days and was followed by a PL decay $F \propto t^{-1.2}$. The plateau has been explained in terms of several plasmoids with different fluxes occurring at different times. Furthermore, GRB 970508 was the clue to the distance: optical spectroscopy obtained during the OA maximum brightness allowed a direct determination of a lower limit for the redshift ($z \geq 0.835$), implying $D \geq 4$ Gpc (for $H_0 = 65$ km s^{-1} Mpc^{-1}) and $E \geq 7 \times 10^{51}$ erg (Metzger et al. 1997). It was the first proof that GRB sources lie at cosmological distances. The flattening of the decay at T_0 + 100 d ($\sim$100 days after the onset of the GRB at T_0) revealed the contribution of a constant-brightness source—the host galaxy—seen in late-time imaging at T_0 + 1 yr. The $\sim$255 GRB redshifts measured so far are in the range $0.36 \leq z \leq 4.50$ with $\langle z\rangle = 1$ and they were derived either from absorption lines in the OA spectrum, from the Lyα break, or from emission lines arising in the host galaxy.

A break deviating from a PL decay was first observed in the GRB 990123 light-curve at T_0 + 1.5 d (Figure 2) and was interpreted as the presence of a beamed outflow with a half opening angle $\theta_0 \sim 0.1$ (Castro-Tirado et al. 1999), i.e., reducing the inferred energy by a factor of $\sim \theta_0^2/4$. Further breaks have been reported in another five GRBs. There are several explanations for the observed breaks, such as the sideways expansion of the jet caused by the swept-up matter and the fact that the jet material might propagate in a uniform density medium so that the observer sees the edge of the jet.

Rapid fading ($\alpha > 2.0$) has been observed in other GRBs. Two possible causes can explain such behavior: the synchrotron emission during the mildly relativistic and non-relativistic phases and the interaction of a spherical burst with a pre-burst Wolf–Rayet stellar wind.

Flux fluctuations are expected because of inhomogeneities in the surrounding medium as a consequence of interstellar turbulence or by variability and anisotropy in a precursor wind from the GRB progenitor. However, short term variability was found neither in GRB 970508 nor in GRB 990510. In GRB 000301C, the high variability observed at optical wavelengths could be due to several reasons: i) refreshed shock effects; ii) energy injection by a strongly magnetic millisecond pulsar born during the GRB; iii) an ultra-relativistic shock in a dense medium rapidly evolving into a non-relativistic phase; and iv) a gravitational microlens.

According to the several theoretical models (e.g., the collapsar model) the light-curve of the afterglow should display a rebrightening at $T_0 + (1+z) \times 15$ d. This "bump" in the light-curve is explained by the optical emission of an underlying supernova. In fact, a peculiar Type Ib/c supernova (SN 1998bw) was found in the error box for the soft GRB 980425

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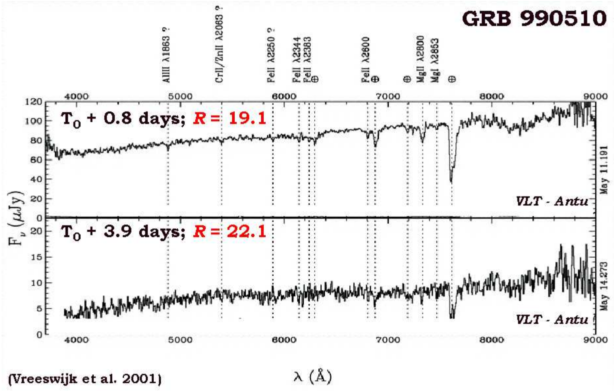

Fig. 3. The optical spectrum of GRB 990510 obtained with the 8.2-m VLT at two epochs. From Vreeswijk et al. (2001). In another burst (GRB 991216), three absorption systems at redshifts $z = 0.77$, 0.80, and 1.02 were found in the optical afterglow spectra.

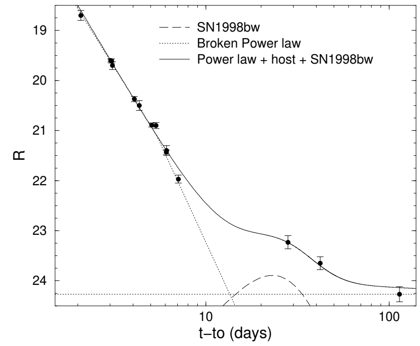

Fig. 4. The GRB 991208 R band light-curve (solid line) fitted with an SN 1998bw-like component at $z = 0.706$ (long dashed line) superposed on the broken power-law OA light curve displaying the second break at $t_{\rm break} \sim 5$ d (with $\alpha_1 = -2.3$ and $\alpha_2 = -3.2$, short dotted lines) and the constant contribution of the host galaxy ($R = 24.27 \pm 0.15$, dotted line). From Castro-Tirado et al. (2001).

(Galama et al. 1998) coincident with a galaxy at $z = 0.0085$, but this SN/GRB relationship is still under debate. "SN-like" bumps have been detected in another six GRBs, with 011121 being the most recent and observed by the *HST* (Garnavich et al. 2002). There are some alternative explanations for the existence of such a bump in the OA light-curves: i) scattering of a prompt optical burst by 0.1 $M_\odot$ of dust beyond its sublimation radius 0.1–1 pc from the burst, producing an echo after 20–30 d; ii) delayed energy injection by shell collision; and iii) an axially symmetric jet surrounded by a less energetic outflow. But this is certainly not the case for all GRBs: GRB 990712 provided the first firm evidence that an underlying SN was not present.

3. GRBS IN THE GTC ERA

By the time of GTC first light, both the *Interplanetary Network* of satellites (*IPN*) and the *HETE-2* spacecraft should be providing GRB positions at a rate of $\sim$50 yr^{-1}. Although the *IPN* will provide accurate positions with a 24–48 hr delay, both *HETE-2* and *INTEGRAL* (launched in 2002 October) should deliver arcmin positions with only a few minutes' delay. *SWIFT* should join them in 2004. It is expected that 30% of total detections will be at $z > 5$, and 5% of total detections will be at $z > 10$.

For GRBs at $z < 7$, GTC + OSIRIS will be able to point to the early optical afterglow and perform spectroscopic studies of an OA as bright as $V \sim 15$–17 mag! Besides determining the redshift, high resolution spectroscopy ($R \sim 2500$) can be performed following the high energy event within (T_0 + 1 d). This will allow a detailed study of the interstellar medium at high redshift and absorption line systems in the line of sight that cannot be studied by any other astronomical techniques (Figure 3). Once the OAs have vanished (i.e., at $\sim T_0$ + 15 d), deep broad band $UBVRI$ imaging (down to $R \sim 25$ mag) and medium resolution spectroscopy ($R \sim 1500$) will allow us to search for an underlying SN. It will also serve for studying the nature of the GRB host galaxy and determine the star forming rate. This will shed more light on understanding the nature and physics of GRBs.

In the case of short duration GRBs, for which the positions will be known with a precision of $\leq 4'$ at T_0 + 1 min, rapid imaging with the GTC instruments will enhance the likelihood of identifying the first counterpart of a short duration GRB at other wavelengths in the range 0.35–20 μm, especially by means of color–color techniques (Gorosabel et al. 2002).

In the case of long duration GRBs with OAs previously detected, and only for those with rapidly decaying afterglows, broad band UVI imaging will allow us to determine the power-law component at late stages and to test whether a "red bump" is present or not at the expected time of the SN peak at $T_0 + 15(1 + z)$ d (Figure 4). Where a bump is present in the GTCO + OSIRIS/EMIR late time curve, broad band spectroscopy at the time of the SN peak can be obtained in order to check for the spectral signature of an SN. An 0.4$''$ slit would be desirable in the case the host galaxy were comparable in brightness in order to isolate the SN contribution from that of the underlying host as far as possible.

Once the OA has vanished, broad band spectroscopy can be attempted in order to determine the star forming rate (SFR) of the GRB host galaxy. Once the optical/near-IR spectral energy distribution has been constructed, several galaxy templates will be fitted. This will allow us to estimate the age of the predominant stellar component, metallicity, and extinction law. As z would hopefully have been determined beforehand, the right grism should be selected accordingly in order to get the redshifted [O II] 3727 and Hβ lines. For instance, a 5000 s spectrum with the OSIRIS G1500B grism will give an S/N of 10 with the 1.0″ slit under 1.0″ seeing.

An additional goal for GTC + OSIRIS will be to perform tunable filter (TF) imaging of extended host galaxies in order to study the GRB location within their host galaxies (Figure 5) and check whether the GRBs "are sitting on" the top of star forming regions. For example, a typical GRB host galaxy like the one for GRB 991208 [4] at $z = 0.707$ can be imaged with TFs in the rest-frame wavelengths of [O II] 3727, H$_\beta$, and [O III] 5007.

For $z \geq 7$, only GTC + EMIR will allow us to detect the transient emission due to the Lymanα break lying in the I band. It will be able to perform imaging/spectroscopy of highly obscured GRBs and, moreover, study the high redshift Universe (see Gorosabel et al., this volume, p. 288).

Following previous *ISO* searches of afterglows at 10 μm (Castro-Tirado et al. 1998), GTC + CanariCam should be also able to detect afterglows in the thermal IR and to perform polarimetric observations with an unprecedent sensitivity from a ground-based observatory.

4. CONCLUSIONS

The large field of view and high sensitivity of the GTC instruments are especially useful for detecting high redshift GRBs.

What are the advantages of observing the most powerful phenomena in the Universe? GTC should provide an answer to the following open questions: i) do the long GRBs represent the final evolutionary stages of very massive stars? ii) are some of them related to Population III stars? iii) are the short GRBs the result of coalescence of compact binary systems?

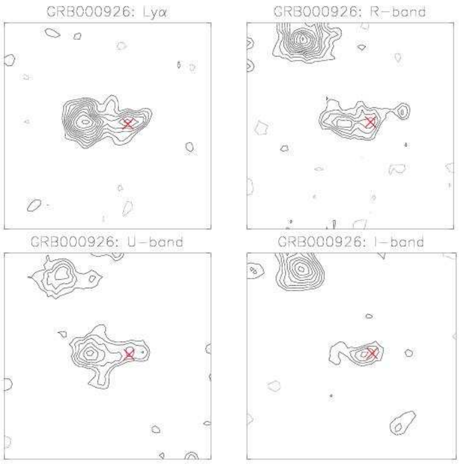

Fig. 5. Lyman*alpha* imaging of the GRB+000926 host galaxy at $z = 2.03$ compared with broad band URI images. From Fynbo et al. (2001).

GRBs should also provide us with unprecedented information on the ionization and metallicity of the intergalactic medium and will provide a measurement of the unobscured star formation rate in the Universe.

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