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VERY LARGE TELESCOPE AND *HUBBLE SPACE TELESCOPE* OBSERVATIONS OF THE HOST GALAXY OF GRB 990705[1,2]

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ABSTRACT

We present Very Large Telescope spectroscopic observations of the GRB 990705 host galaxy and highlight the benefits provided by the prompt phase features of gamma-ray bursts (GRBs) to derive the redshifts of the latter. In the host spectrum, we indeed detect an emission feature that we attribute to the [O II] λλ3726, 3729 doublet and derive an unambiguous redshift $z = 0.8424 \pm 0.0002$ for this galaxy. This is in full agreement with the value $z \sim 0.86 \pm 0.17$ previously derived using a transient absorption edge discovered in the X-ray spectrum of GRB 990705. This burst is therefore the first GRB for which a reliable redshift was derived *from the prompt phase emission itself*, as opposed to redshift determinations performed using putative host galaxy emission lines or interstellar absorption lines in the GRB afterglows. Deep and high-resolution images of the host of GRB 990705 with the Space Telescope Imaging Spectrograph camera on board the *Hubble Space Telescope* reveal that the burst occurred in a nearly face-on Sc spiral galaxy typical of disk-dominated systems at $0.75 \leq z \leq 1$. Assuming a cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$, we derive an absolute B magnitude $M_B = -21.75$ for this galaxy and a star formation rate SFR $\approx$ 5–8 $M_\odot$ yr^{-1}. Finally, we discuss the implications of using X-ray transient features to derive GRB redshifts with larger burst samples and especially examine the case of short and dark long GRBs.

Subject headings: galaxies: individual (GRB 990705 host) — galaxies: spiral — galaxies: starburst — gamma rays: bursts

1. INTRODUCTION

Since the discovery of their X-ray, optical, and radio transient counterparts, the cosmic gamma-ray bursts (GRBs) have been regarded as one of the most promising tools to probe the star formation in the early universe (Totani 1997; Wijers et al. 1998; Mirabel, Sanders, & Le Floc'h 2000; Blain & Natarajan 2000). There is indeed increasing evidence that the long and soft GRBs originate from the core collapse of massive stars within starburst regions of distant galaxies (e.g., Bloom, Kulkarni, & Djorgovski 2002). Since they are likely detectable up to very high redshifts (Lamb & Reichart 2000), GRBs could soon open a new window to sample the star-forming activity at cosmological look-back times and ultimately provide a new glimpse of galaxy evolution.

The possibility to detect emission and/or absorption features in the spectra of GRBs and their afterglows is among the most outstanding benefits of the high-z galaxy selection by these events. Such detections can indeed be done independently of the GRB host luminosities and have already enabled spectroscopic redshifts of very faint galaxies to be derived (e.g., Vreeswijk et al. 2001). This perspective strongly contrasts with the deep survey observations, which can only provide photometric redshifts for the faintest sources. Nonetheless, the correct GRB redshift identifications from the lines detected in *afterglow* spectra are not always straightforward. Absorption features observed in the optical continuum of GRB counterparts may indeed originate from foreground absorbers (e.g., Metzger et al. 1997), while the interpretation of the emission lines detected in the X-ray afterglows has already led to some misidentifications of host redshifts (i.e., GRB 970828; Yoshida et al. 1999; Djorgovski et al. 2001).

In this context, the GRB 990705 event is of remarkable interest. Using data from the *BeppoSAX* satellite, Amati et al. (2000) reported the discovery of a transient absorption edge at ~3.8 keV in the prompt X-ray emission of this burst, which they interpreted as the GRB intrinsic signature of an iron-enriched absorbing medium at $z \sim 0.86$ (see also Lazzati et al. 2001). This has been so far the only GRB for which a feature allowing a possible redshift determination was observed during the *prompt emission* of the burst itself. Following this event, an optical and near-infrared follow-up by Masetti et al. (2000) led to the discovery of a red and rapidly decaying afterglow localized behind the Large Magellanic Cloud (LMC), while deep optical images of the burst location performed with the *Hubble Space Telescope* (*HST*; Holland et al. 2000b) and the

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Very Large Telescope (VLT; Saracco et al. 2001) revealed an $R \sim 22.2$ mag underlying host galaxy.

In this Letter, we report on VLT observations carried out to derive the spectroscopic redshift of this host galaxy and which allowed us to confirm the redshift of GRB 990705 derived by Amati et al. (2000). We also analyze public *HST* data of the host.

2. OBSERVATIONS AND DATA REDUCTION

The spectroscopic observations of the GRB 990705 host galaxy were performed on 2001 December 21 and 22 (burst trigger + ~900 days) with the FORS2 instrument installed on the VLT UT4/Yepun at ESO. Spectra were obtained under moderate seeing conditions (~1″) using a medium-resolution grism (600RI) in combination with a 1″ width slit and totalizing an integration time of 1.5 hr. We thus covered an effective wavelength range ~5600–8000 Å with an instrumental resolution ~4.5 Å. The slit was positioned on the sky so as to cover the outer region of the galaxy where the burst occurred. The galaxy spectra were flux-calibrated using spectroscopic standard stars.

The *HST* observations of the GRB 990705 host galaxy[12] were taken and reduced by Holland et al. (2000a, 2000b) as part of the Survey of the Host Galaxies of Gamma-Ray Bursts using the Space Telescope Imaging Spectrograph (STIS) camera. Images were obtained with the 50 CCD (clear [CL], pivot $\lambda_0 = 5835$ Å) and F28X50LP (long-pass [LP], pivot $\lambda_0 = 7208$ Å) apertures, respectively, on 2000 July 25 and 2000 August 25 (i.e., ~400 days after the burst). The respective total exposure times were 8851 and 8202 s in the CL and LP apertures. We deconvolved the images following a multiresolution wavelet decomposition (Starck, Murtagh, & Bijaoui 1998) and the use of point-spread functions (PSFs) obtained from the combination of foreground stars in the images.

The photometry measurements were performed on the data before deconvolution to preserve reliable flux and noise estimates. We corrected the CL and LP aperture data from absorptions $A_{\rm CL} = 0.36$ mag and $A_{\rm LP} = 0.28$ mag assuming the extinction curve of Cardelli, Clayton, & Mathis (1989) and the Galactic+LMC extinction $E(B-V) = 0.12$ obtained by Dutra et al. (2001). Moreover, we carried out a careful analysis using a multiresolution transform method to subtract from the images the multiple LMC foreground stars superposed on the plane of the galaxy.

3. RESULTS

3.1. *Redshift of the GRB 990705 Host Galaxy*

The final VLT spectrum is shown in Figure 1. An emission feature is clearly detected at ~6868 Å in a region of the spectrum where the residuals from the sky line subtraction are negligible. Attributing this feature, respectively, to Hα or Lyα would imply redshifts $z = 0.05$ and $z = 4.66$, which is inconsistent with the spiral morphology and the angular size of the galaxy (see § 3.2). The line can thus only be due to [O II] $\lambda\lambda$3726, 3729. It is actually not resolved in our spectrum, but its width is in fact consistent with that of the [O II] doublet. Note that the low signal-to-noise ratio longward of 7300 Å does not allow us to detect Hδ and Hγ. From the [O II] line, we derive a secure heliocentric redshift $z = 0.8424 \pm 0.0002$ for the host galaxy and GRB 990705. This is in full agreement with the value $z \sim 0.86 \pm 0.17$ obtained by Amati et al. (2000) from the transient feature

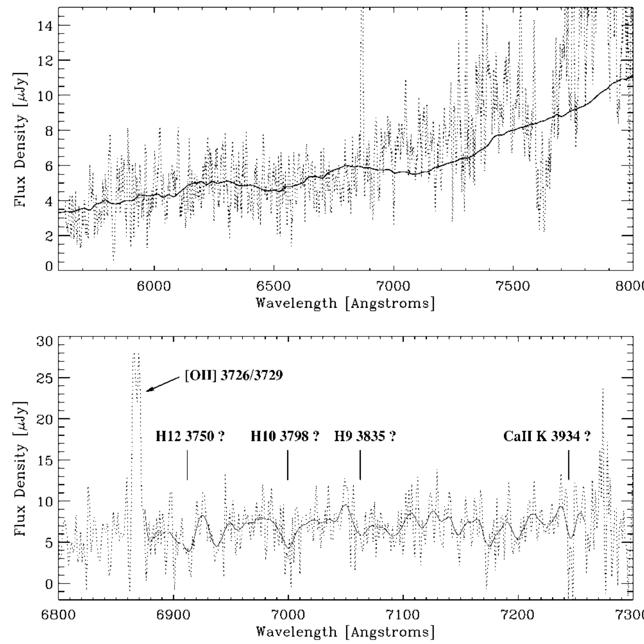

FIG. 1.—*Top:* Dereddened VLT spectrum smoothed by 5 pixels (*dotted line*), overlaid with the template of a local Sc galaxy shifted to $z = 0.8424$ (*solid line*). *Bottom:* Zoom of the ~6800–7300 Å range (*dotted line*), with the smoothed continuum (*solid line*) superposed to emphasize the possible detection of several stellar absorption lines as indicated.

observed in the GRB prompt emission and also appears consistent with the redshift $z = 0.843$ already mentioned by Lazzati et al. (2001). Assuming a standard cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$, we thus measure for the host of GRB 990705 a luminosity distance $d_l = 5.8$ Gpc and a projected scale of 8.2 proper kpc (or 15.2 comoving kpc) per arcsecond on the sky. Because of the extended and rather diffuse emission of the galaxy (see § 3.2), we did not obtain a secure estimate of the [O II] integrated flux lying outside of the slit, and thus we could not derive its [O II] total luminosity. We roughly measured, although with large uncertainties, an observed [O II] equivalent width EW ≈ 40 Å, i.e., ≈20 Å in the rest frame.

In addition to the [O II] emission doublet, we tentatively detect several stellar absorption features at a similar redshift such as H12 (λ3750), H10 (λ3798), H9 (λ3835), and Ca II K (λ3934). The reliability of these features is yet questionable given the low signal-to-noise ratio in the continuum. Finally, in spite of the poor sky subtraction longward of 7300 Å, there is a hint for a break in the continuum around 7400 Å (see Fig. 1). This suggests the presence of the rest-frame 4000 Å break, as indicated by the comparison of our spectrum with the template of an Sc galaxy (Mannucci et al. 2001) shifted to $z = 0.84$, and provides further support to our redshift determination.

3.2. *Structural Parameters of the Galaxy*

High-resolution *HST* images reveal that the host is a face-on Sc spiral galaxy. In Figure 2, we show a pseudo–true-color image of that source, constructed by registering the deconvolved CL and LP data. Two primary spiral arms following an "$m = 2$" wave density mode clearly extend from the northern and southern sides of the central bulge, while other secondary arms are also observable. The disk spreads over a region of ~3″ in diameter, with a half-light radius $R_{0.5} \sim 7.5$ kpc (0″.9) in the range of those characterizing the disk-dominated galaxies at $0.75 \leq z \leq 1$ (Lilly et al. 1998).

[12] See also http://www.ifa.au.dk/~hst/grb_hosts/data/grb990705/index.html.

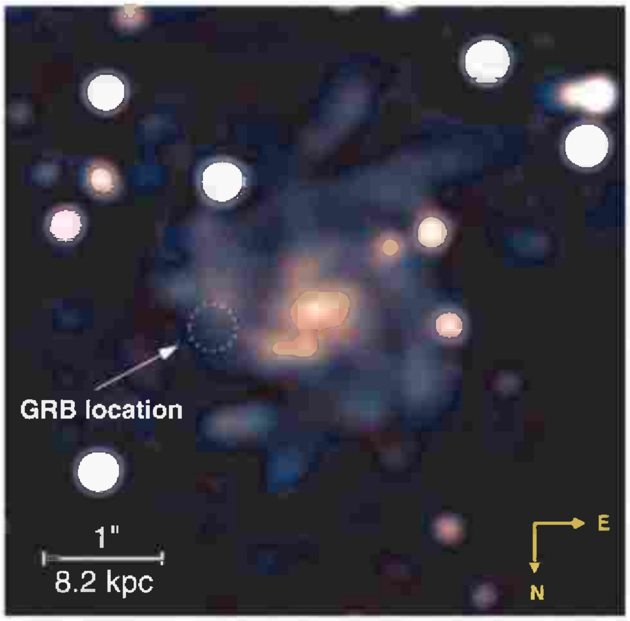

FIG. 2.—Pseudo–true-color image of the GRB 990705 host galaxy, resulting from the combination of the drizzled and deconvolved images taken through the CL and LP apertures. The 3 σ error location of the GRB 990705 event as derived by Bloom et al. (2002) is indicated by the dashed circle. Note that the GRB occurred in the outskirts of a star-forming region within one of the primary spiral arms.

After subtracting the foreground stars, we performed photometry within a 2″ radius aperture centered on the host nucleus using the STIS zero points of Gardner et al. (2000). Dereddened AB magnitudes $M_{\rm AB}({\rm CL}) = 22.45 \pm 0.10$ and $M_{\rm AB}({\rm LP}) = 22.0 \pm 0.1$ were respectively derived from the CL and LP images, the uncertainties being dominated by the subtraction residuals of the stars projected ahead of the galaxy.

An attempt was made to fit the surface brightness profile of the galaxy using a "bulge+exponential disk" decomposition. Disentangling between the two contributions in distant sources requires not only a proper correction from the PSF effects (e.g., Moth & Elston 2002) but also a sufficient sensitivity up to ~10–15 kpc in the averaged profile of the disk to reliably constrain the scale length of the exponential component (see, e.g., Fig. 1 of Rigopoulou et al. 2002). Because of the diffuse and extended emission of the galaxy and the presence of the foreground stars, this was hardly achieved in our data. With large uncertainties, we suggest, however, that the host galaxy is dominated by a large exponential disk (scale length ~5–6 kpc), with a rather small bulge contribution leading to a bulge-to-total light ratio $B/T \approx 0.10$–0.15. We also estimated the central surface brightness of the disk component in the dereddened LP data μ_0(LP), which was then converted into a rest-frame $B_{\rm AB}$ magnitude by applying a cosmological dimming term and a k-correction color factor as follows:

$$\mu_0(B_{\rm AB}) = \mu_0({\rm LP_{AB}}) - 2.5 \log (1 + z)^3 + (B_{\rm obs} - {\rm LP})_{\rm AB}.$$

Since the LP aperture samples the almost rest-frame B emission at the redshift of the host, the color term should be rather small. Using the spectral energy distribution (SED) of a local Sc spiral galaxy shifted to $z = 0.84$ (see § 3.3), we derive a k-correction ~0.1 mag and finally obtain a value $\mu_0(B_{\rm AB}) \approx 20.8$. This is actually less than the canonical Freeman (1970) value $\mu_0(B_{\rm AB}) = 21.6$ observed in local disks but is consistent with those found in higher z spirals (Lilly et al. 1998). It is therefore in agreement with the observed global trend for the disk central surface brightness to significantly increase with redshift up to ~1 (Lilly et al. 1998).

3.3. *Absolute B Magnitude and Star Formation Rate*

At $z = 0.84$, the *rest-frame B* emission of the galaxy is shifted to ~8100 Å. The dereddened continuum of the host of GRB 990705 and the CL−LP color derived from the STIS images are, however, consistent with the SED of a local Sc spiral galaxy (Mannucci et al. 2001) shifted to $z = 0.84$ assuming no evolution. To estimate the luminosity at $B_{\rm rest}$, we thus extrapolated the continuum of our spectrum using the template of Mannucci et al. (2001) and found a flux density $F_\nu(\lambda = 8100\ {\rm Å}) \approx 12\ \mu$Jy. Given the assumed cosmology and the luminosity distance of the galaxy, this implies a rest-frame absolute B-band magnitude $M_B \approx -21.75$, corresponding to a $2L_*$ galaxy at $z \sim 1$ (Lilly et al. 1995).

Using a similar method, we also measured the continuum luminosity at $\lambda_{\rm rest} = 2800$ Å to estimate the level of UV-unobscured star formation activity. From the Sc template SED, we estimate a flux ~1.8 μJy at the corresponding $\lambda_{\rm obs} = 5152$ Å and deduce a UV luminosity $L_{\rm UV} \sim 4$ ergs s^{-1} Hz^{-1} at the redshift of the host. Following the calibration of Madau, Pozzetti, & Dickinson (1998) and assuming a Salpeter (1955) or Scalo (1986) initial mass function, we finally derive star formation rates SFR $\approx 5\ M_\odot$ yr^{-1} or SFR $\approx 8\ M_\odot$ yr^{-1}, which are fairly common values for star-forming galaxies at $z \sim 1$ (Lilly et al. 1995).

4. DISCUSSION AND CONCLUSION

The general properties of the GRB 990705 host have been summarized in Table 1. According to its morphology, star formation activity, and absolute luminosity, we find that it is typical of the (disk) galaxies in the field at similar redshifts.

Taking account of the cumulative surface density distribution of sources with $R \lesssim 22.8$, Masetti et al. (2000) had estimated a probability of only 0.006 for the burst and the underlying

TABLE 1
PROPERTIES OF THE GRB 990705 HOST GALAXY

Parameter	Measure
α (J2000.0) (host nucleus)	$05^{\rm h}09^{\rm m}54\overset{\rm s}{.}8$
δ (J2000.0) (host nucleus)	$-72°07'54''$
Foreground extinction $E(B-V)$	0.12
Spectroscopic redshift	0.8424 ± 0.0002
CL aperture (dereddened) magnitude ($\lambda_0 = 5835$ Å)	22.45 ± 0.10
LP aperture (dereddened) magnitude ($\lambda_0 = 7208$ Å)	22.00 ± 0.10
Half-light radius $R_{0.5}$	~7.5 kpc
Central surface brightness $\mu_0(B_{\rm AB})$	~20.8
Absolute M_B magnitude ($H_0 = 65$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$)	≈−21.75
UV-unobscured star formation rate	~5–8 $M_\odot$ yr^{-1}

galaxy being hazardously superposed on the sky by projection effect and had thus suggested a secure identification of this galaxy with the host of GRB 990705. Our spectroscopic observations reveal that the redshift of the spiral is consistent with the one derived by Amati et al. (2000) for the GRB itself, providing further convincing evidence for a true association between the two. Among the current sample of GRB host galaxies, the host of GRB 990705 has been so far the only case clearly identified with a large disk-dominated spiral structure at high redshift, the others being classified as either compact, irregular, or interacting systems (see, e.g., Fig. 2 of Bloom et al. 2002). With an absolute magnitude $M_B \approx -21.75$ ($H_0 = 65$, $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$), it lies furthermore within the brightest sources of the GRB host sample, which is mostly characterized by subluminous systems.

With a larger sample of GRB hosts, the redshift-dependent proportion of large disks similar to the host of GRB 990705 relative to subluminous blue galaxies could provide indications of the fraction of star formation taking place in massive spirals and thus inform us of the cosmological evolution of the disk-dominated systems. This perspective appears promising since such massive and spiral objects are believed to be responsible for an important fraction of the extragalactic infrared background (Rigopoulou et al. 2002). They could thus harbor star-forming regions enshrouded in dusty environments, which are not sampled by the blue faint galaxy population.

We finally stress the remarkable result obtained by Amati et al. (2000), who derived a reliable estimation of the burst redshift interpreting a transient edge observed in the GRB X-ray spectrum as an iron absorption at $z = 0.86 \pm 0.17$. They showed that intrinsic GRB properties, such as the redshift and the physical conditions of the GRB-surrounding medium, can be derived from the burst detection itself, without the need of any afterglow to be detected and followed up.

Even though GRB 990705 is the only burst in which such a transient edge has been observed so far, which raises the question of whether particular ionizing states of the circumburst environment are required to detect these absorptions, this burst lies among the brightest GRBs ever detected with the *BeppoSAX* satellite (Amati et al. 2000). This suggests that these transient edges could be a more common feature of GRB spectra. Future satellites equipped with more sensitive X-ray detectors, such as the ECLAIRs experiment (Barret 2002), could be entirely dedicated to studying the GRB prompt emission and may provide a systematic detection of these absorption lines. Larger samples of GRB redshifts could be derived, an achievement indeed required to estimate the star formation history in the universe from the GRB occurrence rate.

Furthermore, compelling key results could be obtained toward the class of short GRBs or specific subclasses of long GRBs, such as the so-called dark bursts. The latter, exhibiting X-ray and radio afterglows without any detected optical counterparts, could pinpoint not only GRBs with optical afterglows either locally absorbed by dust or characterized by steep and rapid decays with time but also very high redshift GRBs whose optical emission may be suppressed by the Gunn-Peterson H I trough along their line of sight. The use of transient features in X-ray spectra to derive GRB redshifts could thus provide a new approach to probe very distant GRBs in the early universe. In the case of short GRBs, their distance scale and physical origin are simply still unknown since no detailed follow-up of their afterglows has been possible so far (but see Castro-Tirado et al. 2002). The clues of their formation mechanism directly observed in the GRB prompt emission would undoubtedly improve our current understanding of these particular events.

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