PHOTOMETRIC REDSHIFT OF THE GRB 981226 HOST GALAXY\(^1\)

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ABSTRACT

No optical afterglow was found for the dark burst GRB 981226, and hence no absorption redshift has been obtained. We here use ground-based and space imaging observations to analyze the spectral energy distribution (SED) of the host galaxy. By comparison with synthetic template spectra, we determine the photometric redshift of the GRB 981226 host to be \(z_{\text{phot}} = 1.11 \pm 0.06\) (68% confidence level). While the age-metallicity degeneracy for the host SED complicates the determination of accurate age, metallicity, and extinction, the photometric redshift is robust. The inferred \(z_{\text{phot}}\) value is also robust compared to a Bayesian redshift estimator, which gives \(z_{\text{phot}} = 0.94 \pm 0.13\). The characteristics for this host are similar to other gamma-ray burst (GRB) hosts previously examined. Available low-resolution spectra show no emission lines at the expected wavelengths. The photometric redshift estimate indicates an isotropic energy release consistent with the Amati relation for this GRB, which had a spectrum characteristic of an X-ray flash.

Subject headings: galaxies: distances and redshifts — galaxies: high-redshift — galaxies: starburst — gamma rays: bursts

Online material: color figure

1. INTRODUCTION

The Swift satellite (Gehrels et al. 2004) promises the buildup of a significant sample of GRBs with well-understood selection criteria useful for cosmological studies of high-redshift galaxies (Jakobsson et al. 2005) and the Hubble diagram (Ghirlanda et al. 2004b). The best way of securing GRB redshifts is from absorption-line studies of the afterglow. However, for the first 56 Swift GRBs, only 11 redshifts have been obtained. Alternatively, redshifts can be obtained from host galaxy spectroscopy, although this requires that the host is sufficiently bright and has detectable emission lines.

In this Letter, we explore a third approach suitable for fainter host galaxies, in case a spectroscopic absorption or emission-line redshift has not been obtained. For a sample of 10 GRB host galaxies with spectroscopic redshifts in the range \(0.4 < z < 2\) and photometric measurements in more than four bands, Christensen et al. (2004a) found that photometric redshifts were consistent with the spectroscopic redshifts in all cases, within \(\Delta z \approx 0.21\). An advantage of the method is that it is independent of whether the host galaxy has emission lines.

As the next step in validating the photometric redshift approach, we here predict a redshift from a host galaxy with multiband photometry that is sufficiently bright that a spectroscopic redshift can be measured, and thereby test the photometric redshift. Our target is GRB 981226, which is currently one of the brightest hosts without a spectroscopic redshift.

GRB 981226 was detected by the BeppoSAX satellite on 1998 December 26.41 UT. Its characteristics are consistent with being an X-ray flash (XRF), with the fluences satisfying \(S_X > S_\gamma\) (Frontera et al. 2000). Despite intense optical and near-infrared (IR) follow-up observations initiated 6.5 and 8.4 hr after the burst, respectively (Klose 1998; Castro-Tirado et al. 1998), no optical counterpart was found (Galama et al. 1998; Woźniak 1998; Rhoads et al. 1998; Bloom et al. 1998; Schaefer et al. 1998). The deep \(R\)-band observations carried out by Lindgren et al. (1999) showed \(R > 23\) mag at 9.9 hr after the GRB. This makes GRB 981226 a typical GRB without any detected afterglow (Taylor et al. 1998) and close to being a dark burst (Jakobsson et al. 2004; Rol et al. 2005).

Radio observations revealed a variable source at the position R.A. (J2000): \(23^\text{h}29^\text{m}37^\text{s}.21\), decl. (J2000): \(-23^\circ55'53".8\) peaking ~10 days after the gamma-ray event (Frail et al. 1999).

Identification of the host galaxy was suggested based on the small angular separation between the radio afterglow and an extended object. High spatial resolution images from the Hubble Space Telescope Space Telescope Imaging Spectrograph (HST STIS) show that the galaxy colors change notably over its surface, with the northern part being significantly bluer (Holland 2000). The position of the radio afterglow with respect to the galaxy is \(0^\circ749 \pm 0^\circ328\) (Bloom et al. 2002), which encompasses the blue northern part of the host.

This Letter presents an analysis of all imaging data on the host available in public archives. Ground-based data in the BVRIJK\(_s\) bands and images from the HST make a multiwavelength study appropriate to determine the host, and thus the GRB photometric redshift. Some of the data have been presented previously in the literature in different contexts. An Infrared Spectrometer And Array Camera (ISAAC) \(K_s\)-band image was presented in Le Floc’h et al. (2003), the \(HST\) STIS data in Holland (2000), and a deep \(R\)-band image in Frail et al. (1999); the latter image is not analyzed here.
TABLE 1

| Instrument+Filter | Date       | Exposure Time (s) |
|-------------------|------------|-------------------|
| FORS1 R           | 2000 Oct 05| 18 x 540          |
| FORS1 B           | 2001 May 15| 3 x 300           |
| FORS1 V           | 2001 May 16| 3 x 300           |
| FORS1 R           | 2001 Jun 19| 6 x 540           |
| FORS1 I           | 2001 May 16| 3 x 300           |
| 2001 Aug 13       | 400       |
| 2001 Aug 19       | 400       |
| 2001 Sep 22       | 4 x 600   |
| ISAAC J           | 2001 Sep 22| 10 x 180          |
| ISAAC K           | 2000 Nov 12| 30 x 120          |
| STIS CL           | 2000 Jul 03| 8265             |
| STIS LP           | 2000 Jul 06| 7909             |

2 Total integration time.

2 DATA ANALYSIS

For consistency, we reanalyzed the photometry in all filters. The host galaxy was observed in the optical (BVR) with the Very Large Telescope (VLT) FORS1 and in the near-IR (J and K) with ISAAC. The data were retrieved from ESO’s public archive.\(^2\) To take advantage of all available data on the host, we also included images from the HST using STIS. The host was observed in 2000 July, using a clear aperture (50CCD or CL filter) and a long-pass imaging filter, (LP filter).\(^3\) Table 1 lists the dates of observations, number of integrations, and exposure times.

Data reduction was done using IRAF. All optical data were reduced using standard methods, i.e., bias subtraction and dividing by a combined average flat-field frame obtained from twilight sky exposures. For the near-IR data reduction, sky subtraction was done by creating a sky image from the bracketing eight frames from each individual night. After sky subtraction, each image was divided by a normalized flat-field frame. Near-IR flat-field images were created by subtracting faintly illuminated flat-field frames from bright ones. Eight and ten of such images were combined and used for flat-fielding the J and K images, respectively. Relative shifts were found using cross-correlation procedures before combining the individual exposures.

Additional archive calibration files consisting of bias, sky flat-field, and standard star images from the different nights were retrieved. Photometric zero points from ISAAC and FORS1 were obtained by comparing the instrumental magnitude of the standard star with tabulated values. All the zero points calculated confirmed the values for the given dates that were found in the corresponding instrument Web pages. Extinction and color terms are reported for each month on the FORS1 Web page and were assumed to be appropriate here. For the STIS data, zero points were obtained from the STIS user manual.

Aperture photometry was used to derive host photometry, and all magnitudes of the host listed in Table 2 were derived using a 2” radial aperture. Corrections to larger apertures were found to be negligible. No optical afterglow was found for this burst, and the observations were carried out 1.5–2.5 yr after the burst. Therefore, no contamination of any significant level is expected for the photometry of the host. The magnitudes derived here are consistent with \( R = 24.85 \pm 0.06 \) mag in Frail et al. (1999), \( K_s = 21.1 \pm 0.2 \) mag in Le Floc’h et al. (2003), and \( CL = 25.04 \pm 0.07 \) mag in Holland (2000) (using the same 1’ radial aperture, we find 25.00 ± 0.05 mag).

3 PHOTOMETRIC REDSHIFT

We used the public photometric redshift code HyperZ (Bolzonella et al. 2000) along similar lines as in a series of papers on GRB host galaxies (Gorosabel et al. 2003a, 2003b, 2005; Christensen et al. 2004b). As shown in these papers, photometric redshifts of GRB hosts can be determined to within \( \Delta z = 0.21 \) when multiband observations are available, and when spectral features such as the Balmer jump are bracketed by the observations.

Magnitude offsets between Vega and the AB system were calculated and added to the observed Vega magnitudes listed in Table 2. The HST magnitudes are obtained directly in the AB system (see STIS Instrument Handbook), so the Table 2 fields corresponding to the HST Vega magnitudes are empty. To derive fluxes for the various pass bands, the magnitudes were corrected for a Galactic extinction of \( E(B-V) = 0.022 \) mag, as derived from the dust maps of Schlegel et al. (1998). Flux densities in \( \mu \)Jy were calculated by \( f_\nu = 10^{-0.4(m_{\nu,AB} - m_{\nu,AB})} \) for an AB magnitude \( m_{\nu,AB} \) in each passband.

Fluxes were compared to galaxy template spectra created from the spectral atlas of Bruzual & Charlot (1993). We used different galaxy templates obtained from a Salpeter initial mass function (IMF) (Salpeter 1955, hereafter Sp55) and a Miller & Scalo IMF (Miller & Scalo 1979, hereafter MiSc79) with different star formation histories and a characteristic timescale \( \tau \), where \( \tau = 0 \) corresponds to a starburst template, and \( \tau \to \infty \) to an irregular galaxy template. Values of \( \tau \) in between these extremes correspond to various types of spiral galaxy and elliptical templates. These templates all assume solar metallicity. We also experimented using different extinction curves: a starburst extinction curve (Calzetti et al. 2000), a Small Magellanic Cloud (SMC) extinction curve (Prevot et al. 1984), a Large Magellanic Cloud (LMC) extinction curve (Fitzpatrick 1986), and the Milky Way (MW) extinction curve (Seaton 1979).

In principle, the STIS wide filters might be included to determine the photometric redshift. The CL filter extends from 4000 to 9000 Å and the LP from 5500 to 9000 Å, thus providing poor spectral information. Furthermore, given the widths of the filters, the effective wavelength is sensitive to the assumed spectral template. Thus, as a first step, we decided to not include
them in our analysis, and then discuss the impact that their inclusion has on the $z_{\text{phot}}$ determination.

The best fit of the broadband SED was found with a starburst template at $z = 1.11$ with an age of 0.36 Gyr and an intrinsic extinction of $A_V = 0.20$ mag, as shown in Figure 1. Using a Calzetti extinction curve and a Sp55 IMF gave the smallest reduced $\chi^2$/dof, as indicated in Table 3. Other combinations of template fits are also listed in Table 3. In all cases a starburst template provided the best fit. From these fits we find $z_{\text{phot}} = 1.11 \pm 0.06 \pm 0.10 \pm 0.21$ (68%, 90%, and 99% confidence levels, respectively). In this case, the Balmer jump is well sampled by the observations.

The photometric redshift determination has a well-defined minimum at $z \approx 1.1$, as shown in Figure 2. The best-fit values for the extinction, age, and redshifts are consistent independently of the extinction curve or template used. Using the observed template spectra from Kinney et al. (1996) gives consistent results for the photometric redshift and extinction. If we also include the $HST$ bands in the SED fit, the resulting parameters ($M_L$, age, $A_V$) do not change. Specifically, $z_{\text{phot}}$ does not change at all, but the uncertainty for the photometric redshift decreases by $\sim$50%. However, including the $HST$ photometry increases the $\chi^2$. A fit including the LP band gives $\chi^2$/dof = 1.315, while including the CL as well gives $\chi^2$/dof = 2.850. The reason for this is the calculation of the effective wavelength of the two $HST$ STIS bands. In Figure 2 the $HST$ data points are shown by squares.

We investigated whether using templates with metallicities different from solar values would have an impact on the output parameters. It is expected that the photometric redshift shows no significant difference, while the well-known age-metallicity degeneracy should manifest itself. In Table 4 we list the results of fitting the observed SED with templates of metallicities of 0.2 and 0.4 solar, respectively. The template spectra were calculated using a Sp55 IMF with the GALAXEV code (Bruzual & Charlot 2003). Generally, the best-fit templates have larger ages, while the photometric redshifts are in good agreement with those in Table 3. Lower metallicities as well as templates constructed with a Chabrier (2003) IMF give consistent results for $z_{\text{phot}}$. Since all the fits give similar values of $\chi^2$, we cannot disentangle this age-metallicity-extinction degeneracy using broadband measurements alone (see also Bolzonella et al. 2000).

To check for consistency, we used the Bayesian photometric redshift code (Benítez 2000) to estimate the photometric redshift. This code uses empirical spectral templates for the fits (Coleman et al. 1980). Using the same ground-based photometric points as above, we find $z_{\text{phot, BPZ}} = 0.94 \pm 0.13$ ($\chi^2$/dof = 1.078), which is consistent with the results from HyperZ within $1 \sigma$ uncertainties. Including the $HST$ data points gives $z_{\text{phot, BPZ}} = 0.97 \pm 0.13$ ($\chi^2$/dof = 2.457). The uncertainties reported here are $1 \sigma$ levels.

### Table 3

| Extinction Law | IMF | $z_{\text{phot}}$ (68%, 99%) | $A_V$ (mag) | $\chi^2$/dof |
|----------------|-----|----------------------------|-------------|--------------|
| Cal00          | Sp55   | 1.11 ±0.06 , 0.21         | 0.20        | 0.399        |
|                | MiSc79 | 1.11 ±0.06 , 0.22         | 0.10        | 0.661        |
| SMC            | Sp55   | 1.11 ±0.07 , 0.23         | 0.12        | 0.427        |
|                | MiSc79 | 1.11 ±0.05 , 0.21         | 0.06        | 0.651        |
| LMC            | Sp55   | 1.11 ±0.06 , 0.21         | 0.16        | 0.426        |
|                | MiSc79 | 1.11 ±0.05 , 0.21         | 0.08        | 0.664        |
| MW             | Sp55   | 1.11 ±0.05 , 0.24         | 0.14        | 0.432        |
|                | MiSc79 | 1.11 ±0.06 , 0.21         | 0.06        | 0.662        |

Note.—Template SED fits using a Salpeter or Miller & Scalo IMFs, and different extinction curves. A redshift step of $\Delta z = 0.05$ was used in our fits. Only ground-based photometric points were included in the fits. The derived properties in terms of best-fit template type (starburst), redshift, age (0.36 Gyr), $M_L$ = −20.25, and extinction are basically independent of the input parameters for the assumed IMF and extinction curve. A relative host luminosity $L/L^* \approx 0.5$ is derived assuming $M_L^* = -21$ mag.

### Table 4

| $Z/Z_{\odot}$ (68%, 99%) | Age (Gyr) | $A_V$ (mag) | $\chi^2$/dof |
|--------------------------|-----------|-------------|--------------|
| 0.2                      | 1.11 ±0.06, 0.21 | 0.72        | 0.00         | 0.476        |
| 0.4                      | 1.11 ±0.06, 0.21 | 0.51        | 0.16         | 0.399        |

Note.—Here a Sp55 IMF and the Calzetti extinction law are used for creating the template. Only ground-based photometric points are used in the fits.

### 4. Discussion

Based on multicolor optical and near-IR photometry, we have reported the first precise photometric redshift for a GRB.
host galaxy without a spectroscopic redshift. The host is sufficiently bright that it appears feasible to obtain a spectroscopic redshift confirming or refuting our proposed value. We note, however, that we have been unable to detect emission lines in public VLT spectra in the ESO archive. In this connection it is interesting to note the relatively large mean age of the GRB 981226 host galaxy. This may indicate that emission lines are not prominent in this galaxy; it also reminds us that GRB host samples with spectroscopic redshifts may be biased toward emission-line galaxies. The VLT spectra were obtained at a relatively low resolution (>10 Å), and higher resolution data should be obtained to test the photometric redshift. At z ≃ 1 the optical emission lines could well be contaminated by residuals from subtraction of the skylines. Instruments such as ESI, MIKE, or the next-generation instrument X-shooter could reveal such cases.

In addition to the photometric redshift, the SED also allows us to infer certain physical properties of the host galaxy. Assuming a redshift z = 1.11 and the currently favored flat cosmology with Ω_m = 0.3 and H_0 = 70 km s^{-1} Mpc^{-1}, the luminosity distance is 2.3 × 10^{28} cm. By interpolating a power law function between the observed B and R-band AB magnitudes (corrected for extinction), we find that the rest-frame 2800 Å ultraviolet (UV) flux is 0.27 ± 0.06 μJy. This corresponds to a star formation rate (SFR) of 1.2 ± 0.3 M_☉ yr^{-1}, using the conversion between UV flux and a global SFR (Kennicutt 1998). The absolute magnitude of the host galaxy is M_p = -20.25 mag, which implies a specific SFR of 2.4 ± 0.6 M_☉ yr^{-1} (L/I)^{-1}, where L corresponds to the luminosity of a galaxy with M_p = -21 mag. This specific SFR is smaller that the UV-based SFRs in a sample of 10 GRB hosts (Christensen et al. 2004a). As for other GRBs, there is no indication that the host galaxy is strongly affected by extinction.

Interestingly, the properties of GRB 981226 are consistent with its being both an almost dark GRB (Jakobsson et al. 2004) and an XRF (Frontera et al. 2000). We can use the inferred z_{phot} to estimate the peak energy for the BeppoSAX burst. Integrating a Band function and adding four power-law functions to represent the X-ray to γ-ray spectrum at different time segments with the parameters given in Frontera et al. (2000), the total time integrated fluence is 1.9 × 10^{-6} ergs cm^{-2}, and at z = 1.11 the isotropic energy release is E_iso = 5.9 × 10^{41} ergs. Frontera et al. (2000) divided the light curve into five segments, one of which had E_{peak} = 61 ± 15 keV, the others less than 10 keV. The Amati relation (Ghirlanda et al. 2004b) predicts E_{peak} = 77.6 keV and E_{peak} = 36.9 keV, which is consistent within 2 σ with the BeppoSAX observations of the peak energy. With small uncertainties in the luminosity distances, accurate photometric redshifts for other GRB hosts will help to constrain cosmological parameters through the Ghirlanda relation. The photometric redshift is higher than those reported for other XRFs, but still lower than the median redshifts for GRBs, which is consistent with the hypothesis that XRFs may be off-axis GRBs or dirty fireballs, which both predict lower mean redshifts.

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