The ERO Host Galaxy of GRB020127: Implications for the Metallicity of GRB Progenitors

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ABSTRACT

We present optical and near-IR observations of the host galaxy of GRB020127, for which we measure $R-K_s = 6.2$ mag. This is only the second GRB host to date, which is classified as an ERO. The spectral energy distribution is typical of a dusty starburst galaxy, with a redshift, $z \approx 1.9$, a luminosity, $L \approx 5 \times 10^{41}$ erg, and an inferred stellar mass of $M_* \sim 10^{11} - 10^{12}$ M$\odot$, two orders of magnitude more massive than typical GRB hosts. A comparison to the $z \sim 2$ mass-metallicity ($M-Z$) relation indicates that the host metallicity is about 0.5 Z$\odot$. This result shows that at least some GRBs occur in massive, metal-enriched galaxies, and that the proposed low metallicity bias of GRB progenitors is not as severe as previously claimed. Instead we propose that the blue colors and sub-$L^*$ luminosities of most GRB hosts reflect their young starburst populations. This, along with the locally increased fraction of starbursts at lower stellar mass, may in fact be the underlying reason for the claimed low metallicity bias of $z \lesssim 0.2$ GRB hosts. Consequently, GRBs and their host galaxies may serve as a reliable tracer of cosmic star formation, particularly at $z \gtrsim 1$ where the $M-Z$ relation is systematically lower, and the star formation rate is dominated by sub-$L^*$ galaxies.

Subject headings: gamma-rays:bursts — galaxies:starburst

1. INTRODUCTION

Observations of the host galaxies of long-duration $\gamma$-ray bursts (GRBs) have led to the general consensus that they are faint and blue. This has been interpreted as evidence for intense star formation activity, as well as low metallicity and stellar mass (Fynbo et al. 2003; Le Floc’h et al. 2003; Christensen et al. 2004; Fruchter et al. 2006; Stanek et al. 2006). In particular, a comparison of $z < 0.2$ GRB hosts to Sloan Digital Sky Survey galaxies suggests that GRBs occur preferentially in low metallicity galaxies with $Z \sim 0.1 - 0.5$ Z$\odot$ (Stanek et al. 2006). These authors also propose an upper metallicity cutoff of about 0.15 Z$\odot$ for typical GRBs (i.e., with $E \sim 10^{51}$ erg). At higher redshifts, $z \sim 0.5 - 1$, a comparison to the host galaxies of GOODS supernovae indicates that GRBs tend to occur in lower luminosity galaxies (by about 1 mag) and therefore presumably at lower metallicity (Fruchter et al. 2006). Metallicities measured from afterglow absorption spectra (at $z > 2$) span a wider range, $Z \sim 0.05 - 0.5$ Z$\odot$ (e.g., Berger et al. 2006b; Prochaska 2006). Theoretical studies have also argued for “low” metallicity of GRB progenitors (MacFadyen & Woosley 1999), although we stress that the definition is not well-quantified, and black hole remnants can apparently be formed even above solar metallicity (Heger et al. 2003).

These observations raise two crucial and related questions: (i) Is there in fact a low metallicity bias for GRB progenitors, in both an absolute sense and relative to the average metallicity at any redshift? (ii) Can GRBs and their host galaxies be used as a representative tracer of star formation at high redshift ($z \gtrsim 1$)? The answer to these questions is of great importance given the unique ability of GRBs to probe the interstellar medium and star forming environments of galaxies over a wide redshift range, extending to $z > 6$ (Berger et al. 2006a). It is also crucial to understand the effect of metallicity in light of the redshift evolution of the average metallicity and mass function of galaxies (e.g., Erb et al. 2006). Equally important, the metallicity range for GRB progenitors impacts our understanding of the progenitor population and GRB formation scenarios (MacFadyen & Woosley 1999; Heger et al. 2003).

The prevalence of GRBs in blue galaxies may also reflect an observational bias against dusty galaxies due to obscuration of the optical afterglow. Two lines of evidence suggest that this may not be a significant problem. First, the host galaxies of the “optically dark” GRBs (those with clear evidence for dust obscuration in the optical band) are typically not redder than the hosts of optically-bright GRBs (Berger et al. 2003; Le Floc’h et al. 2003). A notable exception is GRB 030115, with a dust-reddened afterglow and a host galaxy with $R-K = 5.4$ mag (Levan et al. 2006). Second, radio, submillimeter, and IR observations have not led to a preferential detection of the dark GRB hosts (Barnard et al. 2003; Berger et al. 2003; Le Floc’h et al. 2006), despite an expectation that these galaxies should

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have obscured star formation. Conversely, the host galaxies with long-wavelength detections (and hence obscured star formation), have blue colors typical of the GRB host population as a whole (Berger et al. 2003).

Here we present optical and NIR observations of GRB 020127, which reveal that the host galaxy is an extremely red object (ERO) with $R - K_s = 6.2$ mag. The GRB position is obtained from X-ray and radio observations of the afterglow. The host SED is best fit by an obscured starburst galaxy template at $z \approx 1.9$, with a stellar mass of $\sim 10^{11.5} M_\odot$ and an inferred metallicity (Erb et al. 2006) of about 0.5 $Z_\odot$, suggesting that GRB progenitors can in fact exist at near-solar metallicity, and may occur in the most massive galaxies at $z > 1$.

2. AFTERGLOW AND HOST GALAXY OBSERVATIONS

GRB 020127 was discovered by the High Energy Transient Explorer II satellite on 2002 Jan. 27.875 UT, with a positional accuracy of 8\' radius (Ricker et al. 2002). The burst duration and fluence in the 2–400 keV band are 18 s and $2.7 \times 10^{-6}$ erg cm$^{-2}$ (Sakamoto et al. 2005).

Optical observations did not uncover an afterglow candidate, with $R, I > 19.5$ mag at 4.4 and 8.2 hr after the burst, respectively (Lamb et al. 2002), and $R > 21.5$ mag at 3.1 hr over 75% of the error circle (Castro Cerón et al. 2002). The Galactic extinction in the direction of GRB 020127 is low, $E(B-V) = 0.048$ mag (Schlegel et al. 1998).

2.1. X-ray, Radio, and Optical/NIR Imaging

We initiated two 10 ks observations with the Chandra X-ray Observatory, 4.14 and 14.64 d after the burst, to identify the fading X-ray afterglow. The data were obtained with the Advanced CCD Imaging Spectrometer (ACIS) and reduced and analyzed using the CIAO software package\(^8\). A comparison of the two epochs reveals three fading sources not associated with bright stellar counterparts. Of these, only one is detected in both epochs, and has faded with high significance, with 2.6 and 1.0 count ks$^{-1}$ (0.3–7 keV), respectively. Using a Galactic column of $3 \times 10^{20}$ cm$^{-2}$ (Schlegel et al. 1998) and a photon index of 1.5 ± 0.4, we find fluxes of (5.5 ± 0.1) $\times 10^{-14}$ and (2.1 ± 0.7) $\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, respectively, corresponding to a power law decay rate, $F_{\nu} \propto t^{-0.8}$, typical of GRB afterglows. The position of the X-ray afterglow candidate is $\alpha=08^h15^m01.42^s$, $\delta=+36^\circ46'33.9''$ (J2000), with an uncertainty of about 1\'\ in each coordinate.

We observed this source with the Very Large Array (VLA\(^9\)) at a frequency of 8.46 GHz on 2002 Feb. 14.20, 16.23, 21.97, and Mar. 18.10 UT. The data were processed using AIPS. In the first observation we detect an object with a flux of 222 ± 63 $\mu$Jy, coincident with the X-ray position, at $\alpha=08^h15^m01.42^s$, $\delta=+36^\circ46'33.45''$ (J2000), ±0.03\' in each coordinate. Subsequent observations reveal that the object has faded, with 3\sigma limits of 150 $\mu$Jy (Feb. 16.23 and 21.97) and 65 $\mu$Jy (Mar. 18.10), suggesting that this is the radio afterglow of GRB 020127.

Optical observations were obtained with the Large Format Camera (LFC) on the 200-inch telescope at the Mt. Palomar Observatory on 2002 Feb. 4.29 and Feb. 6.34 UT for a total of 4300 s ($g'$), 2400 s ($r'$), and 1800 s ($i'$). The images were bias-subtracted, flat-fielded, and coadded using IRAF, and photometry was performed relative to SDSS. At the position of the X-ray and radio afterglows we detect a faint object with $i' = 23.89 \pm 0.13$ mag, $r' > 23.5$ mag, and $g' > 25.8$ mag; limits are 2$\sigma$ and magnitudes are in the AB system. We identify this object as the host galaxy of GRB 020127. Further observations were obtained with the Echelle Spectrograph and Imager (ESI) on the Keck II 10-m telescope on 2002 Mar. 13.28 UT in $R$ (1500 s) and on 2003 Feb. 28.36 UT in $I$ (600 s). The data were reduced as described above. We measure $I = 23.56 \pm 0.10$ mag and $R = 24.73 \pm 0.15$ mag.

NIR observations in $K_s$ and $J$ were obtained with the Near Infra-Red Camera (NIRC) on the Keck I 10-m telescope on 2002 Oct. 13.63 and Nov. 17.48 UT, respectively, for a total of 1080 s in each filter. The individual frames were dark-subtracted, flat-fielded, and corrected for bad pixels and cosmic rays using custom IRAF routines. Photometry was performed relative to the standard star Feige 16. The host galaxy has $J = 20.37 \pm 0.10$ mag and $K_s = 18.54 \pm 0.05$ mag. Optical/NIR images of the host are shown in Figure 1.

Finally, in 2002 Apr. 6 UT we observed the host galaxy with the Hubble Space Telescope using the Space Telescope Imaging Spectrograph (STIS) as part of program GO 9180 (PI: Kulkarni). A total of 4868 s were obtained with the CL filter. We processed and combined the individual exposures using the IRAF task drizzle (Fruchter & Hook 2002), with pixfrac=0.8 and pixscale=0.5. At the position of the afterglow we detect an extended object with an AB magnitude of 24.8 ± 0.1 mag (Figure 1).

2.2. Optical Spectroscopy

We obtained optical spectra of the host galaxy using ESI on four separate occasions. The data were reduced using custom IRAF routines to bias-subtract, flat-field, and rectify the ten individual echelle orders. Sky subtraction was performed using the method and software described in Kelson (2003). Wavelength calibration was performed using CuAr and HgNeXe arc lamps and air-to-vacuum and heliocentric corrections were applied. The spectrum covers the range 0.39 to 1.05 $\mu$m at a resolution of 11.5 km s$^{-1}$. We detect continuum emission beyond 0.6 $\mu$m, but no emission or absorption lines are clearly identified.

A 5400 $\AA$ spectrum of the host was obtained with the Low Resolution Imaging Spectrometer (LRIS) on the Keck I 10-m telescope on 2004 Apr. 22 UT. The wavelength coverage is 0.36 to 0.96 $\mu$m with a resolution of 3.3 Å (0.36–0.58 $\mu$m) and 5.6 Å (0.58–0.96 $\mu$m). The data were reduced as described above. As in the ESI spectra, we detect the host continuum but no emission or absorption features.

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\(^7\)We use Vega magnitudes (unless otherwise noted), and the standard cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_L = 0.73$.

\(^8\)http://cxc.harvard.edu/ciao

\(^9\)The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
3. HOST GALAXY PROPERTIES

The optical/NIR spectral energy distribution of the host galaxy is shown in Figure 1. With $R-K_s = 6.2 \pm 0.2$ mag the host is classified as an ERO, and is the reddest GRB host to date. EROs fall in two general categories of old, passively-evolving elliptical galaxies, and dust-obscured star forming galaxies (McCarthy 2004). Long GRBs have never been localized to elliptical galaxies, and we further distinguish the two possibilities using the observed SED. We use the hyperz package (Bolzonella et al. 2000) to fit a range of model templates (starburst, E, S0-Sc, and Irr) with the redshift, stellar population age, and extinction as free parameters. We assume a Calzetti et al. (2000) extinction curve. The elliptical galaxy model provides an unsatisfactory fit with a probability of only 0.7% ($\chi^2 = 4.1$; Figures 1 and 2), due to the expected flat slope (in $F_\lambda$) beyond 1 $\mu$m and a brighter $g'$-band magnitude.

The starburst template, on the other hand, provides an excellent fit ($P_{\text{max}} = 99.9\%$; Figure 2). The best-fit parameters are $z = 1.9^{+0.4}_{-0.3}$, an age of about 0.7 Gyr, a rest-frame extinction, $A_V \approx 0.5$ mag, and an absolute rest-frame magnitude, $M_{AB}(B) = -23.5 \pm 0.1$ mag. This corresponds to $L \approx 5 L^*$ (Dahlen et al. 2005; Willmer et al. 2006). A comparison to UV-selected galaxies at $z \approx 2$ (Shapley et al. 2005) indicates that the host mass is $M_* \sim 10^{11-12} M_\odot$. Using the relation of Kennicutt (1998) and the observed R-band ($2200 \text{ Å}$ rest-frame) flux of 0.46 $\mu$Jy, we estimate an unobscured star formation rate of $\sim 6 M_\odot$ yr$^{-1}$. The value corrected for extinction is about an order of magnitude larger.

The host of GRB020127 is distinguished from other GRB host galaxies in several ways. First, it is more than 3 magnitudes redder than the average value for GRB hosts, and even a magnitude redder than the host of GRB 030115 (Figure 4). This is due to the combined effect of extinction and a more evolved stellar population compared to the typical value of about 0.1 Gyr for other GRB hosts (Christensen et al. 2004). Second, it is four magnitude more luminous than the median value of $M_{AB}(B) \approx -19.5$ mag for GRB hosts (with a range of $-16$ to $-22$ mag; Figure 4). Third, the inferred stellar mass is nearly two orders of magnitude larger than the median value of $10^{9.5} M_\odot$ for GRB hosts (Christensen et al. 2004; Savaglio et al. 2006). Finally, the unobscured specific star formation rate of about $1 M_\odot$ yr$^{-1} (L/L*)^{-1}$, is nearly an order of magnitude lower than for other GRB hosts (Christensen et al. 2004), but we note that with the extinction correction it is in fact similar.

Perhaps most importantly, a comparison to the mass-metallicity relation of UV-selected galaxies at $z \sim 2$ (Erb et al. 2006) indicates that the host of GRB02127 has $12 + \log (O/H) \approx 8.6$, or about 0.5 $Z_\odot$. This is also similar to the metallicities of the so-called distant red galaxies (DRGs; $J-K > 2.3$ mag), which have median ages and masses of $\sim 2$ Gyr and $\sim 10^{11} M_\odot$, respectively (Förster Schreiber et al. 2004; van Dokkum et al. 2004).

4. DISCUSSION

The host galaxy of GRB020127, identified through X-ray and radio afterglow observations, is the reddest, and most luminous and massive GRB host discovered to date. Unfortunately, the early optical limits (S2) are too shallow to ascertain whether the afterglow was significantly extinguished by dust; from the X-ray flux at 4.14 d we expect $R \sim 21$ mag at the time of the early optical observations, at the level of the available limits. For GRB030115, the only other burst with an ERO host galaxy, the afterglow itself was shown to be significantly dust extinguished, with $R-K \approx 6$ mag (Levan et al. 2006). It is therefore possible that dusty galaxies are under-represented in the current GRB host sample, due to obscuration of the optical afterglow, but we stress that the hosts of several dark bursts are not significantly redder than the median of the sample (Berger et al. 2003).

The discovery of a GRB in a massive, and hence metal-enriched, starburst galaxy indicates that the proposed low metallicity bias of GRB progenitors ($< 0.1 Z_\odot$; Fruchter et al. 2006; Stanek et al. 2006) is not likely to be as severe as previously claimed, particularly at $z \gtrsim 1$. This appears to be true not only in terms of an absolute metallicity cutoff, but also relative to the mass-metallicity relation of galaxies at high redshift. In particular, while the hosts of GRBs at $z \lesssim 0.2$ appear to have metallicities at the low end of the distribution for local galaxies (Stanek et al. 2006), at least some GRBs at $z \sim 2$ occur in the most metal-enriched galaxies at that redshift. This conclusion is also supported by the metallicities derived from afterglow absorption spectra (at $z > 2$), which range up to solar values (Berger et al. 2006b; Prochaska 2006), as well as by the detection of submillimeter emission from some GRB hosts (Berger et al. 2003). Since GRB progenitors appear to occur at least up to $\sim 0.5 Z_\odot$, and given that the $M-Z$ relations at $z \sim 1$ and $z \sim 2$ are systematically lower by about 0.3 and 0.6 dex, respectively, compared to the local relation (Tremonti et al. 2004; Savaglio et al. 2005; Erb et al. 2006), we conclude that even if a slight low metallicity bias does exist, its effect will diminish beyond $z \sim 1$.

Instead, the blue colors of GRB host galaxies may reflect their young stellar populations. This is likely related to the fact that GRB progenitors are massive stars, which explode within a few million years of formation, thereby leading to the selection of young starburst galaxies. In fact, for $z \sim 1-2$, the average $R-K$ color of a 0.1 Gyr population is about 2.5 mag, in good agreement with the observed colors of GRB hosts, while for 0.3 and 1 Gyr populations it is about 1 and 2.5 magnitudes redder, respectively (Figure 3).

This explanation might also account for the transition at low redshift ($z \lesssim 0.2$) from a representative to a predominantly low luminosity host population, since locally young starburst activity occurs primarily in low mass galaxies. Brinchmann et al. (2004) show that locally the fraction of galaxies with recent starburst activity increases strongly with decreased mass. Similarly, Bell et al. (2005) show that while at $z \sim 0.7$ nearly half of all galaxies with $M \gtrsim 10^{10} M_\odot$ undergo intense star formation activity, locally, this number is less than 1%. In this scenario, the driving parameter is stellar population age, which may be misidentified as a low metallicity bias. Clearly, a study of
the stellar population ages of the low redshift GRB hosts is required to assess whether age, and not metallicity, in fact plays the underlying role.

Thus, we conclude that at least at \( z \gtrsim 1 \), GRBs and their host galaxies are likely to trace star formation in a relatively unbiased way, with possibly a preference for younger starburst populations. At \( z \sim 0 \) there seems to be a bias in favor of low luminosity/mass galaxies (Stanek et al. 2006), but this may be driven by stellar population age and not metallicity. The luminosity function of GRB hosts (see also Jakobsson et al. 2005) therefore indicates that the bulk of the star formation at \( z \gtrsim 1 \) takes place in galaxies fainter than \( L^* \), in good agreement with the steep faint-end slope of the luminosity function of high redshift galaxies.

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References

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Fig. 1.— Spectral energy distribution of the host galaxy of GRB020127 along with the best fit starburst and elliptical galaxy models. The combination of a blue $J - K_s$ color and a deep upper limit in the $g$-band indicates that the starburst template is a much better fit compared to an elliptical galaxy. The top panel shows the host galaxy in each of the five observed bands.
Fig. 2.— Probability distribution (black line) and reduced $\chi^2$ (gray line) for the host galaxy photometric redshift calculated with the hyperz software package (Bolzonella et al. 2000) using a starburst template. The best fit redshift is $z = 1.9^{+0.2}_{-0.4}$. The inset shows the reduced $\chi^2$ for the best fit solution using the various galaxy templates. Clearly, the starburst template provides the only adequate fit to the data.
Fig. 3.— Apparent $R-K_s$ color plotted versus redshift for GRB host galaxies (filled circles; Chary et al. 2002; Le Floc’h et al. 2003; Berger et al. 2003; Levan et al. 2006), LBGs (open circles; Shapley et al. 2001; Steidel et al. 2004), submillimeter galaxies (stars; Smail et al. 2004), and GOODS galaxies (shaded; Somerville et al. 2004). Arrows designate GRB hosts without a measured redshift. The host galaxy of GRB 020127 (black square) is significantly redder than the typical color of $R-K_s \approx 2.5-3$ mag. The gray lines are tracks of $R-K_s$ color as a function of redshift from the population synthesis code of Bruzual & Charlot (2003) for a stellar population age of 0.1 Gyr (solid), 0.3 Gyr (dashed), and 1 Gyr (dot-dashed). The majority of the GRB hosts appear to have ages of $\sim 0.1 - 0.3$ Gyr. These young stellar population ages, and not metallicity, may be the underlying reason for the blue colors and low luminosities of GRB hosts.
Fig. 4.— Distribution of absolute rest-frame $B$-band magnitudes for GRB host galaxies (Berger et al. in prep.). The median value for the sample is $M_{AB}(B) = -19.5$ mag, or $0.1 L^*$, and it does not appear to significantly vary between $z < 1$ and $z > 1$ (values in the figure are the median and standard deviation). GRB 020127 clearly stands out as the most luminous, and thus most massive host galaxy detected to date, but we note that the overall luminosity distribution is in good agreement with that of other high redshift galaxy sample (see also Jakobsson et al. 2005). The dashed curve is a representative Schechter luminosity function with $M_B^* = -21$ mag and $\alpha = -1.4$. 