Chen, HW, Perley, DA, Wilson, CD, Bradley Cenko, S, Levan, AJ, Bloom, JS, Prochaska, JX, Tanvir, NR, Dessauges-Zavadsky, M and Pettini, M

A mature dusty star-forming galaxy hosting GRB 080607 at z = 3.036

The Astrophysical Journal Letters, 723:L218–L222, 2010 November 10 doi:10.1088/2041-8205/723/2/L218

A MATURE DUSTY STAR-FORMING GALAXY HOSTING GRB 080607 AT $z = 3.036$*

Hsiao-Wen Chen[1], Daniel A. Perley[2], Christine D. Wilson[3], S. Bradley Cenko[2], Andrew J. Levan[4], Joshua S. Bloom[2], Jason X. Prochaska[5], Nial R. Tanvir[6], Miroslava Dessauges-Zavadsky[7], and Max Pettini[8]
[1] Department of Astronomy & Astrophysics and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA; hchen@oddjob.uchicago.edu
[2] Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720, USA
[3] Department of Physics & Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada
[4] Department of Physics, University of Warwick, Coventry CV4 7AL, UK
[5] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
[6] Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK
[7] Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[8] Institute of Astronomy, Madingley Rd., Cambridge CB3 0HA, UK
Received 2010 September 18; accepted 2010 October 5; published 2010 October 18

ABSTRACT

We report the discovery of the host galaxy of *Swift* dark burst GRB 080607 at $z_{\rm GRB} = 3.036$. GRB 080607 is a unique case of a highly extinguished ($A_V \approx 3$ mag) afterglow that was yet sufficiently bright for high-quality absorption-line spectroscopy. The host galaxy is clearly resolved in deep *Hubble Space Telescope* (*HST*) WF3/IR F160W images and well detected in the *Spitzer* IRAC 3.5 μm and 4.5 μm channels, while displaying little/no fluxes in deep optical images from Keck and Magellan. The extremely red optical–infrared colors are consistent with the large extinction seen in the afterglow light, suggesting that the large amount of dust and gas surface mass density seen along the afterglow sight line is not merely local but likely reflects the global dust content across the entire host galaxy. Adopting the dust properties and metallicity of the host interstellar medium derived from studies of early-time afterglow light and absorption-line spectroscopy, we perform a stellar population synthesis analysis of the observed spectral energy distribution to constrain the intrinsic luminosity and stellar population of this dark burst host. The host galaxy is best described by an exponentially declining star formation rate of *e*-folding time $\tau = 2$ Gyr and an age of ~2 Gyr. We also derive an extinction-corrected star formation rate of SFR $\approx 125\,h^{-2}\,M_\odot$ yr^{-1} and a total stellar mass of $M_* \sim 4 \times 10^{11}\,h^{-2}\,M_\odot$. Our study provides an example of massive, dusty star-forming galaxies contributing to the γ-ray burst (GRB) host galaxy population, supporting the notion that long-duration GRBs trace the bulk of cosmic star formation.

Key words: dust, extinction – gamma-ray burst: individual (080607) – ISM: abundances

1. INTRODUCTION

Early-time spectra of bright γ-ray burst (GRB) afterglows have revealed numerous absorption features that allow accurate measurements of the chemical composition, dust content, and kinematics in the interstellar medium (ISM) of the host galaxies (e.g., Fynbo et al. 2006; Savaglio 2006; Prochaska et al. 2008). But as much as 50% of long-duration GRBs show a significant suppression in their optical afterglow light (Jakobsson et al. 2004; Cenko et al. 2009). While some of these "dark" bursts occur during the reionization epoch at redshifts $z > 6$ (e.g., Kawai et al. 2006; Greiner et al. 2009; Tanvir et al. 2009; Salvaterra et al. 2009), most result from large extinction columns in the ISM surrounding massive star-forming regions at more typical redshifts of $z = 1$–4 (e.g., Perley et al. 2009).

Swift GRB 080607 at redshift $z_{\rm GRB} = 3.0363$ is a unique case of a highly extinguished ($A_V \approx 3$ mag) afterglow that was yet sufficiently bright for high-quality spectroscopy (Prochaska et al. 2009). The afterglow spectrum displays positive detections of CO $A - X$ band heads (Morton & Noreau 1994) that have also been seen through translucent molecular gas of the Milky Way (e.g., Sonnentrucker et al. 2007). The presence of Ge II 1602 and O I 1355 absorption features indicates that the host ISM has been enriched to roughly solar metallicity. Identifications of vibrationally excited H_2 indicate the presence of substantial molecular gas at a few hundred pc from the burst (Sheffer et al. 2009). The large gas surface mass density ($\approx$400 $M_\odot$ pc^{-2}) and large molecular gas content found in GRB 080607 are unprecedented among either damped Lyα absorbers along random QSO sight lines or GRB host galaxies (cf., Srianand et al. 2008; Noterdaeme et al. 2009). Contrary to the common expectation of GRBs occurring preferentially in low-mass and low-metallicity environments (e.g., Fruchter et al. 2006), the observed large metal and dust contents, together with the mass–metallicity relation known for $z = 2$–3 galaxies (e.g., Mannucci et al. 2009), imply that the host galaxy is massive and intrinsically luminous. Searching for the host galaxy of GRB 080607 therefore bears significantly on our general understanding of GRB host galaxies and particularly the dark burst population.

Here, we report the discovery of the host galaxy of GRB 080607 in an extensive imaging follow-up campaign. The observed broadband spectral energy distribution (SED) from optical to IR wavelengths, together with known dust properties from studies of early-time afterglow light (Perley et al. 2010) and known ISM metallicity from absorption-line spectroscopy (Prochaska et al. 2009), allow us to constrain the intrinsic luminosity and stellar population of the host galaxy of this dark burst. We adopt a Λ cosmology, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$, with a dimensionless Hubble constant $h = H_0/(100$ km s^{-1} Mpc$^{-1})$ throughout the Letter.

* Based in part on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

2. MULTI-WAVELENGTH IMAGING OBSERVATIONS AND DATA ANALYSIS

We have carried out an extensive search of the host galaxy of GRB 080607 in ground-based and space-based imaging observations. Deep optical images of the field around GRB 080607 were obtained using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the 10 m Keck I telescope on the night of 2009 February 19 UT. The total integration times of 2490 s and 2220 s were taken through the G and I bands, respectively. Deep optical r-band images were obtained using the short camera in the IMACS multi-object imaging spectrograph (Dressler et al. 2006) on the Magellan Baade telescope on the night of 2009 May 22 UT. Three exposures of 600 s each were acquired. Images were flat-fielded, registered, and stacked using standard techniques. The final stacked images have a mean seeing of 0ʺ.8, 0ʺ.8, and 1ʺ.1 in G, r, and I, respectively, and are calibrated using common stars in the Sloan Digital Sky Survey (SDSS) photometric catalog.

Near-IR images of the field were obtained using the Near Infrared Camera (NIRC) and the K_s filter on Keck I, on the night of 2009 May 31 UT. A total of 36 exposures of 100 s each were acquired. Images were processed and stacked using standard techniques via a custom Python pipeline. The stacked image has a mean seeing of 0ʺ.75 and is calibrated using standard stars observed throughout the night.

Deep near-infrared images of the field were obtained using the IR channel in Wide Field Camera 3 (WFC3) and the F160W filter on board the *Hubble Space Telescope* (*HST*; PI: Chen). The observations were carried out on 2010 July 25 UT. Three sets of four exposures (900 s each) were obtained. Individual exposures were reduced using standard pipeline techniques, corrected for geometric distortion using drizzle, registered to a common origin, filtered for deviant pixels, and combined to form a final stacked image.

Infrared images of the field were also obtained on 2010 August 8 UT by the *Spitzer Space Telescope* (PI: Perley) in both available warm-mission IRAC channels (3.6 and 4.5 μm). A total of 45 exposures of 100 s each were acquired in each channel using a cycling dither pattern. The post basic calibration data calibrated mosaics were retrieved from the *Spitzer* data archive. Finally, we obtained 850 μm images of the GRB field under the SCUBA-2 (Holland et al. 2006) Shared Risk Observations on the James Clerk Maxwell Telescope (M09BI109, PI: Wilson) on 2010 March 14 and 2010 March 24. A total integration time of 2 hr was acquired. The data were reduced and calibrated as described in Dempsey et al. (2010). The combined image has an rms noise of 2.4 mJy per beam with a beam size of 15ʺ.

Optical and IR images of the field surrounding GRB 080607 are presented in Figure 1. Astrometric solutions were obtained using known SDSS objects with a mean rms scatter of ≈0ʺ.1. The location of the GRB afterglow is marked by the cross, which is determined based on relative astrometry using seven common stars in our *HST* observations and in early-time afterglow images obtained ∼2 hr post-burst by UKIRT. The relative astrometry provides a precise afterglow position with an error radius of 0ʺ.05 (cf., Mangano et al. 2008). At 0ʺ.35 away, an extended source is clearly detected in the WF3/IR F160W image with a half-light radius of $r_{1/2} \approx 0''.3$. We measure $AB(\mathrm{F160W}) = 24.72 \pm 0.03$ over a 0ʺ.8 radius aperture for this source.

To determine whether this source is the host galaxy of GRB 080607, we estimate the probability of finding a random foreground galaxy that has its optical disk intercepting the afterglow sight line. At close projected distances ($\lesssim 20\,h^{-1}$ kpc), we expect that any foreground galaxy would imprint a strong Mg II absorption feature in the afterglow spectrum (e.g., Chen et al. 2010). The available afterglow spectrum of GRB 080607 allows observations of Mg II absorbers at $z = 0.895$–2.2, and indeed two strong Mg II absorbers have been detected at $z = 1.341$ and $z = 1.462$ (Prochaska et al. 2009). At the same time, galaxies A and B are seen within 3ʺ.5 radius of the afterglow sight line with $AB(\mathrm{F160W}) = 22.4$ and $AB(\mathrm{F160W}) = 22.0$, respectively. Their observed optical and near-IR colors are bluer than the host candidate (bottom left panel of Figure 1) and are consistent with galaxies at $z \sim 1.4$. The projected distances are within the expected extent of strong Mg II absorbers (Chen et al. 2010). We therefore attribute the two strong Mg II absorbers to galaxies A and B. To estimate the probability of a random galaxy at $z < 0.895$ occurring within $2 \times r_{1/2}$ of the afterglow position, we calculate the volume density of galaxies with $L > 0.025\,L_*$ (corresponding to $AB(\mathrm{F160W}) = 24.7$ at $z = 0.895$) using the galaxy luminosity function of Faber et al. (2007). We find that the probability of finding a random $z < 0.895$ galaxy within this small volume is <1% which, together with the presence of A and B, leads us to conclude that the extended source at the afterglow position is the most likely host of GRB 080607.

The host is also detected in the G-band image with $AB(g) = 28.2 \pm 0.4$ over a 0ʺ.8 radius aperture, and in the IRAC 3.5 μm and 4.5 μm channels with $AB(3.5\,\mu\mathrm{m}) = 20.5 \pm 0.1$ and $AB(4.5\,\mu\mathrm{m}) = 19.9 \pm 0.1$ over a 1ʺ.2 radius aperture. The adopted aperture sizes roughly match the size of the apertures adopted for the optical and near-IR images after accounting for the differences in the point-spread functions (PSFs). The errors in the IRAC photometry of the host are dominated by contaminating light from A and B and are estimated based on the summed flux in a sequence of increasing-diameter apertures. In the K-band image, we observe at the host position a 1.5σ flux detection, corresponding to $AB(K) = 24.8 \pm 0.7$ or a 2σ upper limit of $AB(K) = 24.5$.

The host galaxy is not detected in the r and I bands. We measure 2σ upper limits of $AB(r) = 27.0$ and $AB(I) = 27.0$. The host is not detected in the 850 μm image. Based on the deboosted 850 μm fluxes of submm sources observed in SCUBA images of comparable rms noises (Coppin et al. 2006), we estimate a 4σ upper limit to the 850 μm flux of 7.6 mJy for the GRB host.

Table 1
Summary of GRB 080607 Host Photometry

Telescope/Instrument	Bandpass	Brightness[a]
Keck/LRIS	G	$AB = 28.2 \pm 0.4$
Magellan/IMACS	r	$AB > 27.0$
Keck/LRIS	I	$AB > 27.0$
HST/WF3/IR	F160W	$AB = 24.72 \pm 0.03$
Keck/NIRC	K_s	$AB = 24.8 \pm 0.7$
Spitzer/IRAC	3.5 μm	$AB = 20.5 \pm 0.1$
Spitzer/IRAC	4.5 μm	$AB = 19.9 \pm 0.1$
JCMT/SCUBA-2	850 μm	$f < 7.6$ mJy

Note. [a] When the host is not detected, we measure a 2σ upper limit for the optical and near-IR bandpasses and a 4σ limit for the 850 μm flux. All magnitudes are corrected for Galactic extinction, $E(B-V) = 0.023$.

3. THE HOST GALAXY OF GRB 080607

To constrain the stellar population and star formation history of the host galaxy, we consider a suite of synthetic stellar

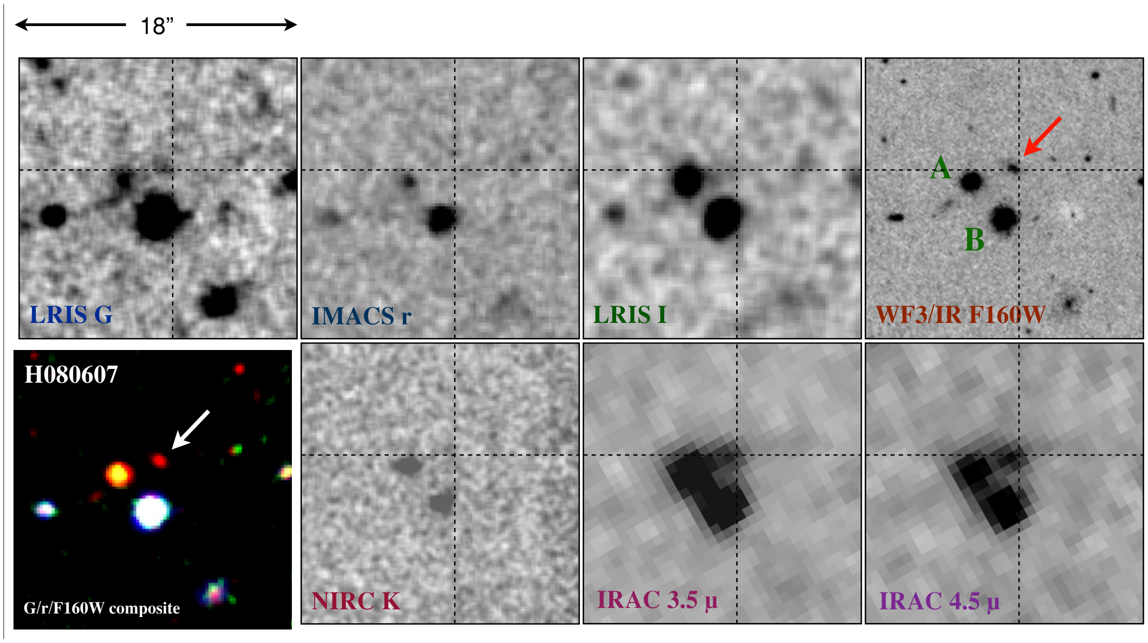

Figure 1. Astrometrically aligned images, 18″ on a side of the field surrounding GRB 080607 at $z_{\rm GRB} = 3.036$. North is up and east to the left. Astrometric solutions were obtained using known SDSS objects with a mean rms scatter of ≈0.″1. The position of the early-time afterglow is at the cross with 0.″05 error. The ground-based images have been smoothed over the FWHM of the PSF for revealing faint features. An extended source is clearly detected at 0.″35 away from the afterglow position in the *HST* WF3/IR F160W image (arrow in the top right panel), which is also well detected in the *Spitzer* IRAC 3.5 μm and 4.5 μm images (two bottom right panels). While the source is not seen in the ground-based *r* and *I* images, it displays traces of flux in the deep *G*- and *K*-band images. The consistent red color (bottom left panel) and astrometric match with the afterglow lead us to conclude that this extended source is the most likely host galaxy, H 080607. Sources *A* and *B* exhibit bluer colors and are likely the absorbing galaxies of two strong Mg II absorbers (Prochaska et al. 2009) at $z = 1.462$ and $z = 1.361$, respectively.

population models generated using a revised Bruzual & Charlot (2003) spectral library that includes a new prescription for the thermally pulsing asymptotic giant branch evolution of low- and intermediate-mass stars (Marigo & Girardi 2007). To improve the uncertainties in the model analysis (such as the age–metallicity degeneracy, e.g., Worthey 1994), we take into account known dust properties from studies of early-time afterglow light (Perley et al. 2010) and known ISM metallicity from absorption-line spectroscopy (Prochaska et al. 2009).

The SED of the host galaxy is found to be extremely red, consistent with the large extinction seen in the afterglow light. As demonstrated in Perley et al. (2010), the observed SED of the GRB afterglow is best described by a combination of a single power-law spectrum (characteristic of the intrinsic afterglow radiation) and an extinction law that is characterized by the broad 2175 Å absorption band, commonly seen in the Milky Way (MW) and the Large Magellanic Cloud (LMC), and a large extinction column of $A_V \approx 3.1$ at $z = 3$. However, the best-fit extinction curve appears to be relatively flat at UV wavelengths with $R_V \approx 4$, and the 2175 Å absorption feature is not as strong as what is seen in MW or LMC. Consequently, Perley et al. (2010) derived a best-fit extinction curve for the host using a general extinction law from Fitzpatrick & Massa (1990), which allows variations in the UV slopes, and the depth and width of the 2175 Å absorption.

The large R_V suggests that the GRB occurred in a dense environment (e.g., Valencic et al. 2004), consistent with the large gas column seen in afterglow spectra. The extremely red colors of the host galaxy suggest that the large amount of dust and gas surface mass density seen in the afterglow light is not merely local to the line of sight to the burst, but likely reflects the global dust content across the entire host galaxy. In addition, the presence of the 2175 Å dust feature suggests that the host galaxy resembles mature galaxies like MW or LMC, rather than young star-forming systems like the Small Magellanic Cloud. In the following stellar population synthesis analysis, we include priors from the best-fit Fitzpatrick & Massa extinction law ($R_V = 4$ and $A_V = 3$) of Perley et al. (2010) and solar metallicity measured for the host ISM from afterglow absorption-line observations. We also examine possible biases due to adopting these priors.

For the stellar population library, we adopt a Chabrier initial mass function (IMF) with a range of star formation histories from a single burst model to an exponentially declined star formation rate (SFR) model with an *e*-folding time ranging from $\tau = 0.1$–2 Gyr. Over the spectral range from rest frame ∼1000 Å to ∼1 μm, the observed emission is dominated by stellar light in dusty galaxies (Hainline et al. 2009). We therefore consider only stellar components in the SED models. We perform a maximum likelihood analysis to compare the observed SED and a grid of model expectations, taking into account both detections and non-detections. The likelihood function of this analysis is defined as

$$\mathcal{L}(\tau, \mathrm{age}) = \left(\prod_{i=1}^{k} \exp\left\{-\frac{1}{2}\left[\frac{f_i - \bar{f}(\tau, \mathrm{age})}{\sigma_i}\right]^2\right\}\right) \times \left(\prod_{i=1}^{l} \int_{-\infty}^{f_i} df' \exp\left\{-\frac{1}{2}\left[\frac{f' - \bar{f}(\tau, \mathrm{age})}{\sigma_i}\right]^2\right\}\right), \quad (1)$$

where f_i is the observed flux (in μJy) of the host in bandpass i, $\bar{f}$ is the model expectation, and σ_i is the measurement uncertainty of f_i. The first product of Equation (1) extends over the k measurements and the second product extends over the l upper

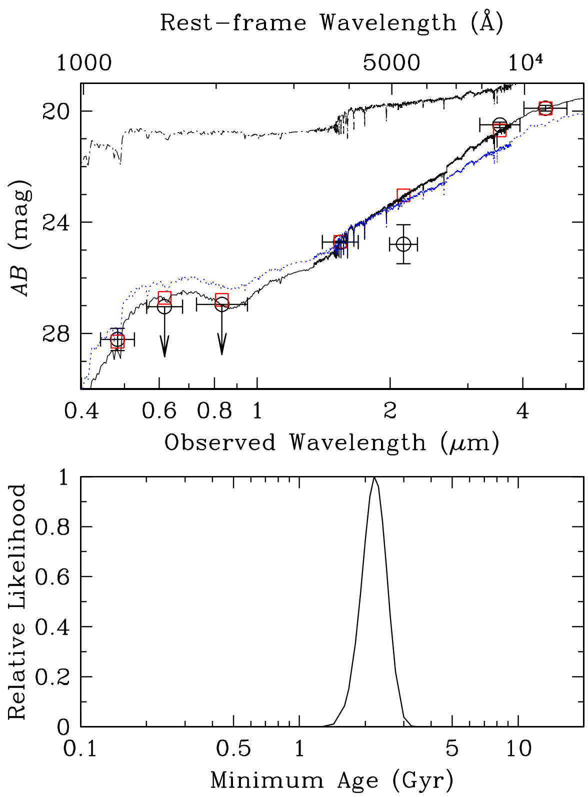

Figure 2. Top: comparison of the observed SED of the dusty host of GRB 080607 at $z_{\rm GRB} = 3.036$ and the best-fit stellar population synthesis model. Optical and infrared photometric measurements are shown in open circles with error bars. We place a 2σ upper limit to the observed brightness, when the galaxy is not detected. The horizontal error bars indicate the FWHM of each bandpass. The solid curve represents the best-fit synthetic model after accounting for dust obscuration (the best-fit Fitzpatrick & Massa law of Perley et al. 2010 with $R_V = 4$ and $A_V = 3$ at $z = 3$). The open squares represent the predicted brightness from the best-fit model. The dash-dotted spectrum at the top shows the intrinsic spectrum prior to the application of dust obscuration. The dotted curve represents a best-fit model based on the same extinction law but with $A_V = 2.5$, indicating that reducing the amount of dust extinction no longer provides a good fit to the observed SED. Adopting the 2σ upper limit for the K band, $AB(K) > 24.5$, does not change the results. Bottom: the likelihood function of the minimum age of the underlying stellar population as described by the broadband SED.

limits. The result shows that, with the adopted solar metallicity and a relatively gray extinction law, the stellar population of the host galaxy is best described by an exponentially declining SFR of $\tau = 2$ at the age of $\sim$2.2 Gyr. The observed SED and the best-fit model are presented in the top panel of Figure 2, showing a good agreement in all bandpasses. The likelihood function of the stellar age is presented in the bottom panel of Figure 2.

The best-fit stellar age of the host is similar to the age of the universe at $z = 3$, indicating that the host galaxy was formed very early in time. The comparable stellar age and star formation e-folding time indicate that the host has been undergoing active star formation since birth. We estimate the SFR and total stellar mass of the host galaxy based on extinction-corrected UV luminosity and mass-to-B-band light ratio. The unobscured best-fit spectrum is displayed in the top panel of Figure 2 (dash-dotted curve). Adopting the best-fit model, we derive a rest-frame, extinction-corrected UV luminosity of $L(1500) = 1.8 \times 10^{30}\ h^{-2}$ erg s^{-1} Hz^{-1} at 1500 Å. For a Chabrier IMF, this corresponds to SFR $\approx 125\,h^{-2}\,M_\odot\,{\rm yr}^{-1}$ (Salim et al. 2007). At the age of $\approx$2 Gyr, we derive a total stellar mass of $M_* \sim 4 \times 10^{11}\ h^{-2}\ M_\odot$. The uncertainty in M_* due to uncertainties in the star formation history is found to be $\approx$50%.

To investigate possible biases due to adopting the afterglow extinction curve and line-of-sight metallicity for the global properties of the host galaxy, we repeat the stellar population synthesis analysis with varying metallicity and the amount of dust extinction. We find that for a fixed amount of extinction, the derived SFR and M_* are insensitive to the adopted metallicity. Reducing the amount of dust extinction in the model SED results in a poor fit to the observed SED for any combination of star formation history and metallicity (e.g., the dotted curve in Figure 2). This exercise confirms that the dust extinction law determined from the afterglow light and the line-of-sight metallicity are representative of the mean properties across the entire host galaxy. We therefore conclude that the best-fit SFR and M_* are robust.

4. DISCUSSION

Our multi-wavelength imaging follow-up has uncovered an extremely red galaxy at the location of the "dark" GRB 080607 at $z_{\rm GRB} = 3.036$. Given the coincident position and consistent red optical and near-infrared colors, we argue that the galaxy is the host of the dusty burst. The host galaxy is clearly extended in the *HST* WF3/IR F160W image with a half-light radius of $\approx 0''.3$, corresponding to a physical half-light radius of 1.8 h^{-1} kpc at $z = 3$. This is typical of what is seen for star-forming galaxies at $z \sim 3$ (e.g., Bouwens et al. 2004). The host galaxy is both massive and actively forming stars. We estimate the mean radiation field I_0 in the host ISM at near-UV wavelengths ($\approx$1500–2000 Å) by averaging the extinction-corrected UV flux over the extent of the host galaxy seen in the *HST* WF3/IR image and find that $I_0 \approx 3 \times 10^{-4}$ photons cm^{-2} s^{-2} Hz^{-2}. The estimated mass and SFR are among the highest known in the GRB host galaxy population (e.g., Christensen et al. 2004; Savaglio et al. 2009; Chen et al. 2009) and in star-forming galaxies at $z \sim 3$ (e.g., Erb et al. 2006), but are comparable to the average of submm sources (e.g., Borys et al. 2005; Dye et al. 2008; Serjeant et al. 2008) and more than five times lower than the brightest submm galaxies (e.g., Tacconi et al. 2006).

Unobscured GRB host galaxies at intermediate redshifts appear to be underluminous and low-mass systems (e.g., Fruchter et al. 2006). It has therefore been argued that long-duration GRBs originate preferentially in relatively metal-deficient star-forming regions (Wolf & Podsiadlowski 2007; Modjaz et al. 2008). A low-metallicity environment is favored by popular progenitor models so that the progenitor star can preserve high spin and a massive stellar core to produce a GRB (e.g., Yoon & Langer 2005; Woosley & Heger 2006). However, statistical studies have shown that the distributions of ISM metallicity and UV luminosity of known GRB host galaxies at $z > 2$ are consistent with the expectations of a UV luminosity selected star-forming galaxy sample (Fynbo et al. 2008; Chen et al. 2009).

GRB080607 represents a unique example of a dark GRB that was luminous enough to allow detailed observations of its afterglow despite it occurring in a heavily obscured galaxy. Thus, we were able to secure an unambiguous redshift of the dusty burst through afterglow absorption-line spectroscopy and to identify the host galaxy based on an astrometric match to the afterglow position. Our current limit at 850 μm is typical of what is seen in GRB host galaxies (e.g., Tanvir et al. 2004). An improved sensitivity limit at the submm wavelengths will provide a different estimate of the SFR (e.g., Chapman et al. 2005) and some constraint on the dust-to-stellar mass ratio of the host. The large gas and dust mass uncovered in the afterglow spectrum together with the IR bright host galaxy already show that mature, dusty star-forming galaxies do contribute to the GRB host galaxy population (see also Levesque et al. 2010), supporting the notion that long-duration GRBs trace the bulk of cosmic star formation. Follow-up near-IR spectroscopy of the host will not only confirm the host identification, but also allow a detailed study of the gas kinematics in the host ISM.

We thank John Mulchaey for obtaining the IMACS *r* images presented in this Letter, and Stéphane Charlot for providing the updated spectral library. Support for the *HST* DD program #12005 was provided by NASA through a grant from the Space Telescope Science Institute. H.-W.C. acknowledges partial support from an NSF grant AST-0607510. The James Clerk Maxwell Telescope is operated by The Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

REFERENCES

Borys, C., Smail, I., Chapman, S. C., Blain, A. W., Alexander, D. M., & Ivison, R. J. 2005, ApJ, 635, 853
Bouwens, R. J., Illionworth, G. D., Blakeslee, J. P., Broadhurst, T. J., & Franx, M. 2004, ApJ, 611, L1
Bruzual, A. G., & Charlot, S. 2003, MNRAS, 344, 1000
Cenko, S. B., et al. 2009, ApJ, 693, 1484
Chapman, S., et al. 2005, ApJ, 622, 772
Chen, H.-W., Helsby, J. E., Gauthier, J.-R., Shectman, S. A., Thompson, I. B., & Tinker, J. L. 2010, ApJ, 714, 1521
Chen, H.-W., et al. 2009, ApJ, 691, 152
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Coppin, K., et al. 2006, MNRAS, 372, 1621
Dempsey, J. T., Friberg, P., Jenness, T., Bintley, D., & Holland, W. S. 2010, Proc. SPIE, 7741, 54
Dressler, A., Hare, T., Bigelow, B. C., & Osip, D. J. 2006, Proc. SPIE, 6269, 13
Dye, S., et al. 2008, MNRAS, 386, 1107
Erb, D. K., Steidel, C. C., Shapley, A. E., Pettini, M., Reddy, N. A., & Adelberger, K. L. 2006, ApJ, 646, 107
Faber, S. M., et al. 2007, ApJ, 665, 265
Fitzpatrick, E. L., & Massa, D. 1990, ApJS, 72, 163
Fruchter, A., et al. 2006, Nature, 441, 463
Fynbo, J. P. U., Prochaska, J. X., Sommer-Larsen, J., Dessauges-Zavadsky, M., & Møller, P. 2008, ApJ, 683, 321
Fynbo, J. P. U., et al. 2006, A&A, 451, L47
Greiner, J., et al. 2009, ApJ, 693, 1610
Hainline, L. J., Blain, A. W., Smail, I., Frayer, D. T., Chapman, S. C., Ivison, R. J., & Alexander, D. M. 2009, ApJ, 699, 1610
Holland, W., et al. 2006, Proc. SPIE, 6275, 45
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., Watson, D., Pedersen, K., Björnsson, G., & Gorosabel, J. 2004, ApJ, 617, L21
Kawai, N., et al. 2006, Nature, 440, 184
Levesque, E. M., Kewley, L. J., Graham, J. F., & Fruchter, A. S. 2010, ApJ, 712, L26
Mangano, V., et al. 2008, GCN Circ., 7847, 1
Mannucci, F., et al. 2009, MNRAS, 398, 1915
Marigo, P., & Girardi, L. 2007, A&A, 469, 239
Modjaz, M., et al. 2008, AJ, 135, 1136
Morton, D. C., & Noreau, L. 1994, ApJS, 95, 301
Noterdaeme, P., Ledoux, C., Srianand, R., Petitjean, P., & Lopez, S. 2009, A&A, 503, 765
Oke, J. B., et al. 1995, PASP, 107, 375
Perley, D. A., et al. 2009, AJ, 138, 1690
Perley, D. A., et al. 2010, AJ, submitted (arXiv:1009.0004)
Prochaska, J. X., Chen, H.-W., Wolfe, A. M., Dessauges-Zavadsky, M., & Bloom, J. S. 2008, ApJ, 672, 59
Prochaska, J. X., et al. 2009, ApJ, 691, L27
Salim, S., et al. 2007, ApJS, 173, 267
Salvaterra, R., et al. 2009, Nature, 461, 1258
Savaglio, S. 2006, New J. Phys., 8, 195
Savaglio, S., Glazebrook, K., & Le Borgne, D. 2009, ApJ, 691, 182
Serjeant, S., et al. 2008, MNRAS, 386, 1907
Sheffer, Y., Prochaska, J. X., Draine, B. T., Perley, D. A., & Bloom, J. S. 2009, ApJ, 701, L63
Sonnentrucker, P., Welty, D. E., Thorburn, J. A., & York, D. G. 2007, ApJS, 168, 58
Srianand, R., Noterdaeme, P., Ledoux, C., & Petitjean, P. 2008, A&A, 482, L39
Tacconi, L. J., et al. 2006, ApJ, 640, 228
Tanvir, N. R., et al. 2004, MNRAS, 352, 1073
Tanvir, N. R., et al. 2009, Nature, 461, 1254
Valencic, L. A., Clayton, G. C., & Gordon, K. D. 2004, ApJ, 616, 912
Wolf, C., & Podsiadlowski, P. 2007, MNRAS, 375, 1049
Woosley, S. E., & Heger, A. 2006, ApJ, 637, 914
Worthey, G. 1994, ApJS, 95, 107
Yoon, S.-C., & Langer, N. 2005, A&A, 443, 643

The Astrophysical Journal Letters, 727:L53 (2pp), 2011 February 1 doi:10.1088/2041-8205/727/2/L53

ERRATUM: "A MATURE DUSTY STAR-FORMING GALAXY HOSTING GRB 080607 AT $z = 3.036$" (2010, ApJ, 723, L218)

Hsiao-Wen Chen[1], Daniel A. Perley[2], Christine D. Wilson[3], S. Bradley Cenko[2], Andrew J. Levan[4], Joshua S. Bloom[2], Jason X. Prochaska[5], Nial R. Tanvir[6], Miroslava Dessauges-Zavadsky[7], and Max Pettini[8]

[1] Department of Astronomy & Astrophysics and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA; hchen@oddjob.uchicago.edu
[2] Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720, USA
[3] Department of Physics & Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[4] Department of Physics, University of Warwick, Coventry CV4 7AL, UK
[5] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
[6] Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK
[7] Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[8] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
Received 2010 December 9; published 2011 January 13

Online-only material: color figure

We have discovered an error in the photometric measurements of the host galaxy in our *Spitzer* IRAC images. The host is detected in the IRAC 3.5 μm and 4.5 μm channels with $\mathrm{AB}(3.5\mu) = 22.9 \pm 0.2$ and $\mathrm{AB}(4.5\mu) = 22.7 \pm 0.2$ mag. The photometric measurements of the host galaxy in other bandpasses remain unchanged. Adopting the revised *Spitzer* IRAC photometry and the original optical and near-IR photometric measurements, we estimate the total stellar mass (M_*) and on-going star formation rate (SFR) of the host galaxy based on the stellar population synthesis analysis described in Chen et al. (2010). Given the uncertainties in the global dust content of the host galaxy, we allow the metallicity, A_V, and dust extinction law to differ from what were found in the afterglow light (e.g., Prochaska et al. 2009; Perley et al. 2011). The likelihood analysis described in Equation (1) of Chen et al. (2010) yields an extinction-corrected SFR of (8–12) $h^{-2}\,M_\odot\,\mathrm{yr}^{-1}$, a mean ISM radiation field $I_0 \approx (2.3\text{–}3.5) \times 10^{-5}$ photons cm^{-2} s^{-2} Hz^{-1}, and $M_* = (0.5\text{–}1.4) \times 10^{10}\,h^{-2}\,M_\odot$ for the host galaxy. These are about an order of magnitude lower than those originally published. We note that the uncertainties in the derived M_*, I_0, and SFR are driven by the uncertainties in the global dust extinction law of the host galaxy. The galaxy is still fairly massive, but not as extreme as previously thought. The observed spectral energy distribution (SED) of the host galaxy is presented in the revised figure below, together with the best-fit synthetic model of super-solar metallicity and a Milky-Way type dust extinction law of $A_V = 1.25$. A Fitzpatrick & Massa (FM) law described in Perley et al. (2011) with $A_V = 1.8$ and super-solar metallicity produces a similarly good fit to the observed SED.

Adopting the priors from the best-fit dust obscuration, the FM law from Perley et al. (2011) with $R_V = 4.2$ and $A_V = 3.3$ at $z = 3$ and solar metallicity from Prochaska et al. (2009) leads to a similar estimate of M_* ($\sim 5 \times 10^9\,h^{-2}\,M_\odot$) but significantly higher SFR ($\sim 230\,h^{-2}\,M_\odot\,\mathrm{yr}^{-1}$). However, this model also predicts an observed optical brightness that is $\Delta\mathrm{AB} = 1$ mag brighter than the observed 2σ upper limits in the r and I bands. We therefore consider this model unlikely to represent the global extinction property of the host galaxy. The result indicates a large spatial variation in the dust content across the host galaxy.

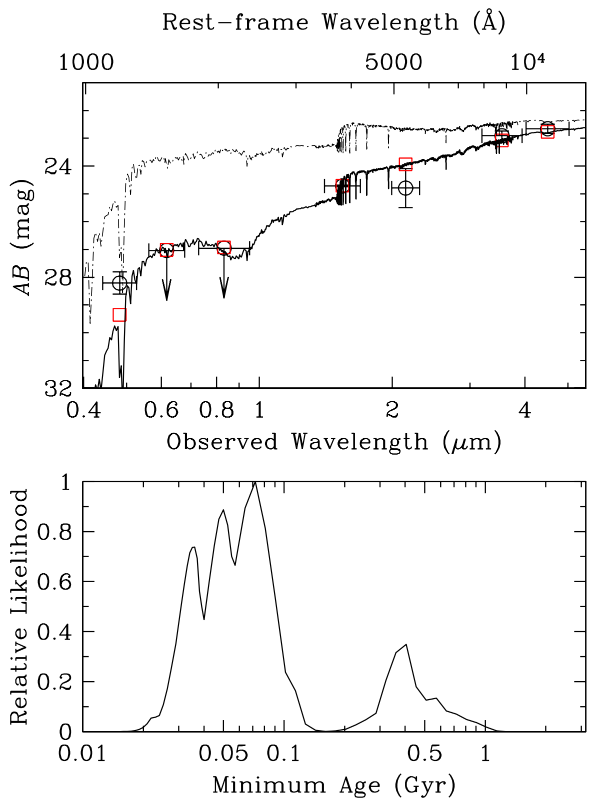

Figure 1. Top: comparison of the observed SED of the dusty host of GRB 080607 at $z_{\rm GRB} = 3.036$ and the best-fit stellar population synthesis models. Optical and infrared photometric measurements are shown in open circles with error bars. We place a 2σ upper limit to the observed brightness, when the galaxy is not detected. The horizontal error bars indicate the FWHM of each bandpass. The solid curve represents the best-fit synthetic model of super-solar metallicity and a Milky-Way type dust extinction law of $A_V = 1.25$. The open squares represent the predicted brightness from this best-fit model. The thin dash-dotted spectrum at the top shows the intrinsic spectrum prior to the application of dust obscuration. Bottom: the likelihood functions of the minimum age of the underlying stellar population as described by the broadband SED.

(A color version of this figure is available in the online journal.)

REFERENCES

Chen, H.-W., et al. 2010, ApJ, 723, L218
Perley, D. A., et al. 2011, AJ, 141, 36
Prochaska, J. X., et al. 2009, ApJ, 691, L27