THE HOST GALAXY OF GRB 970508

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ABSTRACT

We present late-time imaging and spectroscopic observations of the optical transient (OT) and host galaxy of GRB 970508. Imaging observations roughly 200 and 300 days after the burst provide unambiguous evidence for the flattening of the light curve. The spectroscopic observations reveal two persistent features that we identify with $\text{[O}\,\text{II}]\,\lambda3727$ and $\text{[Ne}\,\text{III}]\,\lambda3869$ at a redshift of $z = 0.835$—the same redshift as the absorption system seen when the transient was bright. The OT was coincident with the underlying galaxy to better than 370 mas or a projected radial separation of less than 2.7 kpc. The luminosity of the $\text{[O}\,\text{II}]$ line implies a minimum star formation rate of $1 \, M_\odot$ yr$^{-1}$. Our assumed cosmology, the implied rest-frame absolute magnitude is $M_B = -18.55$, or $L_B = 0.12 \, L_\odot$. This object, the likely host of GRB 970508, can thus be characterized as an actively star-forming dwarf galaxy. The close spatial connection between this dwarf galaxy and the OT requires that at least some fraction of gamma-ray burst progenitors are not ejected in even the weakest galactic potentials.

Subject headings: cosmology: observations — galaxies: general — gamma rays: bursts

1. INTRODUCTION

After an initial brightening lasting $\sim 1.5$ days, the optical transient (OT) of GRB 970508 faded with a nearly pure power-law slope by 5 mag over $\sim 100$ days (e.g., Galama et al. 1998; Garcia et al. 1998; Sokolov et al. 1998). Indications of a flattening in the light curve (Pedersen et al. 1998) were confirmed independently by Bloom et al. (1998), Castro-Tirado et al. (1998), and Sokolov et al. (1998). Recently, Zharikov, Sokolov, & Baryshev (1998) fit the $\text{BVRI}$ light curves of the OT + host and found the broadband spectrum of the presumed host galaxy.

The existence of an $\text{[O}\,\text{II}]$ emission line at the absorption system redshift (Metzger et al. 1997a) was taken as evidence for an underlying, dim galaxy host. After Hubble Space Telescope ($\text{HST}$) images revealed the point-source nature of the light, several groups (e.g., Fruchter, Bergeron, & Pian 1997; Pian et al. 1998; Natarajan et al. 1997) suggested that the source responsible for the $\text{[O}\,\text{II}]$ emission must be a very faint ($R > 25$ mag), compact (less than 1") dwarf galaxy at $z = 0.835$ nearly coincident on the sky with the transient. These predictions are largely confirmed in the present study.

In this Letter, we report on the results of deep imaging and spectroscopy of the host galaxy of GRB 970508 obtained at the 10 m Keck II telescope.

2. OBSERVATIONS AND ANALYSIS

Imaging and spectroscopic observations were obtained using the Low Resolution Imaging Spectrograph (LRIS) (Oke et al. 1995) on the 10 m Keck II Telescope on Mauna Kea, Hawaii. The log of the observations is presented in Table 1. All nights were photometric. The imaging data were reduced in the standard manner.

To follow the light-curve behavior of the OT + host over $\sim 300$ days from the time of the burst, we chose to tie the photometric zero point to a previous study (Sokolov et al. 1998) which predicted late-time magnitudes based on early (less than 100 days) power-law behavior in several bandpasses. This photometric tie provides an internally consistent data set for our purposes. Other studies of the light curve include Galama et al. (1998) and Pian et al. (1998). V. Sokolov (1998, private communication) provided magnitudes of eight "tertiary" field stars ($R = 18.7$ -- 23 mag) as reference, since the four secondary comparison stars (Sokolov et al. 1998) were saturated in all of our images. The zero points were determined through a least-squares fit and have conservative errors of $\sigma_R = 0.05$ and $\sigma_J = 0.01$ mag.

For our spectroscopic observations, we used a 300 lines mm$^{-1}$ grating, which gives a typical resolution of $\approx 15$ Å and a wavelength range from approximately 3900 to 8900 Å. The spectroscopic standards G191B2B (Massey et al. 1988) and HD 19445 (Oke & Gunn 1983) were used to flux-calibrate the data of October and November, respectively. Spectra were obtained with the slit position angle at 51° in order to observe both the host galaxy of GRB 970508 and g1 (see Djorgovski et al. 1997). This angle was always close to the parallactic angle, and the wavelength-dependent slit losses are not important for the discussion below. Internal consistency implied by measurements of independent standards implies an uncertainty of less than 20% in the flux zero-point calibration. Exposures of arc lamps were used for the wavelength calibration, with a resulting rms uncertainty of about 0.3 Å and possible systematic errors of the same order, due to the instrument flexure.

3. RESULTS

Table 1 gives a summary of the derived magnitudes at the position of the OT and, as a comparison, the extrapolated magnitudes from a pure power-law decay fit by Sokolov et al. (1998). The OT + host is brighter by greater than 0.8 mag in both the $B$- and $R$-band, leading to the obvious conclusion that
the transient has faded to reveal a constant source. We used a Levenberg-Marquardt χ² minimization method to fit a power-law flux (OT) plus constant flux (galaxy) to the B and R light curves using data compiled in Sokolov et al. (1998):

\[ f_{\text{total}} = f_0 t^{-\alpha} + f_{\text{gal}} \]

where \( t \) is the time since the burst measured in days. The quantities \( f_0 \) and \( f_{\text{gal}} \) are the normalization of the flux of the transient and the persistent flux of the underlying galaxy, respectively. We find \( B_{\text{tot}} = 26.77 \pm 0.35 \) mag, \( R_{\text{tot}} = 25.72 \pm 0.20 \) mag, \( B_{\text{gal}} = 19.60 \pm 0.04 \) mag, \( R_{\text{gal}} = 18.79 \pm 0.03 \) mag, and \( \alpha_g = 0.35 \pm 0.03, \alpha_g = -1.27 \pm 0.02 \). Note that the power-law decline did not start until day \( \approx 1.6 \), so the normalizations, \( B_0 \) and \( R_0 \), do not actually correspond to the true flux of the transient on day 1.

To search for any potential offset of the OT and the galaxy, we used an early image of the gamma-ray burst (GRB) field obtained on COSMIC at the Palomar 200 inch telescope on 1997 May 13.6 UT while the transient was still bright (\( R \approx 20 \) mag; see Djorgovski et al. 1997). Assuming the power-law behavior continued, the light at the transient position is now dominated by the galaxy, with the transient contributing less than 30% to the total flux (see Fig. 1).

We registered the Keck LRIS and the P200 COSMIC R-band (300 s) images by matching 33 relatively bright (\( R < 23 \) mag) objects in a 4′ × 4′ field surrounding the GRB transient. The coordinate transformation between the two images accounted for pixel scale, rotating, translation, and higher order distortion. The rms of the transformed star positions (including both axes) was \( \sigma = 0.56 \) LRIS pixels (\( \approx 0.121 \)). We find the angular separation of the OT and the galaxy to be less than 0.814 pixels (\( \approx 0.175 \)), which includes the error of the transformation and centering errors of the objects themselves. The galaxy is thus found well within 1.7 pixels (\( \approx 0.37 \) arcsec) of the OT.

The averaged spectrum of the OT + host shows a very blue continuum, a prominent emission line at \( \lambda_{\text{obs}} = 6839.7 \) Å, and a somewhat weaker line at \( \lambda_{\text{obs}} = 7097.7 \) Å (Fig. 2). We interpret the emission features as [O II] \( \lambda \lambda 3727, 3729 \) and [Ne II] \( \lambda 3869 \) at the weighted mean redshift of \( z = 0.8349 \pm 0.0003 \). Our inferred redshift for the host is consistent (within errors) with that of the absorbing system discovered by Metzger et al. (1997b).

The spectrum of the nearby galaxy g1 shows a relatively featureless, blue continuum. We are unable to determine its redshift at this stage.

Our spectroscopic measurements give a magnitude \( R \approx 25.05 \) mag (OT + host) at the mean epoch (=163 days after the GRB) of our observations, in excellent agreement with the magnitude inferred from the fit to direct imaging data (see Fig. 1).

### 4. Discussion

After an initial brightening, the light curve of the optical transient did not deviate significantly from a power law over the first 100 days after the burst (e.g., Galama et al. 1998; García et al. 1998; although see Pedersen et al. 1998). Assuming the blast wave producing the afterglow expanded relativistically (bulk Lorentz factor \( \Gamma \) greater than a few) during the beginning of the light-curve decline, the observed flux was produced from within an angle \( \omega_r \approx 1/\Gamma \) of the emitting sur-

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**TABLE 1**

LATE-TIME GRB 970508 IMAGING AND SPECTROSCOPIC OBSERVATIONS

| DATE (UT) | BAND/GRATING | INTEGRATION TIME (s) | SEEING (arcsec) | \( \Delta t \) (days) | OBSERVED | Pure Power Law | OBSERVERS |
|----------|--------------|----------------------|-----------------|-------------------|----------|----------------|----------|
| Imaging  |              |                      |                 |                   |          |                |          |
| 1997 Nov 28 ....... | \( R \) | 5400 | 1.2 | 203.8 | 25.09 ± 0.14 | 25.63 ± 0.2 | Kulkarni, van Kerkwijk, and Bloom |
| 1997 Nov 29 ....... | \( R \) | 600 | 1.1 | 204.8 | 26.32 ± 0.26 | 26.65 ± 0.25 | Kulkarni, van Kerkwijk, and Bloom |
| \( R \) | 600 | 1.1 | 204.8 | 26.32 ± 0.26 | 26.65 ± 0.25 | Kulkarni, van Kerkwijk, and Bloom |
| 1998 Feb 22 ....... | \( B \) | 2400 | 1.1 | 204.8 | 26.32 ± 0.26 | 26.65 ± 0.25 | Kulkarni, van Kerkwijk, and Bloom |
| 1998 Feb 23 ....... | \( B \) | 2400 | 1.2 | 291.5 | 26.27 ± 0.28 | 27.11 ± 0.25 | Kulkarni, Ramaprakash, and van Kerkwijk |
| Spectroscopy |              |                      |                 |                   |          |                |          |
| 1997 Oct 3 ....... | 300 | 5400 | 0.8 | 147.8 | Djorgovski and Odewahn |
| 1997 Nov 2 ....... | 300 | 5400 | <1.0 | 177.8 | Djorgovski and Gal |

* Magnitudes are derived from V. Sokolov’s tertiary reference stars. The (conservative) 1 σ errors include statistical uncertainties in the reference transformation and the OT + host itself. All nights (imaging observations) were photometric.
* Predicted magnitudes are derived from a pure power-law decline using light curve data from \( \Delta t < 100 \) days (Sokolov et al. 1998). Errors are estimated using the uncertainties in both the magnitude scaling and power-law index.

* The R-band magnitude quoted is derived from the sum of R-band images over two nights.
face. As the blast wave expands, $\omega_p$ increases with time. As long as the angle through which the blast wave is collimated is greater than $\omega_p$, there would be no obvious break in the light curve (e.g., Sari, Piran, & Narayan 1998). One might expect, in addition, the blast wave to eventually become subrelativistic, resulting not only in a larger observed surface area but perhaps in a change in surface emissivity. Curiously, an apparent break expected in either scenario did not materialize.

The spatial coincidence of the transient and the underlying galaxy may simply be a chance projection of the transient, which lies beyond $z = 0.835$ and the galaxy at $z = 0.835$. The surface density of galaxies down to $m = 48.3$ which lies beyond, and the galaxy may simply be a chance projection of the transient, shifts (Hogg et al. 1998). The expected in either scenario did not materialize.

The typical field galaxies at comparable magnitudes and redshifts (e.g., Odewahn et al. 1998) lead us to suggest that this galaxy is the host of GRB 970508.

Assuming a standard Friedman model cosmology with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 0.2$, we derive a luminosity distance of $1.60 \times 10^{28}$ cm to the host galaxy. The observed equivalent width in the [O ii] line is $(115 \pm 5)$ Å, or about 63 Å in the galaxy’s rest frame. However, this also includes the continuum light from the OT at this epoch. Correcting for the OT contribution would then double these values of the equivalent width. This is at the high end of the distribution for the typical field galaxies at comparable magnitudes and redshifts (Hogg et al. 1998).

The implied [O ii] line luminosity, corrected for Galactic extinction, is $L_{3727} = (9.6 \pm 0.7) \times 10^{40}$ ergs s$^{-1}$. Using the relation from Kennicutt (1998), we estimate the star formation rate (SFR) $\approx 1.4 \, M_\odot$ yr$^{-1}$.

An alternative estimate of the SFR can be obtained from the continuum luminosity at $\lambda_{rest} = 2800$ Å (Madau, Pozzetti, & Dickinson 1998). The observed, interpolated continuum flux from the host itself (i.e., not including the OT light) at the corresponding $\lambda_{abs} \approx 5130$ Å is $F_\lambda \approx 0.11 \mu$Jy, corrected for the estimated Galactic extinction ($A_V \approx 0.08$ mag; Djorgovski et al. 1997). For our assumed cosmology, the rest-frame continuum luminosity is then $L_{2800} \approx 1.93 \times 10^{27}$ ergs s$^{-1}$ Hz$^{-1}$, corresponding to SFR $\approx 0.25 \, M_\odot$ yr$^{-1}$. This is notably lower than the SFR inferred from the [O ii] line. We note, however, that neither is known to be a very reliable SFR indicator. Both are also subject to the unknown extinction corrections from the galaxy’s own interstellar medium (the continuum estimate being more sensitive). We thus conclude that the lower limit to the SFR in this galaxy is probably about $0.5-1 \, M_\odot$ yr$^{-1}$.

The observed flux in the [Ne iii] $\lambda 3869$ line is $F_{3869} = (1.25 \pm 0.1) \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$, not corrected for the extinction. The flux ratio of the two emission lines is $F_{3869}/F_{3727} = 0.44 \pm 0.05$. This ratio is about 10 times higher than the typical values for H ii regions. Nonetheless, it is in the range of photoionization models for H ii regions by Stasinska (1990) for different combinations of model parameters but generally for effective temperatures $T_{eff} \geq 40,000$ K.

The inferred host luminosity is in agreement with the upper limit from earlier HST observations (Fink et al. 1998). Further, our derived $B$- and $R$-magnitudes for the galaxy correspond to a continuum with a power law $F_\nu \sim \nu^{-1.0}$. Extrapolating from the observed $R$-band flux to the wavelength corresponding to the rest-frame B-band (about 8060 Å), we derive the observed flux $F_\nu(\lambda = 8060$ Å) $\approx 0.22 \, \mu$Jy. For our assumed cosmology, the implied rest-frame absolute magnitude is then $M_B \approx -18.55$. Thus, the rest-frame B-band luminosity of the host galaxy is about 0.12 $L_\odot$ today.

This galaxy is roughly 2 mag fainter than the knee of the observed luminosity function of all galaxies between redshift $z = 0.77$ and 1.0 (Canada-France redshift survey; Lilly et al. 1995) and 1 mag fainter than late-time, star-forming galaxies in the 2dF survey (Colless 1998). The specific SFR per unit luminosity is high. This object can thus be characterized as an actively star-forming dwarf galaxy. Objects of this type are fairly common at comparable redshifts.

5. CONCLUSIONS

The high effective temperature implied by the relative line strengths of [Ne iii] and [O ii] suggests the presence of a substantial population of massive stars and thus active and recent star formation. This, in turn, gives additional support to
the ideas that the origin of GRBs is related to massive stars (e.g., Wijers et al. 1998; Totani 1997; Djorgovski et al. 1998). An alternative possibility for the origin of the [Ne iii] λ3869 line is photoionization by a low-luminosity active galactic nucleus (AGN). While we cannot exclude this possibility, we note that there is no other evidence in favor of this hypothesis, and moreover we see no other emission lines, e.g., Mg ii λ2799, that would be expected with comparable strengths in an AGN-powered object.

What may be surprising, in the neutron star binary (NS-NS) model of GRB progenitors (e.g., Narayan, Paczynski, & Piran 1992; Paczynski 1986), is that GRB 970508 appears so close (less than 2.7 kpc) to a dwarf galaxy ($L \approx 0.1 L_\ast$). Bloom, Sigurdsson, & Pols (1998) recently found that less than 15% of NS-NS binaries will merge within 3 kpc of a comparable undermassive galaxy. If GRBs are consistently found very near (less than a few kpc) their purported host, then progenitor models such as microquasars (Paczynski 1998), “failed” Type Ib supernovae (Woosley 1993), or black hole–neutron star binaries (Mochkovitch et al. 1993; Mészáros & Rees 1997), all of which are expected to produce GRBs more tightly bound to their hosts, would be favored.

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