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HUBBLE SPACE TELESCOPE AND *SPITZER* OBSERVATIONS OF THE AFTERGLOW AND HOST GALAXY OF GRB 050904 AT $z = 6.295$

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ABSTRACT

We present deep *Hubble Space Telescope* (*HST*) and *Spitzer Space Telescope* observations of GRB 050904 at $z = 6.295$. We detect the afterglow in the H band more than 3 weeks after the burst and confirm the presence of a jet break at $t \approx 2.1$ days. This leads to an estimated opening angle of about 4° and a beaming-corrected energy of about 10^{51} ergs, similar to those of lower redshift gamma-ray bursts (GRBs). We do not detect an underlying host galaxy with either *HST* or *Spitzer*. From the upper limits we infer an extinction-corrected absolute magnitude $M_{\rm UV} \gtrsim -20.3$ mag, or $L \lesssim L^*$, a star formation rate of $\lesssim 5.7\ M_\odot\ {\rm yr}^{-1}$, and a stellar mass of $\lesssim$ few $\times 10^9\ M_\odot$. A comparison to spectroscopically confirmed galaxies at $z > 5.5$ reveals that the host of GRB 050904 is fainter and has a lower star formation rate than at least 80% of these objects. Finally, using our luminosity limits, and the metallicity of about $0.05\ Z_\odot$ inferred from the afterglow absorption spectrum, we place the first limit on the luminosity-metallicity relation at $z > 6$. Future afterglow and host galaxy observations of $z \gtrsim 4$ GRBs should elucidate whether the mass- and luminosity-metallicity relations continue to evolve beyond the present limits of $z \lesssim 2$.

Subject headings: cosmology: observations — galaxies: abundances — galaxies: high-redshift — galaxies: starburst — gamma rays: bursts

1. INTRODUCTION

The questions of how and when the universe was reionized and the history of galaxy formation and metal enrichment appear to be intimately linked. Observations of $z > 6$ quasars and the cosmic microwave background indicate that reionization occurred at $z \sim 7$–13 (Becker et al. 2001; Spergel et al. 2007), but most likely not by quasars alone (Fan et al. 2002). Instead, star-forming galaxies and/or massive Population III stars may have played a dominant role in this process (e.g., Yan & Windhorst 2004). To assess this possibility it is essential to trace the properties and evolution of galaxies and star formation at $z \gtrsim 6$. In recent years, large surveys using narrowband Lyα and Lyman drop-out selection have uncovered $\sim$100 candidate $z \gtrsim 5.5$ galaxies (e.g., Bouwens et al. 2004; Dickinson et al. 2004), of which about half have been confirmed spectroscopically (e.g., Hu et al. 2002; Taniguchi et al. 2005). These surveys provide initial estimates of the star formation rate density and luminosity function at these redshifts (e.g., Bouwens & Illingworth 2006).

Unfortunately, one of the most crucial measurements in the study of galaxy evolution, the metallicity, is beyond the reach of current studies, since at $z \gtrsim 5$ the relevant emission lines[11] are very weak and are redshifted to the mid-IR. Moreover, since spectroscopic confirmation relies on Lyα emission, which is easily obscured by dust, the current samples may be intrinsically biased with respect to dust and metallicity. The alternative approach of studying damped Lyα absorbers (DLAs) detected against background quasars also appears to be limited to $z \lesssim 5$ (Prochaska et al. 2003), and is moreover biased in favor of extended halo gas, which at lower redshifts significantly underestimates the disk metallicities. As a result, the apparent evolution in the mass- and luminosity-metallicity relations (*M-Z* and *L-Z*) from $z = 0$ to $z \sim 2$ (e.g., Kobulnicky & Kewley 2004; Shapley et al. 2004; Savaglio et al. 2005; Erb et al. 2006) cannot be traced to $z > 5$, where such information should shed light on the initial stages of mass buildup and metal enrichment.

For many years it has been speculated that gamma-ray bursts (GRBs) should exist at $z > 6$ and can therefore provide an alternative way to study reionization and to select star-forming galaxies. A truly unique and exciting aspect of GRBs is that spectroscopy of their bright afterglows can easily provide a redshift measurement from UV metal absorption features and/or Lyα absorption, bypassing the reliance on faint Lyα emission lines. More importantly, GRB absorption spectroscopy also provides a measure of the metallicity and kinematics of the interstellar medium *at the location where active star formation is taking place*, and may potentially provide direct information on the nature of the massive progenitor itself. This powerful probe of the metallicity in star-forming galaxies, and its redshift evolution, is now being routinely used for a rapidly growing sample at $z \sim 2$–4 (e.g., Berger et al. 2006; Chen et al. 2005; Starling et al. 2005).

The hope of extending this approach to $z > 6$ was finally realized with the discovery of GRB 050904 at $z = 6.295$ and

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[11] These include [O ii] λ3727; [O iii] $\lambda\lambda$4959, 5007; [N ii] λ6584; and the hydrogen Balmer lines.

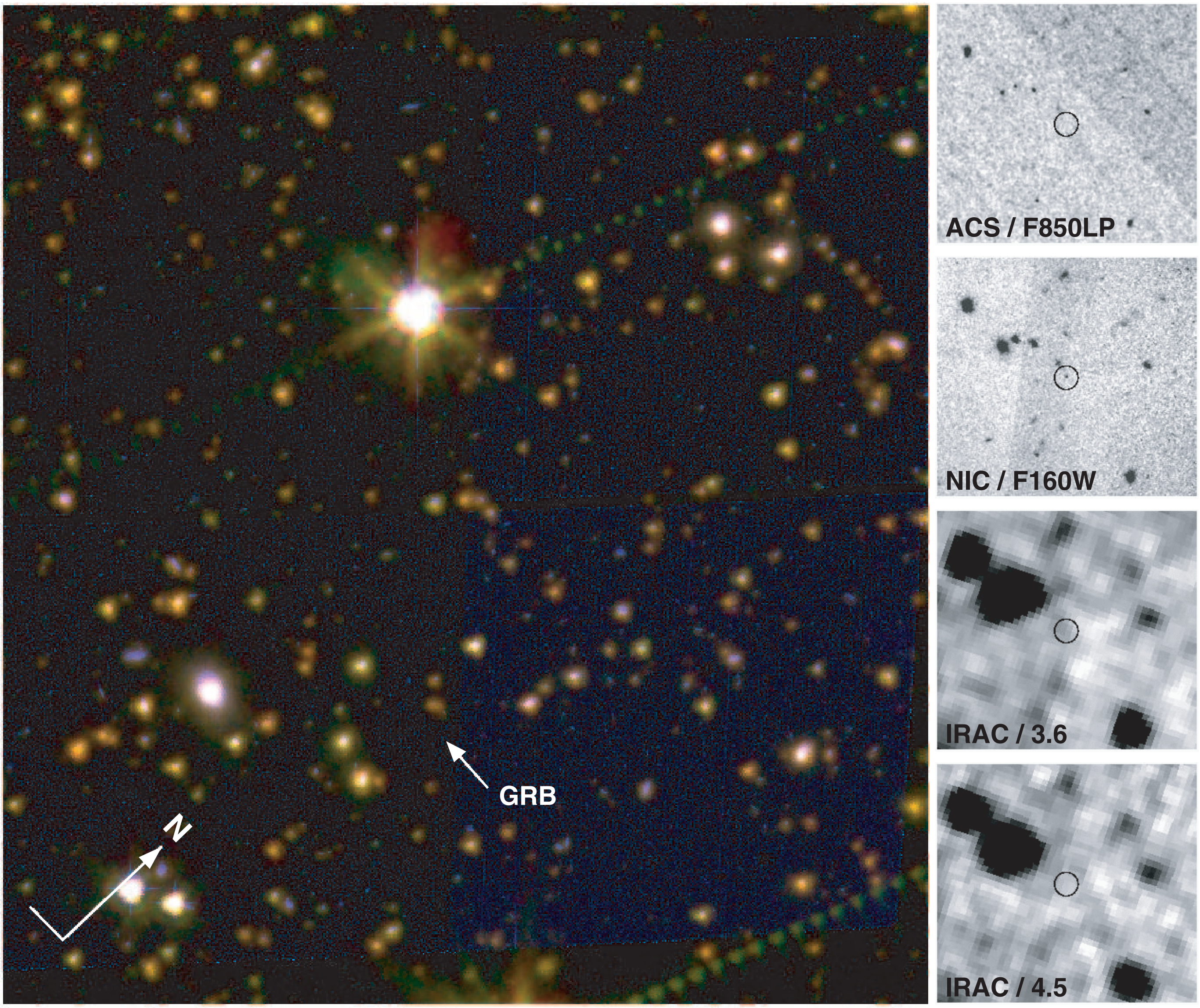

FIG. 1.—Color composite *HST*+*Spitzer* image of the field of GRB 050904. The panels on the right provide a zoom-in on the position of the burst in each of the four available bandpasses. The afterglow is clearly detected in the NICMOS/ F160W image, with subsequent images revealing no source at the position of the burst. The host is marginally detected at 3.6 μm.

spectroscopic observations of its afterglow. Here we present *Hubble Space Telescope* (*HST*) and *Spitzer Space Telescope* follow-up observations of this burst and provide limits on its host luminosity, star formation rate, and stellar mass. We find that the host is a sub-L^* galaxy, with a star formation rate $\lesssim 6\ M_\odot\ \mathrm{yr}^{-1}$ and a stellar mass of $\lesssim$few $\times 10^9\ M_\odot$. Combining these results with the absorption-line metallicity, we place the first limit on the *L*-*Z* diagram of $z > 6$ galaxies.

2. OBSERVATIONS

GRB 050904 was detected by the *Swift* satellite on 2005 September 4.078 UT (Cusumano et al. 2006). The burst redshift was photometrically estimated to be $z \approx 6.2$–6.5 (Price et al. 2006; Tagliaferri et al. 2005; Haislip et al. 2006) and was later confirmed spectroscopically to be $z = 6.295$ (Kawai et al. 2006), making it the highest redshift GRB observed to date. The afterglow absorption spectrum also revealed a damped Lyα absorber with $\log N(\mathrm{H\ I}) \approx 21.6$, a metallicity of $Z \approx 0.05\ Z_\odot$, and appreciable dust depletion (Totani et al. 2006; Kawai et al. 2006).

2.1. *Hubble Space Telescope*

We observed the position of GRB 050904 with *HST* as part of a program to study the host galaxies of $z > 6$ GRBs (GO 10616; PI: Berger). The observations were performed with the Advanced Camera for Surveys (ACS) on 2005 September 26.87 UT, and with the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on two separate occasions: 2005 September 27.28 UT and 2006 July 22.93 UT. A total of 4216, 10240, and 15360 s were obtained in the Wide Field Channel (WFC) F850LP and F160W filters, respectively.

We processed the data using the `multidrizzle` routine (Fruchter & Hook 2002) in the STSDAS package of IRAF. For the ACS data we used `pixfrac` = 0.8 and `pixscale` = 1.0, resulting in a final pixel scale of 0.05″ pixel^{-1}. The NICMOS images were first reprocessed with an improved dark frame created from the Hubble Ultra Deep Field (HUDF) using the IRAF task `calnica` in the NICMOS package. The resulting images were then drizzled using `pixfrac` = 0.7 and `pixscale` = 0.5, leading to a final pixel scale of 0.1″ pixel^{-1}.

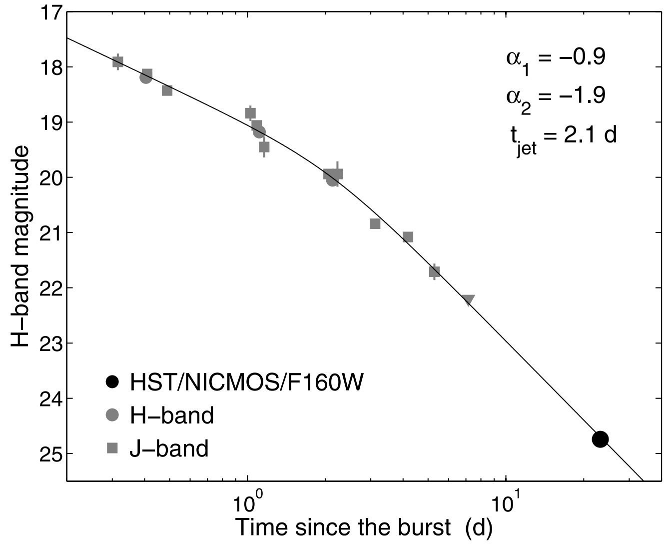

FIG. 2.— Plot of H-band light curve of the afterglow of GRB 050904 using the available ground-based data (Tagliaferri et al. 2005; Haislip et al. 2006) and our *HST* NICMOS data. The J-band data are extrapolated to the H band using the observed spectrum, $F_\nu \propto \nu^{-1.25}$. The solid line is the best-fit broken power-law model (see § 3).

Astrometry was performed relative to a K-band image of the afterglow taken with the Infrared Telescope Facility (IRTF; Haislip et al. 2006). A total of five objects in common to the IRTF and NICMOS images were used, resulting in a 1 σ astrometric uncertainty of about 0.05″. In the first NICMOS observation we identify a single object coincident with the afterglow position at (J2000.0) $\alpha = 00^{\rm h}54^{\rm m}50.846^{\rm s}$, $\delta = +14^\circ05'09.92''$ (0.08″ southeast of the afterglow position); see Figure 1. No corresponding object is detected in the ACS image, or in the second NICMOS observation.

Photometry of the object was performed using the zero points of Sirianni et al. (2005), resulting in $m_{\rm AB}({\rm F850LP}) > 27.0$ mag (3 σ) and $m_{\rm AB}({\rm F160W}) = 26.1 \pm 0.2$ mag (0.13 ± 0.025 μJy) in the first epoch. The upper limit from the second NICMOS observation is $m_{\rm AB}({\rm F160W}) > 27.2$ mag (3 σ).

2.2. *Spitzer Space Telescope*

As part of the same program (GO 20000; PI: Berger) we also observed the field of GRB 050904 with the Infrared Array Camera (Fazio et al. 2004) on *Spitzer* in all four channels (3.6, 4.5, 5.8, and 8.0 μm) on 2005 December 25 UT. The field lies in a region with "medium"-level zodiacal background and cirrus of 34 MJy sr^{-1} at 24 μm and 9.6 MJy sr^{-1} at 100 μm on the date of the observations. We used 100 s integrations with 72 medium-scale dithers from the random cycling pattern for total on-source integration times of 7200 s at each passband. The nominal 3 σ point-source sensitivity limits are 0.26, 0.49, 3.3, and 4.2 μJy, respectively.

Starting with the S13.2.0 pipeline-processed basic calibrated data (BCD) sets we corrected the individual frames for muxbleed and column pull-down using software developed for the Great Observatories Origins Deep Survey. Due to the presence of bright stars in the field, many of the frames at 3.6 and 4.5 μm also showed evidence for "muxstriping." This was removed using an additive correction on a column-by-column basis (J. Surace 2006, private communication). The processed BCD frames were then mosaicked together using the MOPEX routine (Makovoz & Marleau 2005) and drizzled onto a 0.6″ grid. Astrometry was performed relative to the *HST* ACS image using 70 common objects, resulting in an rms uncertainty of 0.07″ (3.6 μm) and 0.09″ (4.5 μm).

Photometry at the position of the afterglow was performed in fixed circular apertures of 1.2″ radius with appropriate beam size corrections applied as stated in the *Spitzer* Observer's Manual. The presence of brighter sources within ~7″ of the host position required that we fit for the wings of the point-spread function from those sources. We find 3 σ upper limits of 0.27 μJy at 3.6 μm, 0.4 μJy at 4.5 μm, 2.7 μJy at 5.8 μm, and 2.5 μJy at 8.0 μm. From the observed afterglow spectral index, $\beta_\nu = -1.25$ ($F_\nu \propto \nu^{\beta_\nu}$; Tagliaferri et al. 2005; Haislip et al. 2006), we expect a 3.6 μm afterglow flux at the time of our observation of $\lesssim 0.005$ μJy, significantly below our limits.

3. AFTERGLOW PROPERTIES

In Figure 2 we plot the H-band light curve of the afterglow of GRB 050904 using all of the available ground-based observations[12] (Tagliaferri et al. 2005; Haislip et al. 2006) and our NICMOS/F160W detection 23.2 days after the burst. Based on the initial observations at $t \lesssim 7$ days it was claimed that the afterglow exhibits a break at $t_b = 2.6 \pm 1.0$ days with pre- and postbreak temporal decay slopes of $\alpha_1 = -0.7 \pm 0.2$ and $\alpha_2 = -2.4 \pm 0.4$ ($F_\nu \propto t^\alpha$; Tagliaferri et al. 2005).

Our *HST* detection provides a significantly longer time baseline, and we indeed confirm the break with a refined value of $t_b = 2.1 \pm 0.3$ days. We further find $\alpha_1 \approx -0.9 \pm 0.1$ and $\alpha_2 = -1.9 \pm 0.1$ ($\chi^2 = 5.8$ for 11 degrees of freedom). Both decay slopes are consistent with the expected relation for a blast wave expanding into a constant density medium, $\alpha_2 = 4\alpha_1/3 - 1 \approx -2.2 \pm 0.2$ (Sari et al. 1999), supporting the notion that this is indeed a jet break. We note that in this scenario we expect to detect an achromatic break in the X-ray band as well. Unfortunately, only a single X-ray measurement exists beyond $t \sim 15$ hr (Cusumano et al. 2007), and we cannot assess whether the break is achromatic or not.

Interpreting the observed break as due to jet collimation, we infer a jet opening angle, $\theta_j \approx 4^\circ(n/10\ {\rm cm^{-3}})^{1/8}$, leading to a beaming-corrected γ-ray energy of $E_\gamma \approx 8.6 \times 10^{50}(n/10\ {\rm cm^{-3}})^{1/4}$ ergs. Frail et al. (2006) infer an isotropic blast wave energy, $E_{K,\rm iso} \sim 9 \times 10^{53}$ ergs, from broadband observations of the afterglow, and a wide range of densities, ~3–700 cm^{-3}. Taking this full range into account, the beaming-corrected energies are $E_\gamma \sim (6\text{–}25) \times 10^{50}$ and $E_K \sim (16\text{–}63) \times 10^{50}$ ergs, typical of (or at most a factor of 2 higher than) most GRBs observed at lower redshifts (Frail et al. 2001; Panaitescu & Kumar 2002).

4. HOST GALAXY PROPERTIES

Using the upper limits from *HST* and *Spitzer* we now place constraints on the physical properties of the host galaxy.[13] We begin by estimating the host extinction using the difference between the observed and expected[14] afterglow spectral indices, $\beta_\nu = -1.25$ and -0.6, respectively (Tagliaferri et al. 2005; Haislip et al. 2006). For a Calzetti (1997) extinction curve we find $A_V \approx 0.3$ mag, or at the observed F160W and F850LP bandpasses, $A_{2200} \approx 0.7$ and $A_{1400} \approx 1.2$ mag. We note that the

[12] We extrapolated the J-band data using the observed spectral index, $\beta \approx -1.25$ ($F_\nu \propto \nu^\beta$).

[13] We use the standard cosmological parameters: $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$, which lead to $d_L = 1.95 \times 10^{29}$ cm and 1″ = 5.76 kpc at $z = 6.295$.

[14] The value of -0.6 is inferred from the optical time decay rate and the typical assumption of $\nu_m < \nu_{\rm opt} < \nu_c$, where ν_m and ν_c are the synchrotron peak and cooling frequencies, respectively.

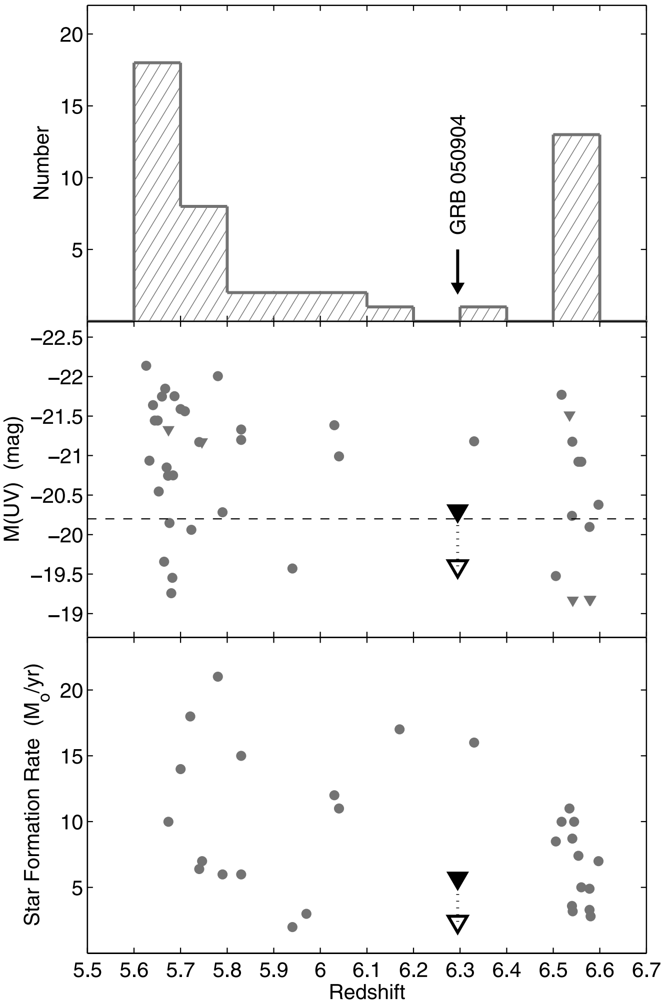

FIG. 3.— Inferred properties of the host of GRB 050904 compared to the published sample of spectroscopically confirmed galaxies at $z > 5.5$ (Hu et al. 1999, 2002, 2004; Bunker et al. 2003; Cuby et al. 2003; Kodaira et al. 2003; Rhoads et al. 2003, 2004; Dickinson et al. 2004; Kurk et al. 2004; Nagao et al. 2004, 2005; Stanway et al. 2004; Chary et al. 2005; Eyles et al. 2005; Stern et al. 2005; Stiavelli et al. 2005; Taniguchi et al. 2005; Westra et al. 2005). Open and filled black triangles designate raw and extinction-corrected limits, respectively, for the host galaxy. Both detections (*circles*) and upper limits (*triangles*) are shown for the distributions of redshifts, absolute rest-frame UV magnitudes, and star formation rates. The dashed line in the middle panel designates an M^* galaxy at $z \sim 6$ (Bouwens & Illingworth 2006).

extinction estimates agree with the significant dust depletion inferred from the afterglow absorption spectrum (Kawai et al. 2006).

At the redshift of the host the observed 3.6 μm band roughly traces the rest-frame optical B band, leading to an extinction-corrected absolute magnitude, $M_{\rm AB}(B) \gtrsim -21$ mag. The rest-frame UV brightness, traced by the observed F160W band, is $M_{\rm AB}(2200) \gtrsim -20.3$ mag, or $M_{\rm AB}(1400) \gtrsim -20.7$ mag if we use the F850LP limit. These values correspond to a luminosity, $L \lesssim L^*$, compared to the luminosity function of $z \sim 6$ candidates in the HUDF (based on photometric redshifts alone; Bouwens & Illingworth 2006); see Figure 3.

We place a limit on the host star formation rate (SFR) using $L_\nu(2200) \lesssim 1.7 \times 10^{28}$ ergs s^{-1} Hz^{-1} and the conversion relation of Kennicutt (1998). This leads to a limit of SFR $\lesssim$ 2.4 $M_\odot$ yr^{-1}, or $\lesssim$5.7 $M_\odot$ yr^{-1} when accounting for rest-frame extinction (Fig. 3). These values are in agreement with the limit of $\lesssim$0.8 $M_\odot$ yr^{-1} inferred from the lack of detectable Lyα emission in the absorption spectrum of GRB 050904 (Totani et al. 2006), although we stress that the latter value has not been corrected for extinction (by about a factor of 4) and is also subject to significant corrections from scattering of the Lyα photons by neutral gas.

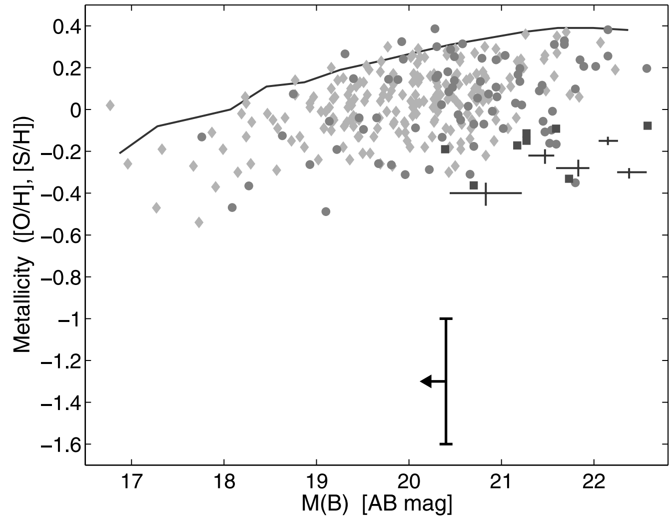

FIG. 4.—Metallicity as a function of luminosity for the host of GRB 050904, our observed *HST*/*Spitzer* limits, and the [S/H] value inferred from the afterglow absorption spectrum (Kawai et al. 2006). Also shown are emission-line oxygen abundances for galaxies from GDDS and CFRS at $z \sim 0.4$–1.0 (*circles*; Savaglio et al. 2005), TKRS at $z \sim 0.3$–1.0 (*diamonds*; Kobulnicky & Kewley 2004), the DEEP2 survey at $z \sim 1.0$–1.5 (*squares*; Shapley et al. 2005), and a compilation of 87 Lyman break galaxies at $z \sim 2.3$ (*error bars*; Erb et al. 2006). The gray lines represent the relations derived for $z \sim 0.1$ galaxies in the SDSS (Tremonti et al. 2004). The host of GRB 050904 lies below the $z \sim 2$ relation for any reasonable luminosity.

Combining the *HST* and *Spitzer* limits, we provide a rough constraint on the stellar mass of the host galaxy. Adopting as a template the $z = 6.56$ galaxy HCM 6A, with $M = 8.4 \times 10^8\ M_\odot$ and a stellar population age of 5 Myr (Chary et al. 2005), we find a rough limit of $\lesssim$few $\times\,10^9\ M_\odot$, similar to that of the Large Magellanic Cloud.

5. DISCUSSION

GRB 050904 is by far the highest redshift spectroscopically confirmed burst observed to date. Equally important, its host galaxy is so far the only $z > 5$ galaxy for which an estimate of the metallicity is available. Given the relatively small number of spectroscopically confirmed galaxies at $z > 5.5$, it is instructive to compare the properties of a GRB-selected galaxy to those selected through narrowband Lyα imaging or the Lyman drop-out technique. In Figure 3 we compare some of the basic properties, which are available for the latter samples, namely the rest-frame absolute magnitudes and UV/Lyα star formation rates. We find that in the published sample, only 14 galaxies are located at a higher redshift than the host of GRB 050904. Moreover, the host has lower UV luminosity and star formation rate than about 80% of all the known galaxies at $z > 5.5$, when accounting for extinction. If we do not include extinction corrections (which are not available for the field galaxies), then the host of GRB 050904 has the lowest star formation rate of any $z > 6$ galaxy discovered to date.

We now turn to a comparison of the metallicity and luminosity of the host of GRB 050904 to those of lower redshift galaxies in the context of the L-Z relation. First, we provide a note of caution that we are comparing a metallicity derived from absorption lines (in this case [S/H], since sulfur is a nonrefractory element) to the oxygen abundance derived from emission lines using the

R_{23} and $N2$ methods. In the case of quasar DLA metallicities a nearly 1 dex discrepancy has been noted compared to emission-line metallicities. However, unlike quasar sight lines, which preferentially probe halo gas, GRB sight lines probe star-forming regions, much like emission-line diagnostics. This is supported by observations of systematically higher metallicities as a function of redshift for GRB-DLAs compared to QSO-DLAs (Berger et al. 2006). Thus, the comparison to emission-line metallicities is most likely robust, and the only remaining caveat is that the inferred metallicity potentially represents the star-forming region local to the GRB, and not the average metallicity of all H II regions in the galaxy. In the absence of additional information, we take the inferred metallicity of $[\mathrm{S/H}] = -1.3 \pm 0.3$ (Kawai et al. 2006) to be representative.

In Figure 4 we plot the metallicity of the host of GRB 050904 versus the limit on its luminosity, as inferred in § 4. For comparison we plot the same data for $z \sim 0.1$ galaxies in the Sloan Digital Sky Survey (SDSS; Tremonti et al. 2004); $z \sim 0.3$–1.0 galaxies from the Gemini Deep Deep Survey (GDDS), the Canada-France Redshift Survey (CFRS), and the Team Keck Redshift Survey (TKRS; Kobulnicky & Kewley 2004; Savaglio et al. 2005); $z \sim 1.0$–1.5 galaxies from the Deep Extragalactic Evolutionary Probe (DEEP2) survey (Shapley et al. 2005); and $z \sim 2.3$ UV-selected galaxies (Erb et al. 2006). As noted by the aforementioned authors, there is clear evolution in the *L-Z* (and also *M-Z*) relation in the sense that galaxies of a given mass/luminosity have lower metallicities at progressively higher redshifts. The implications of this evolution, and of the *M-Z* and *L-Z* relations themselves, are a matter of current investigation, and here we simply note that the host of GRB 050904 may indicate that this trend continues to much higher redshifts for any reasonable luminosity below the extinction-corrected limit of $M_{\mathrm{AB}}(B) \gtrsim -20.5$ mag (Fig. 4).

The detection of additional GRBs at $z \sim 6$ will allow us to examine in detail whether the *M-Z* and *L-Z* relations actually exist at those redshifts, and if they in fact follow the evolutionary trend observed at lower redshifts. Moreover, with the ability to probe galactic-scale outflows in absorption, we can determine whether the origin of these relations is rooted in higher gas fractions for lower mass galaxies, or outflows from their shallower potential wells—a matter of current debate (McGaugh & de Blok 1997; Tremonti et al. 2004; Erb et al. 2006). This applies to the growing sample of GRB absorption spectra at $z \sim 2$–4 as well, which can both fill in the gap from $z \sim 2$ to $z \sim 6$, and through near-IR spectroscopy of the host galaxies allow us to compare emission- and absorption-derived metallicities at $z \sim 2$–3, and directly assess the existence of any systematic differences.

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