The Astrophysical Journal, 545:664–669, 2000 December 20

HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE HOST GALAXY OF GRB 970508

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Received 2000 August 2; accepted 2000 August 6

ABSTRACT

We report on observations of the field of GRB 970508 made in 1998 early August, 454 days after outburst, with the STIS CCD camera on board the *Hubble Space Telescope* (*HST*). The images, taken in open filter (50CCD) mode, clearly reveal the presence of a galaxy that was overwhelmed in earlier (1997 June) *HST* images by emission from the optical transient (OT). The galaxy is regular in shape: after correcting for the *HST*/STIS PSF, it is well fitted by an exponential disk with a scale length of $0''.046 \pm 0''.006$ and an ellipticity of 0.70 ± 0.07. All observations are marginally consistent with a continuous decline in OT emission as $t^{-1.3}$ beginning 2 days after outburst; however, we find no direct evidence in the late-time *HST* image for emission from the OT, and the surface brightness profile of the galaxy is most regular if we assume that the OT emission is negligible, suggesting that the OT may have faded more rapidly at late times than is predicted by the power-law decay. Due to the wide bandwidth of the STIS clear mode, the estimated magnitude of the galaxy is dependent on the galaxy spectrum that is assumed. Using colors obtained from late-time ground-based observations to constrain the spectrum, we find $V = 25.4 \pm 0.15$, a few tenths of a magnitude brighter than earlier ground-based estimates that were obtained by observing the total light of the galaxy and the OT and then subtracting the estimated OT brightness, assuming that it fades as a single power law. This again suggests that the OT may have faded faster at late time than the power law predicts. The position of the OT agrees with that of the isophotal center of the galaxy to $0''.01$, which, at the galaxy redshift $z = 0.83$, corresponds to an offset from the center of the host of $\lesssim 70$ pc. This remarkable agreement raises the possibility that the gamma-ray burst may have been associated with either an active galactic nucleus or a nuclear starburst.

Subject headings: cosmology: observations — galaxies: active — galaxies: starburst — gamma rays: bursts — stars: formation

1. INTRODUCTION

The detection and rapid localization of GRB 970508 by the Gamma-Ray Burst Monitor and the X-ray Wide Field Camera on *BeppoSAX* (Piro et al. 1998) led to the identification of an optical counterpart within 4 hr (Bond 1997), and subsequently to Keck spectroscopy of the counterpart, which revealed a system of absorption lines at $z = 0.835$ (Metzger et al. 1997). This lower limit on the gamma-ray burst (GRB) redshift was the first direct constraint on the distance and energy scale of a classical gamma-ray burst. Because of its early discovery, as well as the great interest attracted by the redshift measurement, the fading counterpart of GRB 970508 has been more thoroughly studied than any other GRB counterpart. The optical light curve, for example, has been intensively observed from a few hours to over a year after the GRB. The optical flux reached a peak at $R \sim 19.8$ 2 days after the GRB, then began a power-law decay, $t^{-\beta}$, with $\beta = 1.141 \pm 0.014$, that continued for over 100 days (Pian et al. 1998b; Galama et al. 1998c). At that point, the decay curve began to flatten (Pian et al. 1998a; Pedersen et al. 1998; Bloom et al. 1998a; Zharikov, Sokolov, & Baryshev 1998; Sokolov et al. 1999), as expected if the measured flux were becoming dominated by light from a host galaxy. GRB 970508 was also the first GRB for which a radio counterpart was detected (Frail et al. 1997; Galama et al. 1998b). The broadband (radio to X-ray) spectrum of the afterglow (Waxman, Kulkarni, & Frail 1998; Galama et al. 1998a) provided strong support for the synchrotron-emitting shock model for afterglows (see, e.g., Sari, Piran, & Narayan 1998).

Despite the wealth of data on the GRB counterpart itself, the host galaxy has proven a more difficult observational target. Spectroscopy has revealed [O II] and [Ne III] emission features, and these, together with colors of the galaxy obtained by fitting observations of the combined light from the optical transient (OT) and the galaxy, have led to the suggestion that the host is an actively star forming dwarf galaxy (Bloom et al. 1998a; Sokolov et al. 1999). However, attempts to resolve the host galaxy from the ground have proven fruitless. Even early *Hubble Space Telescope* (*HST*) observations, less than a month after outburst, found no evidence for an extended source at the position of the optical transient, down to faint levels, $R \gtrsim 24.5$ (Pian et al.

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1998b). In this paper, we describe *HST* observations taken more than a year after outburst, which have finally allowed us to resolve the host galaxy of GRB 970508. These show that GRB 970508 occurred remarkably close—within about 70 pc—to the host galaxy center, and suggest that the brightness of the OT may have fallen faster at late times than would be predicted by a simple power-law fit. Finally, we discuss the implications of these observations for understanding the progenitor objects and energetics of GRBs.

2. OBSERVATIONS, IMAGE ANALYSIS, AND RESULTS

The field of GRB 970508 was imaged during four *HST* orbits in 1998 August 5.78–6.03 UT, using the STIS CCD in clear-aperture (50CCD) mode. Two exposures of 1446 s each were taken at each of four dither positions for a total exposure time of 11,568 s. The images were bias- and dark-subtracted, and flat-fielded using the STIS pipeline. The final image was created and cleaned of cosmic rays and hot pixels using the variable pixel linear reconstruction algorithm (a.k.a. Drizzle) developed for the Hubble Deep Field (Williams et al. 1996; Fruchter & Hook 1997). An output pixel size of 0″.025 across (one-half the size of the detector pixels on the sky) and a "pixfrac" of 0.6 were used. The (small) geometric distortion of the STIS CCD (Malamuth & Bowers 1997) was removed during the drizzling process. A section of the final image is shown in Figure 1.

The total emission from the OT and galaxy were measured by summing the counts in a box 1″.5 on a side and subtracting the local sky. We find 3.13 ± 0.12 counts s^{-1} in the aperture. The photometric calibration of the images was performed using the synthetic photometry package SYNPHOT in IRAF/STSDAS; however, a 12% aperture correction has been applied (Landsman 1997) to account for light lost to large-angle scattering. The STIS CCD in clear-aperture mode has a broad bandpass, with a significant response from 200 to 900 nm that peaks near 600 nm. As a result, STIS instrumental magnitudes are best translated into the standard filter set by quoting the result as a V magnitude; however, knowledge of an object's intrinsic spectrum is required for an accurate conversion to the standard filter system. Using a spectral energy distribution (SED) flat in $f(\nu)$, one finds $V = 25.1 \pm 0.1$. However, as mentioned in the introduction, ground-based observers have fitted for the host galaxy magnitude under the assumption that the power-law index of decay of the OT has been constant with time. We can therefore estimate the V magnitude using the color information from these observations. Although the estimated galactic magnitudes have changed with time (a point we return to below), all observers have found a blue host, and Sokolov et al. (1999) suggest that the galaxy colors are best fitted by an object intermediate between an Scd and an irregular (Im) redshifted to $z = 0.83$. Using either the measured galaxy colors, obtained by a rough averaging of the values obtained by previous observers (Bloom et al. 1998a; Zharikov et al. 1998; Sokolov et al. 1999), or an SED created by interpolating between

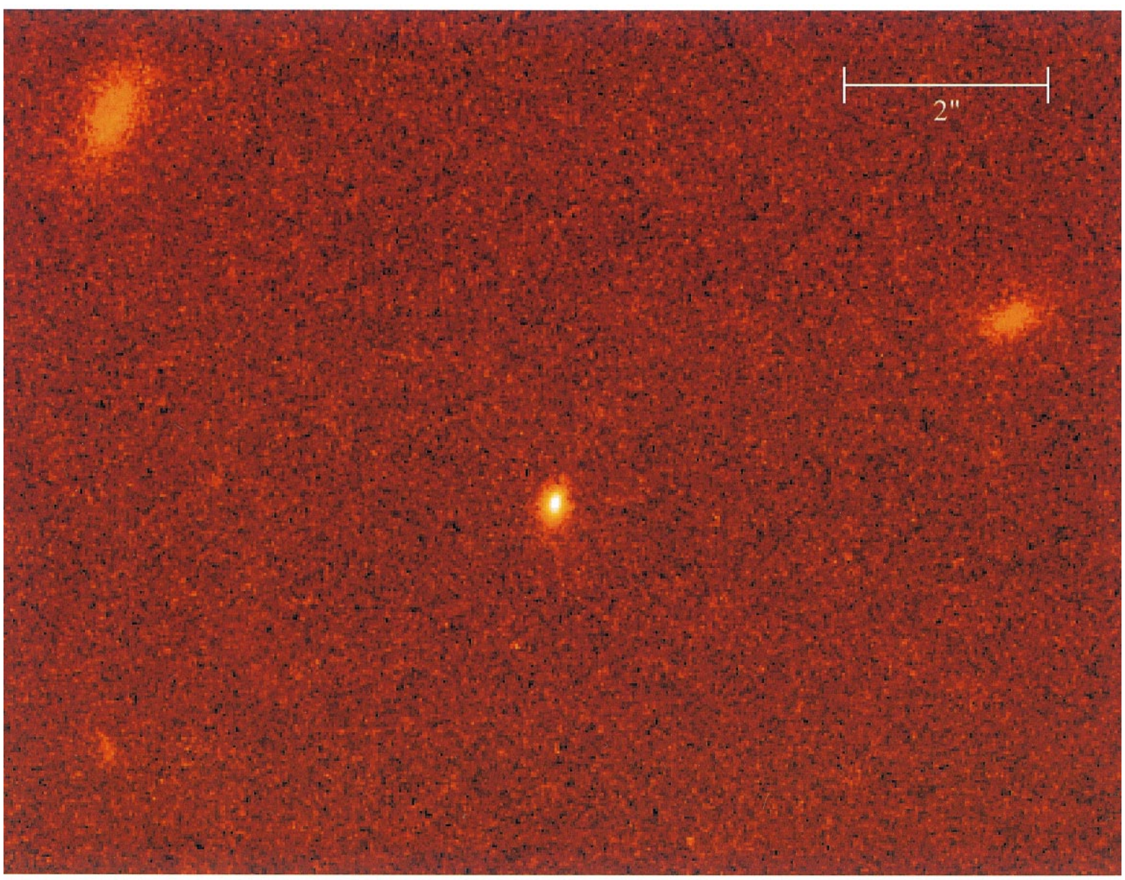

FIG. 1.—Section of the STIS CCD image of the field around GRB 970508. North is up, east is to the left. The host galaxy is near the center of the field. The estimated position of the OT agrees with the center of the host to 0″.01.

Coleman, Wu, & Weedman (1980) Scd and Im SEDs and redshifting to $z = 0.83$, we estimate $V = 25.40 \pm 0.15$, where the error is dominated by our uncertainty over the SED. This, however, represents the sum of the emission from the host galaxy and any remnant of the OT. We next place a limit on the magnitude of the OT.

In order to register the position of the OT on the late-time image, the positions of nine compact sources were found on both the 1997 June (Pian et al. 1998b) and 1998 August drizzled images. A shift (in x and y) and rotation were then fitted between the two images using the IRAF task *geomap*. The accuracy of this transformation was checked by comparing the observed and predicted positions of four bright, pointlike sources. An rms scatter of 0.25 drizzled pixels (0″.006) was found in each coordinate, for a position uncertainty of less than 0″.01. When the position of the OT on the 1997 June image was transformed to that of the 1998 August image using the shift and rotation measured, we found it to be exactly at the center of the host. To verify this observation, we fitted the host galaxy with elliptical isophotes using the IRAF task *ellipse*. We find that the isophotal center of the galaxy is stable as a function of radius and agrees with the predicted position of the OT to better than our astrometric error of 0″.01.

In Figure 2 we show a plot of the measured surface brightness profile of the galaxy compared with an $r^{1/4}$ model and an exponential disk model. In both cases, we have convolved the model with the STIS PSF. In addition to the measured surface brightness profile, we show that profile after subtracting an estimated remnant OT. To do this, we went back to the 1997 June observation and rescaled and subtracted the STIS PSF until the remaining counts s^{-1} in a circle of a radius of 4 drizzled pixels equaled that in the same region of the late-time image. This PSF should be a good estimate of the OT at 24.7 days after outburst, and was rescaled to the expected magnitude at

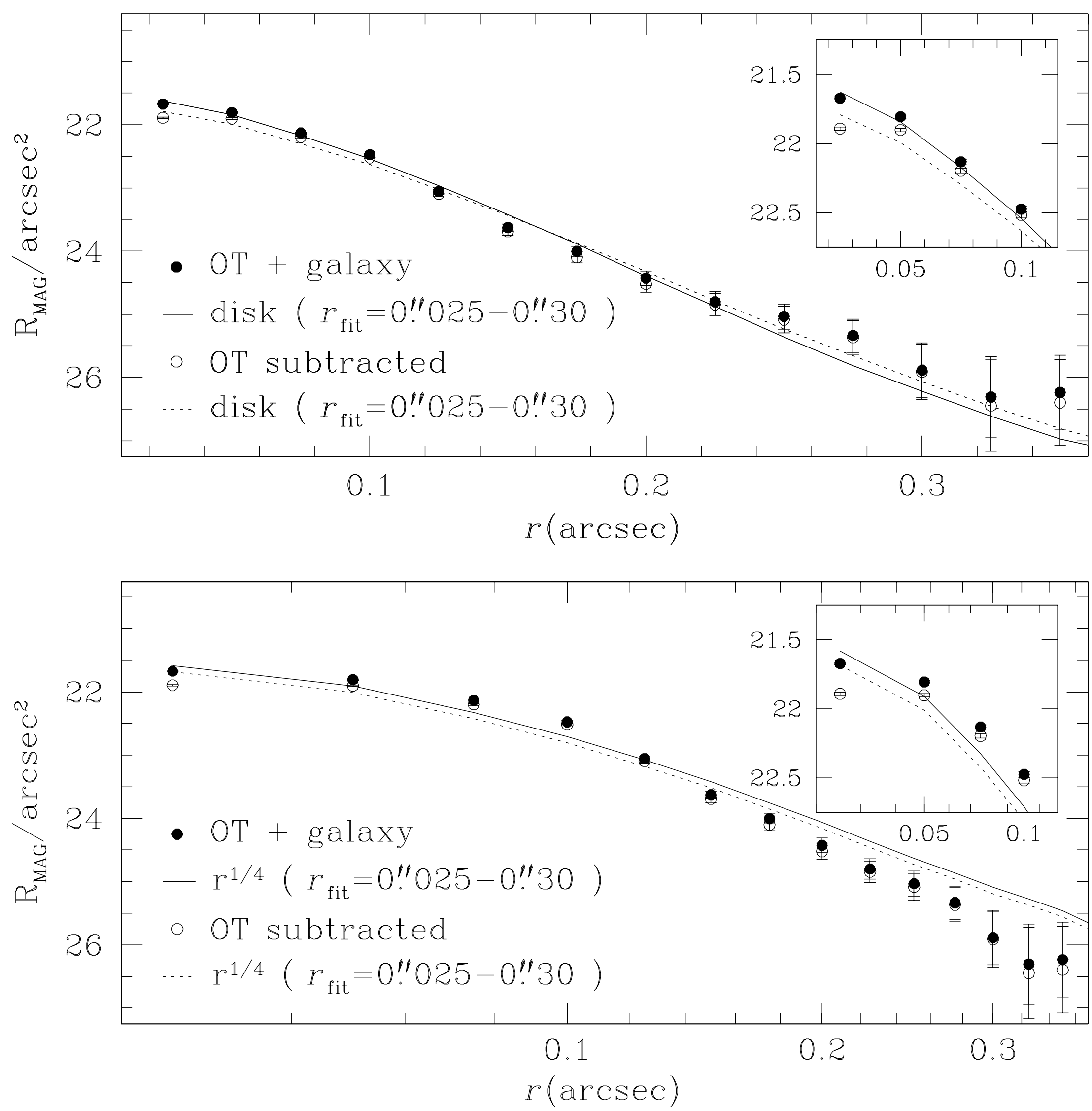

FIG. 2.—Surface brightness profile of the host galaxy with and without the OT removed. The top plot shows the measured isophotes of the host compared with our best-fitting exponential-disk model. The filled circles show the measured values on the original image. The open circles show the values measured after subtraction of an OT with $R \sim 27.4$, corresponding to a decay of the OT with time as $t^{-1.3}$. The model has been fitted to both the observed data (*solid line*) and the galaxy with OT subtracted (*dashed line*). The fit was done over radii from 1 to 12 drizzled pixels (0″.025–0″.30). The bottom graph shows the same information for an $r^{1/4}$ law fit.

454 days after outburst using the $t^{-1.14}$ power law found in Pian et al. (1998b). When subtracted from the galaxy, this estimate of the OT produced a clear "hole" in the center of the host. Under the assumption that galaxies (convolved to ~ 500 pc resolution by the PSF) should have surface brightness profiles rising toward the center, we reject this subtraction. Indeed, if the underlying galaxy surface brightness distribution is continuously rising toward the center, the brightest OT that can be accommodated is one that has declined between the two *HST* observations as $t^{-1.3}$ (see Fig. 3). This power law is 2 σ below the power law reported by Pian et al. (1998b), but agrees well with that found by Bloom et al. (1998a) and is within 2 σ of that found by Zharikov et al. (1998). (We note that the Pian et al. fit was slightly contaminated by the then-unmeasured light from the host galaxy.)

As can be seen from Figure 2, the surface brightness profile of the host galaxy is far better fitted by an exponential disk model than by an $r^{1/4}$ law. The best-fit model is an exponential disk with scale length $= 0''.046 \pm 0''.006$ and ellipticity $= 0.70 \pm 0.07$ before convolution with the STIS PSF. In the figure shown, we have used the *HST* Tiny Tim software (Krist, Hasan, & Burrows 1992) to produce the PSF used in the convolution; the results obtained when the model is convolved using an observed stellar PSF are quite similar. The convolved exponential disk can itself be approximated by an exponential disk with scale length $\sim 0''.060$ and ellipticity ~ 0.3. A true exponential disk plotted as magnitude versus radius would, of course, have a surface brightness profile that is a straight line; however, at its core, the surface brightness of the observed galaxy is averaged over the width of the PSF, and at large radii the true light of the galaxy is overwhelmed by light scattered from the center. It is worth noting that given the large ellipticity observed, the poor fit of the $r^{1/4}$ law is not unexpected. In spite of their names, ellipticals rarely have ellipticities approaching 0.7.

The fit between the galaxy models and the data is substantially better when *no* OT is subtracted than when we remove an OT scaled as $t^{-1.3}$. Nonetheless, as can be seen in Figure 3, this power law largely fits the available ground-based *R*-band photometry. For this figure, a galaxy magnitude of $R = 25.2$ has been removed from previous photometry. This corresponds to a flat [in $f(\nu)$], i.e., very blue, galaxy spectrum between *R* and *V*. The colors found by Sokolov et al. (1999) are somewhat redder; however, their *V* galaxy magnitude of 25.65 ± 0.17 is somewhat fainter than ours. In 1998 August, an OT falling as $t^{-1.3}$ would have $V \sim 27.8$, implying a corrected galactic magnitude of $V = 25.5 \pm 0.15$. However, there has been a continuing trend among the ground-based estimates of the host magnitude. The later the data used to fit the host galaxy, the fainter the host was found to be (Bloom et al. 1998a; Zharikov et al. 1998; Sokolov et al. 1999). The differences are visible in all bands (*B*, *V*, *R*, and *I*), and are typically at the 2 σ level. Furthermore, the preference of our surface brightness fit for no continuing emission from the OT, and the prevalence of upper limits, rather than detections beyond day 150 in Figure 3, all suggest a single conclusion—the OT may have faded much more rapidly than $t^{-1.3}$ after day ~ 100.

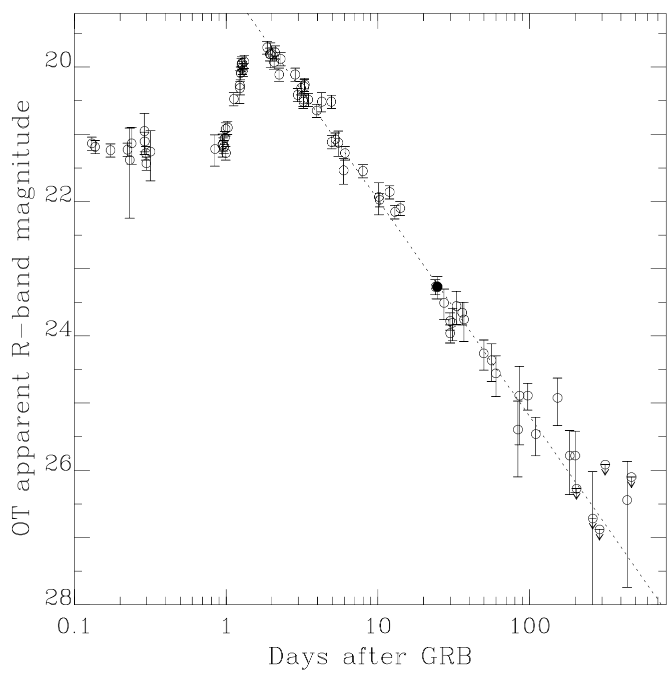

FIG. 3.—*R*-band light curve of the OT of GRB 970508. A constant host *R* magnitude of 25.2 has been subtracted from all observed values. The solid line shows a power law with slope $t^{-1.3}$. The 2 σ upper-limits are marked by a downward-pointing arrow. The data have been taken from Pian et al. (1998b), Bloom et al. (1998a), Zharikov et al. (1998), and Sokolov et al. (1999) and references therein. The filled circle shows the *HST* measurement of 1997 June.

3. DISCUSSION

Our imaging has revealed the faint galaxy host of GRB 970508. We find that the OT is located, within astrometric errors of the order of $0''.01$, at the isophotal center of the host. In Pian et al. (1998b), we argued that the large depth of the Mg I absorption and the presence of [O II] emission at $z = 0.83$ implied that these spectral lines were unlikely to be the result of a random intervening system, but rather were evidence that the GRB was located within a host galaxy, albeit a very faint one. The extraordinary alignment of the OT and the center of the galaxy now proves that contention. At the redshift of GRB 970508, $z = 0.83$, the 1 σ limit on the offset between the OT and the center of the galaxy of $0''.01$ corresponds to ~ 70 pc.

The surface brightness profile of the host better fits an exponential disk than the $r^{1/4}$ profile of an elliptical, and agrees best when no OT is assumed to be adding to the profile; however, we cannot rule out a power-law decay of the OT as $t^{-\beta}$, where $\beta \geq 1.3$. Both our data and the ground-based observations tend to support a steepening of the early power-law decay curve sometime after day ~ 100. Such a break is naturally expected when the expanding fireball has swept up the material from the interstellar medium (ISM) comparable in rest mass to the energy of the initial explosion at

$$t \approx 1\ yr \left(\frac{E_{52}}{n}\right)^{1/3},$$

where E_{52} is the initial energy of the explosion in units of 10^{52} ergs, and n is the density of the surrounding medium in protons per cm^3 (Wijers et al. 1997). Wijers & Galama (1999) have used the multiwavelength observations of the afterglow emission of GRB 970508 to estimate the physical parameters of the burst and its surrounding interstellar medium, assuming that the afterglow is dominated by synchrotron emission. They find a total burst energy of $\sim 4 \times 10^{52}$ ergs and $n \sim 0.04$ cm^{-3}. These values would cause us to expect a break somewhat after 1 yr. However, the uncertainties in these estimated parameters are large (perhaps an order of magnitude; R. A. M. J. Wijers 1999, private communication). A transition to a more rapid decay could also be caused by collimation of the GRB afterglow, although because of the very shallow nature of any observed falloff, the collimation angle in the case of GRB 970508 would have to be relatively large (Waxman et al. 1998; Rhoads 1999a, 1999b; Frail, Waxman, & Kulkarni 2000).

Although the precise behavior with time of the OT is uncertain, its position on the host is not. The extraordinary coincidence of the OT with the isophotal center of the host galaxy raises the question of whether the GRB is related to the galactic nucleus, either through a nuclear starburst or an active galactic nucleus (AGN). The Keck spectroscopy by Bloom, Sigurdsson, & Pols (1998a) shows strong [O II] and [Ne III], both of which are present in galaxies with active nuclei. However, in a large spectroscopic sample of galaxies (McQuade, Calzetti, & Kinney 1995; Storchi-Bergmann, Kinney, & Challis 1995), no ellipticals or spirals without AGNs show [Ne III]. About one-third of the starbursts in the sample show this line, and these are by and large the most active starbursts in the group. Furthermore, only the most extreme starbursts and the Seyfert galaxies have a [Ne III] equivalent width or the large [Ne III] to [O II] ratio (indicative of a temperature in excess of 40,000 K) seen in this galaxy. Thus, the spectroscopic evidence does not allow us to distinguish between a host that possesses an AGN and one that is simply showing signs of vigorous star formation. Nonetheless, we tend to prefer the latter explanation for two reasons. First, if cosmological GRBs are produced by a single mechanism, that mechanism is unrelated to AGNs. The OT of GRB 970228 is located at the very edge (rather than the center) of a galactic disk (Fruchter et al. 1999a). Furthermore, *HST* images of other GRBs (Odewahn et al. 1998; Bloom et al. 1998b; Fruchter et al. 1999b), while less conclusive, all tend to discourage an AGN interpretation. Second, our recent work has shown that other GRB hosts possess unusually blue optical-to-infrared colors, implying that these galaxies are actively star forming (Fruchter et al. 1999b). NICMOS imaging should soon allow us to determine whether this is also the case for the host galaxy of GRB 970508. Until then, we note that in many ways, this host galaxy has a strong resemblance to the classic nearby starburst dwarf NGC 5253, in its integrated colors, morphology, and line strengths (McQuade et al. 1995; Storchi-Bergmann et al. 1995). Furthermore, NGC 5253 has a hot, young star cluster in its nucleus, suggesting that the resemblance may be very good indeed, by providing a natural explanation for the location of the OT.

The hosts of four GRBs (970228, 970508, 971214, and 990123) have now been imaged and clearly resolved by *HST* (Sahu et al. 1997; Fruchter et al. 1999a, 1999b; Odewahn et al. 1998; Bloom et al. 1999). In each case, the OT is superposed on the stellar field. We note that this may be a result of selection effects and not the true distribution of GRBs with respect to host galaxies, since all of these GRBs were localized by detection of an OT, which itself may require the presence of a dense external working surface such as ISM (Paczyński & Rhoads 1993; Mészáros & Rees 1997). Furthermore, only $\sim 50\%$ of the GRB localizations by the *BeppoSAX* satellite have resulted in the discovery of an optical transient. This fraction is consistent with a model of GRB formation from the merger of neutron star–neutron star binaries, since a substantial fraction of neutron star–neutron star binaries are likely to be ejected from the galaxy by the momentum imparted to the neutron stars at birth (Bloom et al. 1999; Livio et al. 1998). However, it is not immediately clear that star formation can properly account for the fraction of GRBs detected in the optical. Local estimates of dust obscuration in star-forming galaxies (Calzetti & Heckman 1999), as well as some estimates of the same effect in high-redshift galaxies (Pettini et al. 1998; Blain et al. 1999), suggest that about one-third of the light emitted in the UV escapes from star-forming galaxies before being absorbed by dust and reprocessed to IR or radio wavelengths. (We typically view the OTs of GRBs in the UV rest wavelength, since they have observed redshifts between 0.8 and 3.4; see also Hogg & Fruchter 1999.) A reduction by a factor of 3 of the light emitted by GRBs would be roughly consistent with what we observe: about one-half of GRBs are missing, and of the order of one-half of those observed have redder spectra than expected based on the afterglow theory (Bloom et al. 1998b; Fruchter et al. 1999a; Halpern et al. 1998), perhaps suggesting the presence of moderate extinction. However, other authors (Meurer et al. 1997) have claimed significantly higher absorption by dust at high redshift. In addition, deep submillimeter observations of several high Galactic latitude fields (Hughes et al. 1998; Barger et al. 1998) have suggested that a few obscured objects in each field that are undetectable in the optical could be producing more stars than all the galaxies visible in the optical. If these more extreme estimates of the importance of dust obscuration are correct, and GRBs are related to star formation, it may be difficult to explain the success optical observers have had in finding OTs—especially ones such as 970508, which is quite probably at the nucleus of a highly inclined starburst galaxy, yet whose color in the rest-frame UV (Pian et al. 1998b) shows no sign of significant extinction, unless GRBs are able to destroy the dust encasing them (Waxman & Draine 2000).

We thank Bob Williams for allocating Director's Discretionary time to observe GRB 970508 using STIS and John Krist for preparing Tiny Tim STIS PSFs for us.

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