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HUBBLE SPACE TELESCOPE AND PALOMAR IMAGING OF GRB 990123: IMPLICATIONS FOR THE NATURE OF GAMMA-RAY BURSTS AND THEIR HOSTS

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ABSTRACT

We report on *Hubble Space Telescope* and Palomar optical images of the field of GRB 990123, obtained in 1999 February 8 and 9. We find that the optical transient (OT) associated with GRB 990123 is located on an irregular galaxy, with a magnitude of $V = 24.20 \pm 0.15$. The strong metal absorption lines seen in the spectrum of the OT, along with the low probability of a chance superposition, lead us to conclude that this galaxy is the host of the gamma-ray burst (GRB). The OT is projected within the $\sim 1''$ visible stellar field of the host, nearer the edge than the center. We cannot, on this basis, rule out the galactic nucleus as the site of the GRB, since the unusual morphology of the host may be the result of an ongoing galactic merger, but our demonstration that this host galaxy has extremely blue optical-to-infrared colors more strongly supports an association between GRBs and star formation. We find that the OT magnitude in 1999 February 9.05, $V = 25.45 \pm 0.15$, is about 1.5 mag fainter than expected from the extrapolation of the decay rate found in earlier observations. A detailed analysis of the OT light curve suggests that its fading has gone through three distinct phases: an early, rapid decline ($f_\nu \propto t^{-1.6}$ for $t < 0.1$ days); a slower, intermediate decline power-law decay ($f_\nu \propto t^{-1.1}$ for $0.1 < t < 2$ days); and then a more rapid decay (at least as steep as $f_\nu \propto t^{-1.8}$ for $t > 2$ days). The break to a steeper slope at late times may provide evidence that the optical emission from this GRB was highly beamed.

Subject headings: cosmology: observations — gamma rays: bursts — stars: formation

1. INTRODUCTION

The gamma-ray burst GRB 990123 was an astrophysical event of astonishing proportions. It was the brightest burst yet detected with the wide-field cameras on the *BeppoSAX* satellite (Feroci et al. 1999), and it has a total fluence among the brightest 0.3% of bursts detected by the BATSE instrument on the *Compton Gamma-Ray Observatory* (*CGRO*). Optical observations, which began with the ROTSE-I telephoto array while the gamma-ray event was still in progress, detected an optical transient (OT) that reached a peak magnitude of $V \sim 9$ about 40 s after the start of the burst (Akerlof & McKay 1999). Within hours, spectroscopy revealed metal absorption lines in the spectrum of the OT at $z = 1.60$ (Kelson et al. 1999; Hjorth et al. 1999a), constraining the gamma-ray burst (GRB) redshift to be at least this great. If the GRB emission was directed isotropically, the implied energy release is $\gtrsim 2 \times 10^{54}$ ergs.

Recognizing the importance of the rapid observations of this object and the extraordinary level of interest by the astronomical community, *Hubble Space Telescope* (*HST*) observations were scheduled using director's discretionary time, for immediate public release (Beckwith 1999a, 1999b). To help ensure rapid access, we processed the data on the day of the observation and made the resulting images and a first report on the results of the imaging freely available on the Web (Fruchter et al. 1999c). In this Letter, we present a more detailed analysis and combine the *HST* data with additional optical images that we have obtained at the Palomar 5 m telescope. Together, these observations allow us to study both the light curve of the OT and the nature of the host galaxy of GRB 990123.

2. OBSERVATIONS

The field of GRB 990123 was observed by *HST* over the course of three orbits between 1999 February 8 (23:06:54 UT) and 9 (03:21:43 UT) using the Space Telescope Imaging Spectrograph (STIS) in clear aperture mode. Two images of 650 s each were taken at each of six dither positions for a total exposure time of 7800 s. The images were processed using the standard STIS data pipeline; however, a "dark" was first constructed using data obtained the week before the observations, and this was used instead of the standard calibration file, dramatically reducing the number of hot pixels in the pipeline-calibrated image. The standard pipeline performed a first pass cosmic-ray removal using the two images at each dither position. The remaining cosmic rays and hot pixels were eliminated and the images combined using the drizzle algorithm and

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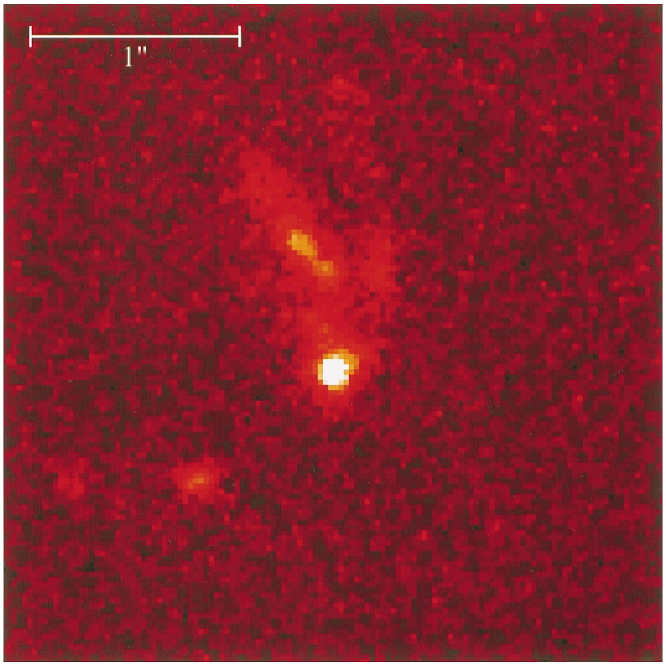

FIG. 1.—Central 3″.2 of the *HST* image of the field of GRB 990123. The OT is the bright point source at the center of the image. North is up, and east is to the left. The two small objects to the southeast have been included in the measured magnitude of the galaxy because their projected separation from the main body of the galaxy (<7 kpc) makes it likely that they are now or will soon be part of the host galaxy.

associated techniques (Fruchter & Hook 1999). The final output image was created with an output pixel size of 0″.025 on a side, or one-half that of the original pixels. A "pixfrac" of 0.6 was used. Figure 1 shows the central region of the final image.

The total counts associated with the OT were determined by two methods: (1) obtaining the counts above an estimated galactic background in an aperture with radius 4 output pixels and then applying an aperture correction (a factor of 1.5) determined using a STIS point-spread function (PSF) star obtained from the *HST* archives, and (2) directly subtracting the PSF star from the image while scaling to minimize the image residuals. The values obtained by these methods agreed to within 5%. The total counts in a box 2″.5 on a side were then found, and the counts from the OT were subtracted to obtain the counts associated with the galaxy.

Photometric calibration of the images was performed using the synthetic photometry package SYNPHOT in IRAF/STSDAS. We refer the reader to Fruchter et al. (1999b) for further discussion of the STIS/CCD and its photometric calibration. We found that on 1999 February 9.05 UT, the OT of GRB 990123 had a magnitude of $V = 25.45 \pm 0.15$, and the galaxy on which it is superposed was $V = 24.20 \pm 0.15$. (Unless otherwise stated, all magnitudes in this Letter are Vega magnitudes; Landolt 1992.)

Observations of the GRB host were also obtained using the Palomar 5 m telescope with the COSMIC camera in direct imaging mode on 1999 February 8.4–8.5 UT (approximately 12 hr before the *HST* observations). The detector in COSMIC is a 2048 × 2048 CCD with 24 μm pixels, projecting to 0″.28 on the sky. Three dithered 300 s exposures were obtained in the *B* band, 3 × 300 s in *V*, and 4 × 300 s in *R*. The seeing measured in the final images varies from 1″.0 in *V* to 1″.5 in *B*.

Photometric calibration was performed using images of the PG 1633 field (Landolt 1992). A comparison with the fainter stars measured by Nilakshi et al. (1999) shows agreement to better than 0.1 mag. Aperture photometry of the host galaxy was performed using a 5 pixel radius aperture, including a rough correction to the large aperture that was derived from the curve of growth measured for bright nearby point sources. The resulting magnitudes are $B = 24.4 \pm 0.2$, $V = 23.96 \pm 0.05$, and $R = 23.62 \pm 0.05$. Given the magnitude measured for the OT in the *HST* images taken hours later, we estimate that the galaxy alone is approximately 0.3 mag fainter.

The USNO A2.0 stars surrounding GRB 990123 have been used by a number of observers as standards for performing relative photometry on the OT. We have therefore used our observations to recalibrate 47 of the USNO A2.0 standards that fall in the frame and are sufficiently faint to avoid saturation. We find that in this region, the USNO calibration is ~0.2 mag too bright. This correction is in the opposite sense of that reported by Skiff (1999).

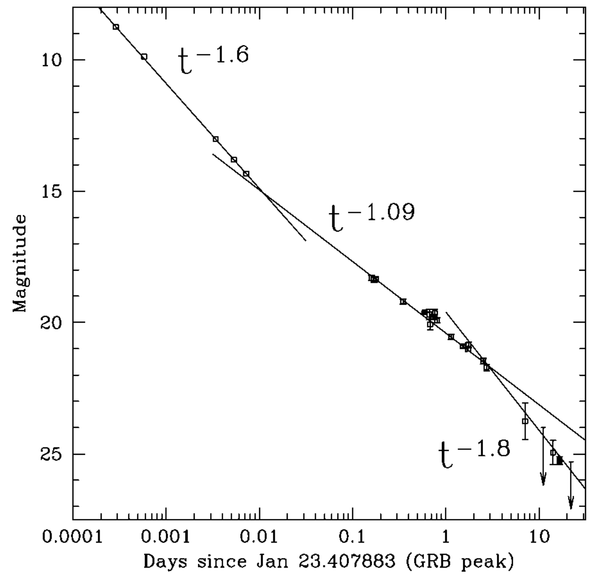

FIG. 2.—*R*-band light curve of the OT associated with GRB 990123. All points, except for the *HST* point (*rightmost filled square*), were taken from the literature as discussed in the text and reduced to a common flux standard with the galaxy flux subtracted. Error bars are shown where available (1 σ), and arrows indicate 95% confidence upper limits.

3. LIGHT CURVE OF OPTICAL TRANSIENT

In Figure 2, we show the *R*-band light curve of the counterpart of GRB 990123, combining our observations with those reported in the literature. We have attempted to reduce all available observations to the photometric standards measured by Nilakshi et al. (1999). Observations by Sagar et al. (1999) and Veillet (1999) have been directly referenced to these standards, and we have been able to reference published photometry from Sokolov et al. (1999), Garnavich et al. (1999), Yadigaroglu et al. (1999), Yadigaroglu & Halpern (1999), and Halpern et al. (1999) to the same standards. Other observations, including Zhu & Zhang (1999), Zhu, Chen, & Zhang (1999), and Masetti et al. (1999), were made relative to USNO A1.0 stars. Observations made relative to USNO A2.0 stars (Ofek & Leibowitz 1999; Lachaume & Guyon 1999) were adjusted by 0.2 mag, as indicated by our photometry of A2.0 stars described above. Gunn *r*-band observations made with the Palomar 1.5 m telescope (Gal et al. 1999) were reduced to Cousins *R* assuming $r-R = 0.45$. Observations using the ROTSE-I telephoto array

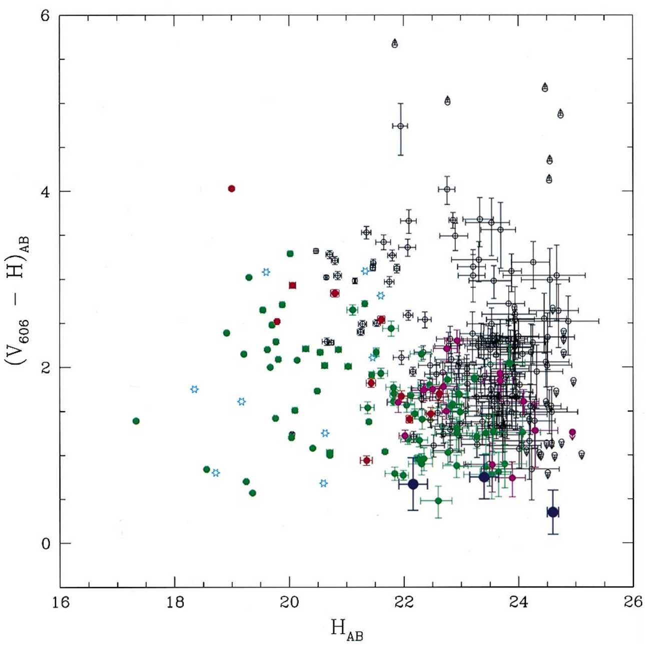

FIG. 3.—Host galaxies of GRB 970228, GRB 980703, and GRB 990123 on a color-magnitude diagram along with objects in the HDF. The stars are displayed as light blue stars. The galaxies in the HDF with spectrophotometric redshift are shown in green for $0 < z < 1$, red for $1 < z < 2$, and magenta for $z > 2$. The GRB host galaxies are shown in dark blue. The upper and lower limits are shown with arrows. Because we do not have an H magnitude for the host of GRB 990123, its K magnitude has been used instead. We would expect the measured H-values to be slightly brighter and bluer than shown, which would move the point down and to the left. From brighter to fainter mag (*left to right*) the GRB hosts are GRB 980703, GRB 990123, and GRB 970228.

and an unfiltered CCD (Akerlof & McKay 1999) were reported as approximate V magnitudes relative to catalog values for nearby reference stars. For these data, as well as the STIS data, we have estimated the R-band flux assuming $V-R \approx 0.2$, which is consistent with the measured colors of the transient at later times (Masetti et al. 1999).

We have analyzed the OT light curve in terms of a broken power law. As seen in Figure 2, at least three power-law segments are required to fully characterize the data. First, it is important to note that the measured power-law index at early times depends strongly on the assumed time origin. One common choice is the BATSE trigger time. However, this time is dependent on the design of the BATSE instrument, and particularly on the trigger energy band, since both the gamma-ray onset and duration were strongly energy dependent. The OSSE and COMPTEL instruments on *CGRO* detected a much narrower burst from GRB 990123 at MeV energies (Matz et al. 1999; Connors et al. 1999) than did BATSE in the hard X-ray. In Figure 2, we have chosen the time origin to be the time-of-peak hard X-ray and gamma-ray emission, which was independent of energy. With this choice of origin, the ROTSE (Robotic Optical Transient Search Experiment) data are well described by a simple power-law decay, with $\beta = 1.6$. Using the BATSE trigger as an origin would steepen the curve at early times and would produce a poorer fit.

Independent of the choice of time origin, R-band observations made between 0.16 and 2.75 days after the GRB are well described by a power law with index $\beta = 1.09 \pm 0.05$. The data are consistent with a break to this shallower decay slope ~15 minutes after the GRB, although more complicated light-curve behavior during the data gap between 10 minutes and 3.8 hr cannot be ruled out. Beginning 1 week after the GRB (Yadigaroglu et al. 1999), the data are consistently fainter than the extrapolation of the $\beta = 1.09$ power law; the OT magnitude measured by STIS is ~1.5 mag fainter than expected. If the fading behavior of the transient since day 4 is described by another power law, its slope must be at least as steep as $\beta = 1.8$, as can be seen in Figure 2, but a slope as steep as $\beta = 2.5$ cannot be ruled out. Determining whether this is a true break in the long-term fading behavior or a temporary fluctuation around a long-term $t^{-1.1}$ power law (as was seen in the GRB 970228 light curve; Fruchter et al. 1999b) will require further observations. If the OT continues to fade at $\beta = 1.8$, it will become essentially undetectable, even from *HST*, in the spring of 1999.

There are numerous possible physical causes for the observed breaks in the OT light curve, and in the absence of broadband spectral information, a definitive classification of temporal breaks is impossible. One physically plausible way to account for the early break from steep decay to shallower decay at early times is to suppose that the early ($\lesssim 10^{-2}$ days), rapidly fading optical flash arises in the reverse shock that propagates from the fireball–interstellar medium (ISM) boundary back into the ejecta material, while the more slowly fading optical emission seen on timescales of a few hours arises in the forward shock propagating into the ISM (Sari & Piran 1999a, 1999b). A possibility for a break to a steeper power law at late times is the spread of the opening angle of a strongly beamed (or jet-dominated) flow (Rhoads 1997; Piran 1999). This occurs when fireball material has decelerated to $\Gamma \sim \theta^{-1}$, where θ is the opening angle of the beam. However, Mészáros & Rees (1999) have pointed out that a break may occur at this time due to the observer beginning to see the edge of the jet. They predict an increase in the power-law index of 0.75, which is approximately equal to the lower limit of the break observed here.

4. NATURE OF HOST GALAXY

Eleven OTs associated with GRBs have been reported, at least nine of which are well established, and with at most one exception these appear to lie on host galaxies (Hogg & Fruchter 1999). Reasonable models predict that in about 20% of cases, the host galaxy will be fainter than $R \sim 27$, too faint to be detected by the ground-based telescopes that have been used (Hogg & Fruchter 1999). Hence, the association between GRBs and galaxies is well established, leading to a reasonable presumption that a galaxy coincident with a GRB is its host. The particular case of GRB 990123 (as in GRB 970508; Metzger et al. 1997) is even stronger because spectra obtained by the Keck telesocpe and the Nordic Optical Telescope show a deep metal line absorption system at $z = 1.60$ (Kelson et al. 1999; Hjorth et al. 1999b) but no evidence of other absorption-line systems.

Given that the observed galaxy is at $z = 1.60$, what can we learn about it from the optical observations presented here and the K-band data reported by Bloom et al. (1999)? (Note that Bloom et al. also discuss the *HST* data analyzed here.) In Figure 3, we compare the colors of the host galaxy with those of other objects in the Hubble Deep Field North (HDF-N; Williams et al. 1996)[15] and with those of two other host gal-

[15] See also http://www.stsci.edu/ftp/science/hdf/clearinghouse/irim/irim_hdf.html, maintained at STScI by M. E. Dickinson (1997).

axies, GRB 980703 (Bloom et al. 1998a) and GRB 970228 (Castander & Lamb 1998; Fruchter et al. 1999b). As is common in papers on the HDF, the colors are shown in AB magnitudes (for all colors, AB mag 23.9 = 1 μJy). All three hosts lie on the locus that defines the bluest edge of observed galaxies. Unfortunately, there are few galaxies with spectroscopic redshifts $z \sim 1.6$ that are as faint as the host of GRB 990123; however, one can compare this object with galaxies in the HDF that have estimated spectroscopic redshifts of $z \sim 1.6$ using the catalog of Fernandez-Soto, Lanzetta, & Yahil (1999). One finds that the host is among the bluest of galaxies at that redshift in $V-K$, but it is not particularly bright. Indeed, there are on the order of a dozen galaxies in that catalog in the range $1.3 < z < 1.9$ that are brighter in the *blue* (rest-frame UV) than the host of GRB 990123. Therefore, while the host is rapidly star-forming for its mass (or population of old stars), it is not a particularly bright galaxy.

5. GRB PROGENITORS

The position of the GRB on the host can also provide information on the progenitors of these extraordinary outbursts. We now have four GRBs with *HST* imaging: GRB 970228 (Sahu et al. 1997; Fruchter et al. 1999b), GRB 970508 (Fruchter & Pian 1998), GRB 971214 Odewahn et al. 1998), and GRB 990123. In all four cases, the OT occurs superposed on the stellar field. Thus, neutron star–neutron star mergers, which on occasion should happen well outside the stellar field because of kicks given by supernovae at their birth (Dewey & Cordes 1987; Bloom, Sigurdsson, & Pols 1998b), are perhaps disfavored both by this evidence and by the fact stated earlier that nearly all OTs have host galaxies. However, it is possible that without a dense external working surface, no OT would appear (Mészáros & Rees 1993; Sari & Piran 1997), and so by only localizing GRBs with bright OTs, we may be selecting for events that occur in stellar fields.

If all GRBs at cosmological distances are produced by the same mechanism, then the images of GRB 970228 would have ruled out active galactic nuclei (AGNs) as the source of GRBs: GRB 970228 lies at the edge of an undistinguished galactic disk. On the other hand, it is difficult to use GRB 990123 as further evidence against AGNs, for if one were to ask what local galaxy the host of GRB 990123 resembles, one might well choose NGC 4038/4039—the "Antennae," the most well-known galaxy merger (Whitmore et al. 1995). In the early stages of merger, the massive black hole(s) need not be near the apparent center of the remnant. Furthermore, if more than one mechanism causes cosmological GRBs, then one must wonder whether the remarkable $0''.01$ coincidence of GRB 970508 with the center of that regular host galaxy (Fruchter et al. 1999a) suggests the presence of a nuclear starburst or a massive black hole.

We wish to thank Steven Beckwith, the Director of STScI, for using director's discretionary time to observe GRB 990123 and for making the data public. We also thank Jen Christensen for assistance in creating appropriate STIS dark files. Note that the reduced *HST* images discussed in this Letter can be retrieved in FITS format at http://www.stsci.edu/˜fruchter/GRB/990123.

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