HST 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 HST and Palomar optical images of the field of GRB 990123, obtained on 8 and 9 February 1999. We find that the optical transient (OT) associated with GRB 990123 is located on an irregular galaxy, with magnitude $V = 24.20 \pm 0.15$. The strong metal absorption lines seen in the spectrum of the OT, along with the low probability of a chance superposition, lead us to

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conclude that this galaxy is the host of the 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 on 1999 Feb 9.05, $V = 25.45 \pm 0.15$, is about 1.5 mag fainter than expected from 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 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

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 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 $V \sim 9$ about 40 seconds 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 GRB redshift to be at least this great. If the gamma-ray burst emission was directed isotropically, the implied energy release is $\gtrsim 2 \times 10^{54}$ ergs.

Recognizing the importance of rapid observations of this object and the extraordinary level of interest in the astronomical community, *Hubble Space Telescope* (HST) observations were scheduled using director's discretionary time, for immediate public release (Beckwith 1999b; Beckwith 1999a). 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. 1999a). In this paper we present a more detailed analysis, and combine the HST data with further optical images 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.

The Observations

The field of GRB 990123 was observed by HST over the course of three orbits between 8 February 23:06:54 UT and 9 February 03:21:43 UT, using 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. Remaining cosmic rays and hot pixels were eliminated and the images combined using the Drizzle algorithm and associated techniques (Fruchter & Hook 1999). The final output image was created with an output pixel size of $0\farcs025$ 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 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 5%. The total counts in a box $2\farcs5$ 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.* (1999c) for further discussion of the STIS/CCD and its photometric calibration. We find that on 1999 Feb 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 paper 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 Feb 8.4-8.5 UT (approximately 12 h before the HST observations). The detector in COSMIC is a 2048x2048 CCD with

24 micron pixels, projecting to 0.28” on the sky. Three dithered 300 s exposures were obtained in B-band, 3x300 s in V, and 4x300 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 to 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, and including a rough correction to large aperture 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 mags 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).

The Light Curve of the 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 and Halpern (1999) and Halpern *et al.* (1999) to the same standards. Other observations, including Zhu and Zhang (1999), Zhu, Chen and 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 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 $V - R \approx 0.2$, 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 Fig. 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 strongly dependent on the particular 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 Fig. 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 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 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, though more complicated light curve behavior during the data gap between 10 min and 3.8 hrs cannot be ruled out. Beginning one 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 mags fainter than expected. If the fading behavior of the transient since day four is described by another power law, its slope must be at least as steep as $\beta = 1.8$, as can be seen in Fig. 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.* 1999c) 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-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; Sari & Piran 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 and 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.

The Nature of the 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 1998). Reasonable models predict that in about 20% of cases the host galaxy will be fainter than R $\sim$ 27, and thus too faint to be detected by the ground-based telescopes that have been used (Hogg & Fruchter 1998). The association between GRBs and galaxies is hence 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 970508, Metzger *et al.* 1997) is even stronger, because spectra obtained by the Keck and NOT telescopes 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: Bloom *et al.* also discuss the HST data analyzed here.) In Fig. 3, we compare the colors of the host galaxy with those of other objects in the HDF-N (Williams et al. 1996; Dickinson 1997) and with those of two other host galaxies, GRB 980703 (Bloom et al. 1998) and GRB 970228 (Castander & Lamb 1998; Fruchter et al. 1999c). 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 which 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 to galaxies in the HDF which have estimated spectroscopic redshifts of $z \sim 1.6$ using the catalog of Fernandez-Soto, Lanzetta and 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 of order a dozen galaxies in that catalog in the range $1.3 < z < 1.9$ which 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.

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: 970228 (Sahu et al. 1997; Fruchter et al. 1999c), 970508 (Fruchter & Pian 1998), 971214 (Odewahn et al. 1998) and 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 due to kicks given by supernovae at their birth (Dewey & Cordes 1987; Bloom, Sigurdsson, & Pols 1998), 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), so by only localizing GRBs with bright OTs we may be selecting for events which 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 AGN 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 AGN, 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 $0\farcs01$ coincidence of GRB 970508 with the center of that regular host galaxy (Fruchter et al. 1999b) suggests the presence of a nuclear starburst or a massive black hole.

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Note: The reduced HST images discussed in this paper can be retrieved in FITS format from http://www.stsci.edu/∼fruchter/GRB/990123. The GCN circulars mentioned in the bibliography are available from http://gcn.gsfc.nasa.gov.

REFERENCES

Akerlof, C. W., & McKay, T. A. 1999. IAU circular 7100

Beckwith, S. 1999a, GCN notice 254

Beckwith, S. 1999b, GCN notice 245

Bloom, J. S., et al. 1998, ApJ, 508, L21

Bloom, J. S., et al. 1999, ApJ, submitted, astro-ph/9902182

Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1998, MNRAS, submitted

Castander, F. J., & Lamb, D. Q. 1998, in Gamma Ray Bursts: The 4th Huntsville Symposium, ed. C. A. Meegan, R. D. Preece, & T. M. Koshut (AIP Conference Proceedings, 428), 520

Connors, A., Kippen, R. M., Barthelmy, S., & Butterworth, P. 1999, GCN notice 230

Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780

Dickinson, M. E. 1997, http://www.stsci.edu/ftp/science/hdf/clearinghouse/irim/irim_hdf.html

Fernandez-Soto, A., Lanzetta, K., & Yahil, A. 1999, ApJ, in press, astro-ph/9809126

Feroci, M., Piro, L., Frontera, F., Torroni, V., Smith, M., Heise, J., & in 't Zand, J. 1999. IAU circular 7095

Fruchter, A., & Pian, E. 1998, GCN notice 151

Fruchter, A., Sahu, K., Ferguson, H., Livio, M., & Metzger, M. 1999a, GCN notice 255

Fruchter, A. S., & Hook, R. N. 1999, PASP, submitted, astro-ph/9808087

Fruchter, A. S., et al. 1999b, ApJ, submitted, astro-ph/9903236

Fruchter, A. S., et al. 1999c, ApJ, in press, astro-ph/9807295

Gal, R. R., Odewahn, S. C., Bloom, J. S., Kulkarni, S. R., & Frail, D. A. 1999, GCN notice 207

Garnavich, P., Jha, S., Stanek, K., & Garcia, M. 1999, GCN notice 215

Halpern, J. P., Yadigaroglu, Y., Leighly, K. M., & Kemp, J. 1999, GCN notice 257

Hjorth, J., et al. 1999a, GCN notice 219

Hjorth, J., Andersen, M. I., Pedersen, H., Zapatero-Osorio, M., Perz, E., & A. J. Castro T. 1999b, GCN notice 249

Hogg, D. W., & Fruchter, A. S. 1998, ApJ, submitted, astro-ph/9807262

Kelson, D. D., Illingworth, G. D., Franx, M., Magee, D., & van Dokkum, P. G. 1999. IAU circular 7096

Lachaume, R., & Guyon, O. 1999. IAU circular 7096

Landolt, A. U. 1992, AJ, 104, 340

Masetti, N., et al. 1999, GCN notice 233

Matz, S. M., Share, G. H., Murphy, R., & Kurfess, J. D. 1999, GCN notice 231

Mészáros, P., & Rees, M. J. 1993, ApJ, 405, 278

Mészáros, P., & Rees, M. J. 1999, ApJ, submitted, astro-ph/9902367

Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., Steidel, C. C., Adelberger, K. L., Frail, D. A., Costa, E., & Frontera, F. 1997, Nature, 387, 879

Nilakshi, R. K. S. Y., Mohan, V., Pandey, A. K., & Sagar, R. 1999, Bull. Astr. Soc. India, in press

Odewahn, S. C., et al. 1998, ApJ, 509, L5

Ofek, E., & Leibowitz, E. M. 1999. IAU circular 7096

Piran, T. 1999, Phys. Rep., in press

Rhoads, J. E. 1997, ApJ, 487, L1

Sagar, R., Pandey, A. K., Mohan, V., Nilakshi, R. K. S. Y., Bhattacharya, D., & Castro-Tirado, A. J. 1999, accepted, astro-ph/9902196

Sahu, K. C., et al. 1997, Nature, 387, 476

Sari, R., & Piran, T. 1997, ApJ, 485, 270

Sari, R., & Piran, T. 1999a, preprint, astro-ph/9902009

Sari, R., & Piran, T. 1999b, preprint, astro-ph/9901338

Skiff, B. A. 1999. IAU circular 7098

Sokolov, V., Zharikov, S., Nicastro, L., Feroci, M., & Palazzi, E. 1999, GCN notice 209

Veillet, C. 1999, GCN notice 253

Whitmore, B. C., Schweizer, F., Leitherer, C., Born, K., & Robert, C. 1995, AJ, 106, 1354

Williams, R. E., et al. 1996, AJ, 112, 1335

Yadigaroglu, I. A., & Halpern, J. P. 1999, GCN notice 248

Yadigaroglu, I. A., Halpern, J. P., Uglesich, R., & Kemp, J. 1999, GCN notice 242

Zhu, J., Chen, J. S., & Zhang, H. T. 1999, GCN notice 217

Zhu, J., & Zhang, H. T. 1999. IAU circular 7095

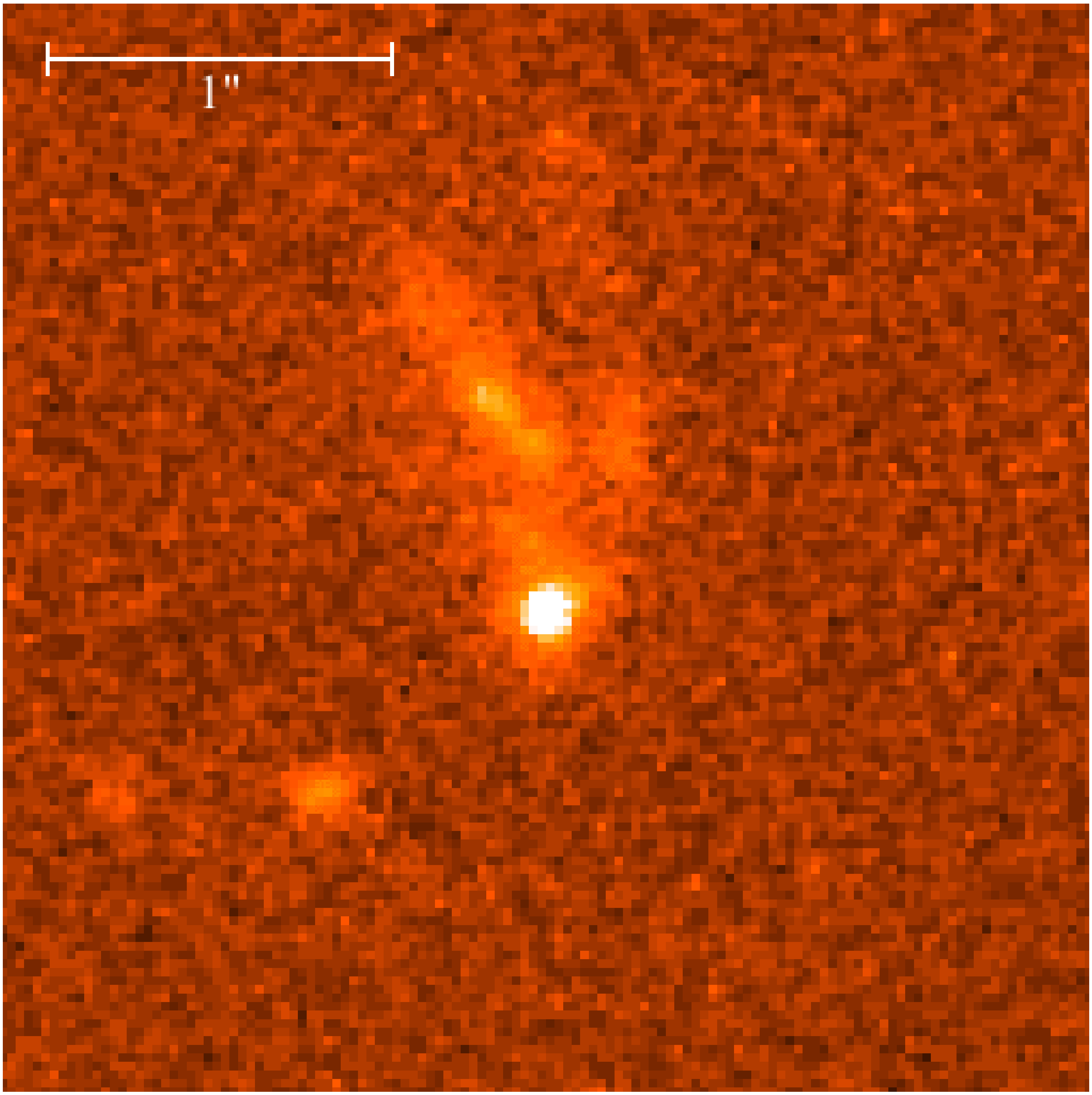
This preprint was prepared with the AAS LaTeX macros v4.0.

Figure Captions

Figure 1: The 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, East to the left. The two small objects to the south-east 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.

Figure 2: The R band light curve of the OT associated with GRB 990123. All points, except for the HST point (solid fill, on right), 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 (1σ), arrows indicate 95% confidence upper limits.

Figure 3: The host galaxies of GRB 970228, 980703 and 990123 on a color-magnitude diagram along with objects in the HDF. Stars are displayed as light blue stars. 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. 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 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 980703, 990123, 970228.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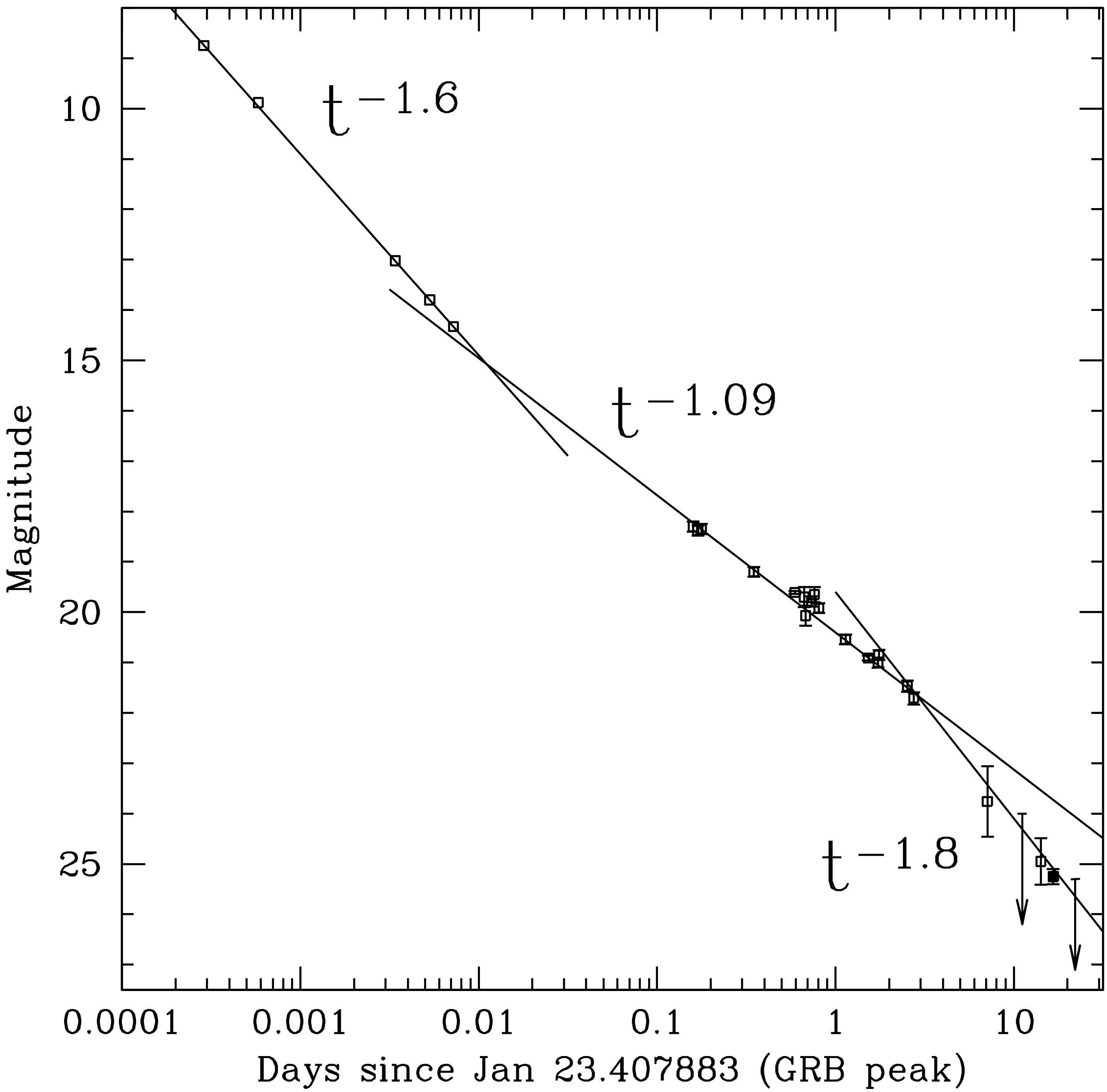
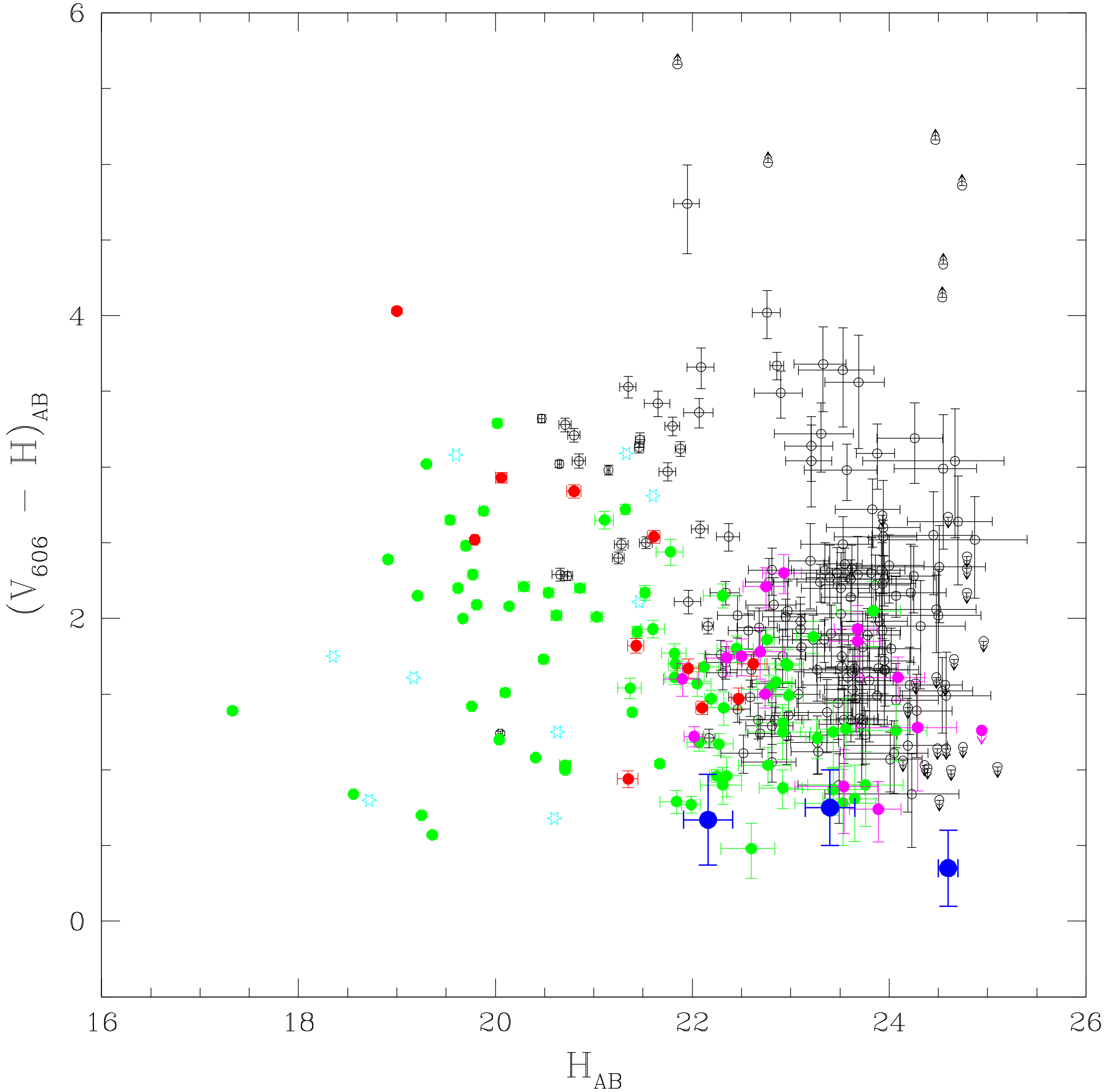


$t^{-1.6}$
$t^{-1.09}$
$t^{-1.8}$
Magnitude
10
15
20
25
0.0001
0.001
0.01
0.1
1
10
Days since Jan 23.407883 (GRB peak)


6
4
2
0
$(V_{606} - H)_{AB}$
16
18
20
22
24
26
H_{AB}