HST/STIS Observations of the Optical Counterpart to GRB 970228

Andrew S. Fruchter\textsuperscript{1}, Elena Pian\textsuperscript{2}, Stephen E. Thorsett\textsuperscript{3}, Rosa Gonzalez\textsuperscript{1}, Kailash C. Sahu\textsuperscript{1}, Max Mutchler\textsuperscript{1}, Filippo Frontera\textsuperscript{2,6}, Titus Galama\textsuperscript{7}, Paul Groot\textsuperscript{7}, Richard Hook\textsuperscript{9}, Chryssa Kouveliotou\textsuperscript{8}, Mario Livio\textsuperscript{1}, Duccio Macchetto\textsuperscript{1}, Jan van Paradijs\textsuperscript{7}, Eliana Palazzi\textsuperscript{2}, Larry Petro\textsuperscript{1}, Marco Tavani\textsuperscript{4,5}

\textsuperscript{1}Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
\textsuperscript{2}Istituto di Tecnologie e Studio delle Radiazioni Extraterrestri, C.N.R., Via Gobetti 101, I-40129 Bologna, Italy
\textsuperscript{3}Joseph Henry Laboratories and Dept. of Physics, Princeton University, Princeton, NJ 08544, USA
\textsuperscript{4}Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
\textsuperscript{5}Istituto di Fisica Cosmica e Tecnologie Relative, C.N.R., Via Bassini 15, I-20133 Milano, Italy
\textsuperscript{6}Dip. Fisica, Università di Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy
\textsuperscript{7}Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
\textsuperscript{8}NASA Marshall Space Flight Center, ES-84, Huntsville, AL 35812, USA
\textsuperscript{9}Space Telescope European Coordinating Facility, D-85748 Garching, Germany

Abstract. We report on observations of the fading optical counterpart of the gamma-ray burst GRB 970228, made on 4 September 1997 using the STIS CCD on the Hubble Space Telescope. The unresolved counterpart is detected at $V = 28.0 \pm 0.25$, consistent with a continued power-law decline with exponent $-1.14 \pm 0.05$. No proper motion is detected, in contradiction of an earlier claim. The counterpart is located within, but near the edge of, a faint extended source with diameter $\sim 0'8$ and integrated magnitude $V = 25.7 \pm 0.25$. Comparison with WFPC2 data taken one month after the initial burst and NTT data taken on March 13 shows no evidence for fading of the extended emission.

After adjusting for the probable Galactic extinction in the direction of GRB 970228 of $A_v \sim 0.7$, we find that the observed nebula is consistent with the sizes of galaxies of comparable magnitude found in the Hubble Deep Field and other deep HST images, and that only $2\%$ of the sky is covered by galaxies of comparable magnitude and similar or greater surface brightness. We therefore conclude that the extended source observed about GRB 970228 is most likely a galaxy at moderate redshift, and is almost certainly the host of the gamma-ray burst.
INTRODUCTION

Identification and analysis of long wavelength counterparts of gamma-ray bursts (GRBs) has for many years been considered a promising path towards understanding the nature of the burst events. But while many attempts have been made to identify GRB counterparts (Schaefer et al. 1987, Schaeffer 1992, Fenimore et al. 1993, Larson 1997) until recently the uncertainties in the position of the gamma-ray sources proved too large to allow sufficiently sensitive surveys for associated optical transients (OTs). The situation improved dramatically in early 1997, when gamma- and X-ray observations by the BeppoSAX satellite provided a sub-arcminute position of burst GRB 970228, allowing the first firm optical identification of a fading GRB counterpart (van Paradijs et al. 1997). A second optical GRB counterpart, this time of GRB 970508, was discovered two months later (Bond 1997, Djorgovski et al. 1997).

Although broadly similar in their fading behavior, phenomenological differences between the two counterparts in the weeks after their discoveries seemed to compound rather than clarify the mystery of the GRBs. HST imagery of GRB 970228 suggested the presence of a nebulosity centered 0′.3 arcsecond from the point-like fading transient source (Sahu et al. 1997), while no extended source brighter than $R = 24.5$ has been found near GRB 970508 (Pian et al. 1997). Furthermore, a proper motion of 550 mas yr$^{-1}$ was reported (Caraveo et al. 1997) for GRB 970228, though the measurement was disputed (Sahu et al. 1997b). Additionally, tentative evidence for the fading of the adjacent nebulosity (Metzger et al. 1997a) was proposed. Either result would ineluctably lead to the conclusion that GRB 970228 was a Galactic event. In contrast, the measurement of absorption lines with redshift $z \geq 0.835$ in the spectrum of GRB 970508 (Metzger et al. 1997b) demonstrates its extragalactic nature.

To help resolve the situation, we have reobserved the GRB 970228 with HST six months after the initial outburst. Although the earlier HST observations of GRB 970228 employed WFPC2, we have availed ourselves of the newly installed STIS CCD camera. The excellent throughput and broad bandpass of this instrument, combined with the long time baseline since the gamma-ray burst, provide us with a superb opportunity to study the nature of the source and its environment.

OBSERVATIONS, IMAGE REDUCTION AND PHOTOMETRY

The field of GRB 970228 was imaged during two HST orbits on 1997 September 4 from 15:50:33 to 18:22:41 UT, using the STIS CCD in Clear Aperture (50CCD) mode. Two exposures of 575s each were taken at each of four dither positions for a total exposure time of 4600s. The exposures were dithered to allow removal of hot
FIGURE 1. The STIS image of GRB 970228. North is up; East is to the left. An arrow points to the OT. The nebula can be seen extending to the north of the OT.

pixels and to obtain the highest possible resolution. 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 Drizzle and Blot algorithms developed for the Hubble Deep Field (HDF) (Williams et al. 1996, Fruchter and Hook 1997). An output pixel size of 0\arcsec0.025 across, or one-half the size of the input pixels, was used.

The magnitude of the OT was determined from the drizzle image via aperture photometry. The flux in an aperture of radius four drizzled pixels, or 0\arcsec, was determined, and our best estimate of the surrounding nebular background was subtracted. An aperture correction of 0.50 magnitudes was derived for this aperture using the bright star visible in Figure 1 to the west of the nebula. We find a total magnitude for the point source OT of V = 28.0 ± 0.25.

In figure 2 we plot the magnitude of the OT as a function of time since the burst last February. The STIS magnitude has been converted to R by interpolating the WFPC2 V and I colors. A power law of the form $f(t) = a_0 \ast t^\alpha$ has been fitted to the HST points and extrapolated back to earlier times. We find a best
FIGURE 2. The R magnitude of the OT as a function of time. A nebular R magnitude of 25.3 has been subtracted from all non-HST magnitudes. The line shows the best fit power law through the three HST observations (shown in black). See Rees and Meszaros (1997) for a possible explanation for the deviation of the observed points deviation from the power law.

Fit of \( \alpha = -1.14 \pm 0.05 \). All non-HST photometry has been adjusted under the assumption that the R magnitude of the nebula is 25.3, which was obtained by interpolating the STIS V and WFPC2 I measurements (see below).

We determined the magnitude of the nebula by summing all pixels in a region of approximately 1.4 sq. arcsec. surrounding the object. The flux of the point source was then subtracted from the sum. We derive a magnitude of \( V = 25.7 \pm 0.25 \) for the nebula. Due to the very wide bandpass of the STIS clear observations (the only constraint on the bandpass comes from the optics and the response of the CCD), the primary source of photometric error is the correction of the STIS magnitude for the color of the object. This is particularly large for the nebula, as the only measurement of the color of this object comes from the previous, rather noisy, Planetary Camera observations of the field (these images are discussed in more detail in the next section).

In order to determine whether the optical transient displayed proper motion or
the nebula faded we have compared the STIS images to the previous HST WFPC2 images obtained of GRB 970228 (Sahu et al. 1997a). The images taken on March 26 with WFPC2 provide a baseline of 162 days and are used here to look for proper motion of the optical transient.

The positions of the four reference stars used in Sahu et al. (1997b) agree with their positions in the STIS images to within the expected uncertainties of 2 to 3 mas, which shows that the transformations between the two images have been done correctly. The uncertainty in the position of the OT is about 10 mas in each of the two colors. We find that any motion of the GRB between the two epochs is less than about 16 mas. This corresponds to a motion of less than 36 mas per year. This is a factor of \( \sim 15 \) less than the value claimed by Caraveo et al. (1997), and improves the upper limit on the proper motion reported by Sahu et al. (1997b) by a factor of six.

To check on the photometry of the optical transient and nebula, the point source magnitude was determined by using circular apertures of radii 1 and 3 pixels in the WFPC2 images and adjusting the observed fluxes according to the aperture corrections found by Holtzman et al. (1995). The nebular magnitude was redetermined in the WFPC2 images by taking the sum of all counts above sky in a box approximately 1′′.5 × 1′′.0, and subtracting the counts (estimated as above) attributable to the point source. The position of this box was determined by the position of the nebula in the STIS image. It is, however, somewhat larger than the observed nebula in all directions. Averaging together the two WFPC2 observations, we obtain an I magnitude of 24.4 \( \pm \) 0.2 and a V magnitude of 25.5 \( \pm \) 0.2. These magnitudes are easily consistent with the STIS observation.

We have also re-examined the NTT observation of March 13 (Galama et al. 1997) to further test whether the nebular magnitude may have varied with time. We have again used the stellar image \( \sim 2′′.5 \) to the west of the OT as a point spread function. We find that we can subtract a point source from the position of the OT which is fainter than the extrapolation of the power-law, yet which leaves behind a “nebula” which is as faint, or fainter than, the HST nebular magnitude. Thus, we find no evidence that the nebula has changed magnitude with time.

**ASTROPHYSICAL IMPLICATIONS**

There is little room for doubt that the fading point source is associated with the gamma-ray event. Between 28 February and 4 September 1997, the source faded by a factor of about 350, and as shown in Figure 2, this dramatic fall in luminosity largely followed a power-law whose index, \(-1.14 \pm 0.05\), is within the errors indistinguishable from the index of power-law decline of the optical counterpart to GRB 970508 (Pian et al. 1997). Given the lack of any other astrophysical objects with similar behavior, and the theoretical prediction of a power-law fall-off with time of the luminosity of afterglow (Meszaros and Rees 1997), we believe there is no reasonable alternative to the conclusion that we are observing the optical afterglow
Furthermore, in simple blast wave models, a break in the power-law to $F \sim t^{-1.8}$ is expected (Wijers, Rees and Meszaros 1997) when the remnant enters a Sedov-Taylor phase after sweeping up a rest mass energy equal to its initial energy $E$ at time:

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

(1)

where $n$ is the density of the surrounding medium in protons per cubic centimeter. However, were the GRB a Galactic rather than an extragalactic phenomenon, the amount of energy available would only be of order $10^{41}$ ergs, and for any imaginable density the break would occur on a timescale of days rather than many months. Therefore, the power law fit is in itself a strong argument for the extragalactic nature of the burst.

If the burst is extragalactic, then it is natural to inquire whether the apparently constant nebula seen under the OT is the host galaxy. The Galactic extinction in the direction of GRB 970228 has been estimated as $A_v \sim 0.7$ (Burstein and Heiles 1982, Schlegel, Finkbeiner and Davis 1997) – a figure that we have been able to independently verify by comparing the counts and colors of background galaxies in the WFPC2 field with the HDF. Adjusting the surface brightness limit to reflect the $\sim 0.7$ mags of extinction in the direction of GRB 970228, we find that only about 2% of the sky in the HDF is covered by galaxies of comparable magnitude, and that the size of the putative host of GRB 970228, while larger than the mean 25th magnitude galaxy in the HDF, is not, by any means, extraordinary.

Although we have no spectroscopic information on the redshift of this object nor do we have sufficient colors to attempt a photometric redshift (though planned NICMOS observations may rectify this problem), we can attempt to place a crude constraint on the plausible redshift simply from the luminosity of the object. Were the object closer than $z \sim 0.5$ it would be more than four magnitudes fainter than $L_\ast$ (Lilly et al. 1995), and this is unlikely even given the steep luminosity function at that redshift (Ellis et al. 1996). On the other hand, the apparent host is as bright as any “U dropout” in the HDF (Madau et al. 1996), and therefore would be an unusually bright galaxy were it at the typical redshift of these dropouts, $z \sim 2.5$. Thus a plausible redshift range for the host is $0.5 \lesssim z \lesssim 2.5$. However, while the luminosity function of galaxies is a rather blunt instrument for estimating the redshifts of GRB hosts, we will show in the journal paper associated with this work that GRB hosts may prove a rather better tool for determining the luminosity function of galaxies.

We thank the Director of STScI, Bob Williams, for allocating Director’s Discretionary time to this program.

REFERENCES

1. Bond, H. E. 1997, IAUC, 6654.
2. Burstein, D. and Heiles, C. 1982, *Astron. J.*, **87**, 1165–1189.
3. Caraveo, P. A., Mignani, R. P., Tavani, M., and Bignami, G. F. 1997, *Astr. Astrophys.*, **326**, L13–L16.
4. Djorgovski, S. G. *et al.* 1997, *Nature*, **387**, 876–878.
5. Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., and Glazebrook, K. 1996, *Mon. Not. R. Astr. Soc.*, **280**, 235–251.
6. Fenimore, E. E. *et al.* 1993, *Nature*, **366**, 40.
7. Fruchter, A. S. and Hook, R. N. 1997, in *Applications of Digital Image Processing XX*, *Proc. SPIE*, Vol. 3164, ed. A. Tescher, SPIE, 120–125.
8. Galama, T. *et al.* 1997, *Nature*, **387**, 479–481.
9. Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., and Worthey, G. 1995, *Publ. Astr. Soc. Pacific*, **107**, 1065+.
10. Larson, S. B. 1997, *Astrophys. J.*, **491**, 86.
11. Lilly, S. J., Tresse, L., Hammer, F., Crampton, D., and Le Fevre, O. 1995, *Astrophys. J.*, **455**, 108–124.
12. Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., and Fruchter, A. S. 1996, *Mon. Not. R. Astr. Soc.*, **283**, 1388–1404.
13. Meszaros, P. and Rees, M. J. 1997, *Astrophys. J.*, **476**, 232.
14. Metzger, R. M., Cohen, J. G., Chaffee, F. H., and Blandford, R. D. 1997a *IAUC* 6676.
15. Metzger, R. M., Djorgovski, S. G., Kulkarni, S. R., Steidel, C. C., Adelberger, K. L., Frail, D. A., Costa, E., and Frontera, F. 1997b, *Nature*, **387**, 878.
16. Pian, E. *et al.* 1998, *Astrophys. J.*, **492**, L103.
17. Rees, M. J. and Meszaros, P. 1997. astro-ph/9712252.
18. Sahu, K. C. *et al.* 1997a, *Astrophys. J.*, **489**, L127.
19. Sahu, K. C. *et al.* 1997b, *Nature*, **387**, 476.
20. Schaefer, B. 1992, in *Gamma-Ray Bursts: Observations, Analyses and Theories*, ed. C. Ho, R.I. Epstein, and E.E. Fenimore, Cambridge University Press, 107.
21. Schaefer, B. E. *et al.* 1987, *Astrophys. J.*, **313**, 226–230.
22. Schlegel, D. J., Finkbeiner, D. P., and Davis, M. 1997. astro-ph/970327.
23. van Paradijs, J. *et al.* 1997, *Nature*, **386**, 686–689.
24. Wijers, R. A. M. J., Rees, M. J., and Meszaros, P. 1997, *Mon. Not. R. Astr. Soc.*, **288**, L51–L56.
25. Williams, R. E. *et al.* 1996, *Astron. J.*, **112**, 1335–1389.