A PHOTOMETRIC INVESTIGATION OF THE GRB 970228 AFTERGLOW AND THE ASSOCIATED NEBULOSITY

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Received 1998 July 20; accepted 1999 May 8

ABSTRACT

We carefully analyze the WFPC2 and STIS images of GRB 970228. We measure magnitudes for the GRB 970228 point-source component in the WFPC2 images of \((V = 26.20 \pm 0.14, I_c = 23.94 \pm 0.10)\) and \((V = 26.52 \pm 0.16, I_c = 24.31 \pm 0.15)\) on March 26 and April 7, respectively; and \(R_c = 27.09 \pm 0.14\) on September 4 in the STIS image. For the extended component, we measure magnitudes of \(R_c = 25.48 \pm 0.22\) in the combined WFPC2 images and \(R_c = 25.54 \pm 0.23\) in the STIS image, which are consistent with no variation. This value is fainter than previously reported (Galama et al. 1998) and modifies the previously assumed magnitudes for the optical transient when it faded to a level at which the extended-source component contribution was not negligible, alleviating the discrepancy with a power-law temporal behavior. We also measure a color of \((V_606 - I_{814})_F = -0.18 \pm 0.51\) for the extended-source component. Taking into account the extinction measured in this field, this color implies that the extended source is most likely a galaxy with ongoing star formation.

Subject headings: gamma rays: bursts — galaxies: photometry — galaxies: starburst

1. INTRODUCTION

On 1997 February 28 the Gamma-Ray Burst Monitor aboard the BeppoSAX satellite detected a gamma-ray burst (GRB), and the Wide Field Camera (WFC) instrument imaged it. A few hours later, the BeppoSAX team disseminated a positional error circle of 3° radius to the astronomical community (Costa et al. 1997a). Eight hr after the burst, and again 3 days later, the BeppoSAX Narrow-Field Instrument observed this error circle, revealing a rapidly fading X-ray source at a position that was consistent with both the WFC position and with the Interplanetary Network (IPN) annulus. ASCA (Yoshida et al. 1997) and ROSAT (Frontera et al. 1997, 1999) observations showed that the X-ray source continued to fade over the following 2 weeks. They provided a 10° radius position for this source.

Ten days after the burst, Groot et al. (1997a) announced the detection of a fading optical source \((V = 21.3)\), which turned out to be the first optical counterpart of a GRB detected. Two days later Groot et al. (1998b) and Metzger et al. (1997b) reported the presence of an extended source \((R = 23.8)\) at a position consistent with that of the optical transient (OT). Groot et al. (1997b) and van Paradijs et al. (1997) claimed that the extended source was the host galaxy, but a subsequent ground-based optical observation indicated that the extended source had faded (Metzger et al. 1997a). Once the position of the afterglow was firmly established, early observations were revisited and new ones taken. These new detections provide a better sampling of the optical afterglow behavior (Klose, Stockelm, & Tufts 1997; Margon et al. 1997; Soifer et al. 1997; Metzger et al. 1997a; Pedichini et al. 1997a; Djorgovski et al. 1997). The Hubble Space Telescope (HST) Wide Field and Planetary Camera 2 (WFPC2) provided another breakthrough. Observations made on March 26 revealed two components, one consistent with a point source and the other consistent with an extended source (Sahu et al. 1997a). Further observations on April 7 showed that the point source was fading, while the extended source remained unchanged, within the observational uncertainties (Sahu et al. 1997b). The GRB 970228 optical afterglow was observed again with HST on September 4 using the Space Telescope Imaging Spectrograph (STIS) (Fruchter et al. 1997). The point source showed further dimming, while the extended component showed no appreciable variation, after correction of the magnitudes reported by Sahu et al. (1997c) (Fruchter et al. 1997, 1998).

Reichart (1998) and Wijers, Rees, & Mészáros (1997) discussed early observations of GRB 970228 in the context of theoretical models. They found that the gamma-ray burst afterglow behavior was consistent with the expectations of relativistic fireball models. Later, Galama et al. (1998) (revising and updating Galama et al. 1997) compiled the most relevant photometric measurements of GRB 970228, converting them into a single photometric band when necessary and subtracting the contribution of the extended-source component. They fitted the optical transient temporal evolution to a power law with \(\alpha = -1.10 \pm 0.04\) \((\chi^2 = 2.3, 9\) degrees of freedom [dof]).

In a companion paper (Castander & Lamb 1999; hereafter CL99) extending our earlier results (Castander & Lamb 1998), we have determined the Galactic extinction toward GRB 970228, performing a careful analysis of the publicly available observations. González, Fruchter, & Dirsch (1999) and Fruchter et al. (1998) have also estimated the extinction toward the GRB 980228 field. Here we focus on the photometric properties of the pointlike and extended components revealed in the HST observations and analyze their magnitudes, taking into account the measured extinction. In §2 we detail our analysis of the WFPC2 and STIS HST images. In §3 we discuss our results, and in §4 we summarize our conclusions.

2. HST PHOTOMETRY

2.1. Wide Field and Planetary Camera 2 Observations

GRB 970228 was observed by the HST WFPC2 on March 26 and April 7. In both observations the optical counterpart
was centered in the middle of the PC1 CCD, but there was a 2:40 difference in rotation angle. At both epochs, four exposures were taken in the F606W filter and two exposures were taken in the F814W filter, totalling 4700 and 2400 s, respectively (Sahu et al. 1997c).

In order to accurately estimate the magnitudes and especially the errors of the objects in the GRB position, which consist of a faint point source coincident with an extended faint surface brightness component, we developed some specific software to carry out the photometry. First, we combined the observations in a fashion similar to the method used by standard software, eliminating cosmic rays by σ clipping with three different threshold passes cutting at 8, 5, and 3 σ and also eliminating hot pixels masked out by the standard reduction pipeline. After combining the images, we ended up with four values for every pixel: (1) total counts of nonrejected pixels, (2) number of valid nonrejected pixels used, (3) total exposure of combined pixels used, and (4) error on the total counts in (1), estimated as the square root of the counts plus the contribution of the readout noise.

We then calculated the centroid position of objects S1 and S2 (the brightest stars in the PC1 CCD at 2'9 west and 16'8 east from the GRB, respectively; see Fig. 2 of CL99 for a finding chart) and the point- and extended-source components of the GRB. Centering in these computed positions for each object, the sky was computed from 30 annuli differing in their outer radii. A different sky value with its associated variance was computed for pixels that had different numbers of rejections in the cosmic-ray and hot-pixel rejection process. We obtained the final sky value and its variance for each number of pixel rejections with a weighted mean of the 30 annuli sky and variance data. Subsequently, we calculated aperture photometry in circular and elliptical (only for the extended component of the GRB) apertures at radii and semimajor axes varying from 1 to 30 pixels around each object. We added the pixel values (and fractional pixel values at the edges) within the apertures, subtracting the sky values for the appropriate number of pixel rejections, taking into account the error of both counts and sky, and normalizing to a common exposure. Each aperture therefore had a properly computed count flux and error.

We used stars S1 and S2 to define the point spread function (PSF). Figure 1 shows the normalized counts for both stars at all apertures used, together with the approximate encircled energy curve for the PC1 given by Holtzman et al. (1995a), which serves as comparison.

Table 1 summarizes our photometric measurements. We first analyzed the point-source component. We measured its magnitude, minimizing the χ² of the fit of the inner radial bin counts of the point source to the same bins for stars S1 and S2 and the PC1 PSF, where the normalization of the stars is the free parameter being fitted. We fitted the inner 30 pixel radius circle counts to the three model PSFs. The extended component was measured in circular and elliptical apertures, beginning at the estimated centroid and extending out to 30 pixel radius/semimajor axis. We then plotted the counts enclosed in every aperture as a function of aperture radius/semimajor axis and assigned the counts of the extended and point components to the value at which the counts remained approximately unchanged with increasing radius. We estimated the error as the error in the aperture where the counts started to flatten, α ≃ 12 pixels (see Fig. 2). We found that the exact choice of the centroid and ellipticity did not affect our measurements. These measured counts and errors correspond to both the point and extended components, since both lie within the apertures where the counts flatten. We calculated the extended-component magnitude by subtracting the point-source contribution to the total counts. Once we had this first estimation of the extended source, we then estimated the extended-source contribution to the pixels where the point component was measured and redid the χ² fit to the point source including this contribution. Having obtained this new value and the previously measured point + extended counts, we again calculated the extended-component magnitude and its error.

2.2. Space Telescope Imaging Spectrograph Observations

On September 4 the STIS instrument on-board HST imaged the GRB 970228 from UT 4.6601 to 4.7657. Two exposures of 575 s each were taken in the clear aperture (50 CCD) mode at each of four dithered positions for a total exposure time of 4600 s. We retrieved the pipeline-processed images from the HST archive once they became public, almost 2 months after being taken. We reduced them in a fashion similar to that used for the WFPC2 images. We

| Table 1 | WFPC2 Magnitudes of the GRB Point and Extended Components |
|-----------------|---------------------------------|
| Band | Point | Date | Extended | Date |
| V606 | 26.09 ± 0.08 | 1997 Mar 26 | 25.91 ± 0.23 | 1997 Mar 26 |
| V606 | 26.42 ± 0.10 | 1997 Apr 07 | 26.25 ± 0.19 | 1997 Apr 07 |
| I614 | 25.37 ± 0.09 | 1997 Mar 26 | 26.50 ± 0.27 | 1997 Mar 26 |
| I614 | 25.74 ± 0.11 | 1997 Apr 07 | 26.05 ± 0.37 | 1997 Apr 07 |
| V | 26.20 ± 0.11 | 1997 Mar 26 | 25.85 ± 0.26 | Combined |
| R | 25.17 ± 0.09 | 1997 Mar 26 | 25.46 ± 0.22 | Combined |
| I | 23.94 ± 0.10 | 1997 Mar 26 | 24.84 ± 0.44 | Combined |
| V | 26.52 ± 0.18 | 1997 Apr 07 | ... | ... |
| R | 25.52 ± 0.11 | 1997 Apr 07 | ... | ... |
| I | 24.31 ± 0.11 | 1997 Apr 07 | ... | ... |

2 All four sets of images were clipped at these levels except the F814W 970407 set, which presented a higher background level and was clipped at a somewhat lower threshold in the last step (8, 5, and 2.5 σ).

3 Pixel scale: 0.0455 pixel.
again ended up with an image having four values per pixel: 
(1) total number of nonrejected counts, (2) number of valid 
nonrejected pixels used, (3) total nonrejected exposure, and 
(4) error on the total counts.

Table 2 summarizes our photometry. Count rates were 
computed as for the WFPC2 images (see § 2.1 and Fig. 3).

3. DISCUSSION

We have undertaken an effort to determine the photometry of the optical and extended components of the GRB 970228 optical counterpart, as observed by the HST WFPC2 and STIS instruments. We have tried to perform the best magnitude determination with a rigorous treatment of the errors. We started by combining the original pipeline-processed images, retaining the rejection information to propagate it into our error analysis. Our subsequent sky subtraction was based on a multiaperture estimation that takes into account the number of rejected pixels in the combination process. Although the sky varies depending on the exact area used to estimate it, our multiaperture estimation reduces problems that could arise from selecting an area with deviant values. Our error also takes into account the variance of the sky estimation due to the selected area. Although the fraction of rejected pixels per unit area is relatively stable throughout all regions of the images studied, we also apply a different sky correction depending on the number of rejected pixels.

We have chosen to determine the magnitude of the point-source component by fitting the inner counts radial profile to the PSF. We use the radial profile within the inner 3.0 pixels (0\'136) for the WFPC2 images and the inner 2.0 pixels (0\'1) for the STIS images, taking into account in a second phase the contribution of the extended component as well. The radius used in the STIS analysis was smaller, in an attempt to reduce the uncertainties of the contribution of the extended source, since the point source is significantly fainter in this observation. Once the fit is done, we extrapolate the PSF profile to obtain the total counts (see previous section for further details). We use the two brightest stars in the field, S1 and S2, and the Holtzman et al. (1995a) and
R. D. Robinson et al. 1997\textsuperscript{4} determination of the PSF for WFPC2 and STIS, respectively, as the model PSF to which the point-component data were fitted. Table 3 provides the reduced $\chi^2/\nu$ values for the different filters and epochs of the observations. Fits are acceptable in all cases except the April F606W and the STIS images. In both of these cases the radial count distribution profile is more extended than that of the stars and model PSF. Our choice of measuring method by profile fitting is not optimal in these two cases, but is more accurate than single-aperture photometry. The outermost radius we use in the fits encloses approximately 80\% and 65\% of the counts (WFPC2 and STIS images, respectively), so our extrapolation of the profile only contributes at most ~35\% of the total counts. If we change the outermost radius in the fits, our extrapolated total counts do not vary appreciably. Finally, we would like to emphasize that we include an estimated contribution of the extended component in the pixels measured when performing the fit.

We estimate the total counts of the extended + point components by elliptical aperture photometry (see § 2). We increase the semimajor axis until the counts flatten with radius. Because of different centroiding, the counts do not flatten at the same semimajor axis value in all cases. In Fig. 2 we can see how the number of counts levels off and remains approximately constant with increasing semimajor axis for the F606W filter, providing a relatively safe count estimation. For the F814W filter, however, the number of counts still varies somewhat at large radii. In this case the image combination was performed with only two images, and the cosmic ray/hot pixel removal is more difficult. For example, if we choose a lower threshold rejection in the combination process, the increase in the number of counts in the F814W April 7 image at semimajor axis values from 15 to 18 pixels disappears, since this feature is due to a count excess present in only one of the images, which was not rejected properly with the threshold used.

With the measured counts and exposure times, we compute ST magnitudes\textsuperscript{5} for the WFPC2 images (Table 1). For the STIS image, we present count rates (Table 2), since the STIS ST magnitude in open mode is not very useful, given that an assumed spectrum is required to convert STIS 50 CCD count rates to other broadband filter magnitudes. In order to compare the $HST$ observations with other ground-based magnitude measurements, we convert our values to Johnson-Cousins magnitudes. Instead of using color-transformation relations (Holtzman et al. 1995b), we fitted a spectrum to the observed colors, convolving the spectrum with the filter responses. We then compute the expected magnitude in a particular filter with the spectral fit.

We fitted a power-law spectrum for the point-source and a galaxy spectrum for the extended component. In both cases we assume a foreground $R_p = 3.1$ extinction law of $A_V = 1.09$ (CL99) and no intrinsic reddening at the source. Obviously, the reddening assumed for the point-source component is irrelevant, since the extinction law behaves approximately as a power law in the wavelength range used, and the only effect is a change in the power-law slope of the fit. The point-source spectrum is fitted at both epochs for the WFPC2 images. In order to compute standard filter magnitudes for the point source from the STIS number counts, we assume an $A_V = 1.09$ extincted power-law spectrum that gives the mean of the color between the two WFPC2 observations, $V_{606} - I_{814} = 0.70$. The errors in the magnitudes come from varying the power-law indices to allow for all possible values of the observed $V_{606} - I_{814}$ color in the WFPC2. We assumed that there was no color evolution for the point-source component from the March 26 and April 7 WFPC2 observations to the September 4 STIS observations.

We have combined the two WFPC2 observations in order to provide the best magnitudes and errors for the extended component. We add the measured counts, weighting them by their relative errors. With them, we compute the resulting magnitudes and errors. We obtain $V_{606} = 26.03^{+0.19}_{-0.16}$ and $I_{814} = 26.21^{+0.45}_{-0.33}$. For the extended source, we assume a galaxy spectrum to convert from the combined $HST$ measurements to standard filter magnitudes. To allow for the different spectra that are consistent with the observed color errors, we compute the color transformation for a variety of synthetic galaxy spectra that bracket the measured error in the $V_{606} - I_{814}$ color. Therefore, the errors in the standard filters include the measured color error plus the contribution due to the different spectral energy distributions (SED) allowed. Our search for SEDs compatible with the observed colors has been extensive but by no means complete. Nevertheless, we believe that the estimated contribution to the error due to the allowed SEDs is appropriate. In the STIS case, we proceed in a similar fashion to compute magnitudes from count rates fitting synthetic SEDs. The error quoted comes from the combination of the contribution due to the error in the measured count rate and the contribution due to the allowed SEDs as determined by the measured colors in the WFPC2 observations. Tables 1 and 2 present our measured magnitudes.

Once we have measured the point- and extended-source magnitudes, what can we learn about them? For the point-source component, the magnitudes we measure are consistent with those measured by Sahu et al. (1997c) in the $V$ band, but are 0.3 mag brighter in $I_c$. Overall, our computed color ($V - I_c = 2.23$) is redder than that of Sahu et al. ($V - I_c = 1.85$). Our $R_c$ magnitudes are, nevertheless, almost identical to those computed by Galama et al. (1997) from the data of Sahu et al. We are unable to comment on

\begin{table}
\centering
\caption{GRB Afterglow Point-Source Component Fit to PSF}
\begin{tabular}{llllll}
\hline
Fit & F606W(03/26) & F606W(04/07) & F814W(03/26) & F814W(04/07) & STIS(09/04) \\
\hline
$\chi^2/\nu$ & 0.73 & 5.71 & 0.21 & 0.38 & 5.77 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{4} Robinson’s examination of the STIS point-spread function is available at: http://www.stsci.edu/ftp/instrument_news/STIS/performance/psf/psf_robinson.ps.

\textsuperscript{5} All magnitudes that we quote for the GRB 97028 point and extended components are in the ST system for the WFPC2 filters and in the Vega system for standard Johnson-Cousins and near-infrared filters.
the discrepancy of the $I_c$ magnitudes, since Sahu et al. (1997c) do not provide enough details for a comparison. In the STIS image we measure a count rate of $0.232^{+0.023}_{-0.022}$ for the point source. Our estimated $V$ and $R_c$ magnitudes are consistent within the errors with those measured by Fruchter et al. (1998, 1999) and Galama et al. (1998). Fruchter et al. (1999) measure $0.206 \pm 0.02$ counts s$^{-1}$ and derive $V = 28.0 \pm 0.25$, while we measure a count rate of $0.232^{+0.023}_{-0.022}$ and derive $V = 28.10^{+0.24}_{-0.22}$. Although consistent within the errors, our measured count rates are somewhat different. We believe that the difference could be due to the different measuring methods: aperture photometry with correction (Fruchter and collaborators) versus PSF fitting (ours). Our conversion factor from STIS count rate to a $V$ magnitude is also different. Although Fruchter et al. (1999) do not specify which input spectrum they used to convert from count rate to $V$ magnitude, the difference must be due to the different spectrum assumed. In the end, our best-value $V$ magnitudes differ by 0.1 mag but are consistent within the errors. In the $R_c$ filter, our measurement, $R_c = 27.09^{+0.24}_{-0.23}$, is more discordant with that of Galama et al. (1998), $R_c = 27.25 \pm 0.27$. In this case, the conversion between STIS counts and $R_c$ magnitudes is less dependent on the assumed spectrum (as can be seen in Table 2, where the error bars are smaller for this filter), and the 0.16 mag difference in our best values is probably entirely due to different measured count rates. There are indications that the OT becomes redder as it evolves (e.g., Galama et al. 1998). The spectrum assumed to convert count rates to magnitudes has not taken into account this possibility. However, the effect should be small and should not affect our $R_c$ magnitude appreciably.

For the extended component, our measured magnitudes for the WFPC2 and STIS images agree remarkably well. To convert from STIS count rate to a $V$ magnitude, we have assumed a spectrum that fits the WFPC2 colors. This is why the colors for the extended component are the same in the WFPC2 and STIS images (Tables 1 and 2). Compared to previous work, our $V$ magnitudes agree within the errors with those of Fruchter et al. (1997, 1999) ($V = 25.6 \pm 0.25$ and $V = 25.8 \pm 0.25$ for WFPC2 and STIS, respectively). However, we disagree with the $R_c = 25.0 \pm 0.3$ magnitude quoted by Galama et al. (1998). Combining the WFPC2 and STIS magnitudes, we obtain $R_c = 25.51^{+0.18}_{-0.15}$. This magnitude would imply a slightly different temporal behavior for the OT than that reported by Galama and collaborators, because they overcorrected for the contribution of the extended component when the OT faded to fluxes comparable to that of the extended component. Figure 4 shows the $R_c$ light curve of Galama et al. (1998) (top) along with our revised light curve (bottom). In the bottom panel we also plot the points from Galama et al. as open circles in order to compare the difference that the revised extended component magnitude makes in the OT magnitudes. The new revised OT magnitudes produce a better fit to a power-law behavior than before at late epochs (after the first week). If we consider only the last seven photometric points, that is, the evolution after March 6, we obtain a power-law temporal decay of $\alpha = -0.86 \pm 0.06$ ($\chi^2/\nu = 0.27$, 5 dof). The same points with the Galama et al. values would give $\alpha = -0.82 \pm 0.10$ ($\chi^2/\nu = 0.71$, 5 dof). The extrapolation to early epochs (before the end of the first day after the burst) would agree with the observed magnitude at UT February 28.83 (Guarnieri et al. 1997) but disagree with the observations at UT February 28.81 (Pedichini et al. 1997b) and UT February 28.99 (Galama et al. 1997). Nevertheless, considering all the photometric points, we obtain $\alpha = -1.04 \pm 0.03$ ($\chi^2/\nu = 2.49$, 9 dof; note the overly small errors in the slope due to the poor $\chi^2$ fit) versus the $\alpha = -1.10 \pm 0.04$ ($\chi^2/\nu = 2.3$, 9 dof) using the data from Galama et al. Given the small error in the William Herschel Telescope (WHT) UT February 28.99 measurement and ignoring any possible zero-point error (the observation was not carried out in the $R$-band filter), it appears that the temporal decay is slowing down or that the early behavior differs from the extrapolation of the later temporal behavior to earlier times, although caution is necessary when interpreting the first photometric measurements, since, for example, the second point disagrees with the first and third if the behavior is monotonic. We believe this explanation (steady power-law decay at late times and uncertain photometric measurements at early times) is more plausible than a strong deviation from the power-law behavior at “intermediate” times, as suggested by Galama et al. (1998). The apparent shallower power-law behavior could also be a manifestation of the OT becoming redder.

What can we learn from the HST observations of the extended component? Several authors (e.g., Sahu et al. 1997c; Castander & Lamb 1998; Livio et al. 1998; Fruchter et al. 1998, 1999) have previously discussed the properties of the extended component. Fruchter et al. (1998, 1999) find that the size of the extended component is consistent with
the sizes of galaxies of comparable magnitude in the Hubble Deep Field (HDF). Based on this and the surface number density of galaxies of similar surface brightness, they conclude that the extended source is most likely a galaxy at moderate redshift, and is almost certainly the host galaxy of GRB 970228. Here we concentrate on the observed colors, taking into account the measured extinction, in order to constraint the nature of the likely galaxy. For that purpose, we will compare them to the colors obtained from synthetic galaxy spectra computed with PEGASE (Fioc & Rocca-Volmerange 1997), a galaxy synthesis code that reproduces the observed colors of nearby galaxies.

As mentioned before, for the extended component we measure a color of $(V - I)_{ST} = 0.18 \pm 0.01$ in the WFPC2 images and a count rate of $1.161 \pm 0.192$ in the STIS image, and we obtain a local Galactic extinction of $A_V = 1.09 \pm 0.10$ (CL99). We prefer to use the measured color in the WFPC2 filters and the count rate in the STIS image in order to avoid introducing errors in transformations to other filters. Fruchter et al. (1999) also measure $H = 23.3 \pm 0.1$ and $K = 22.8 \pm 0.3$ for the extended source using NICMOS and the Keck I telescope, respectively. The top panels of Figures 5, 6, 7, and 8 present the expected colors and STIS count rates, including a local $R_V = 3.1$ extinction law (Cardelli, Clayton, & Mathis 1987; O'Donnell 1994) of $A_V = 1.09$, for three different synthesized spectral energy distributions (SEDs) corresponding to Sa (solid line), Sc (dotted line), and Irregular (dashed line) galaxies as a function of redshift, together with the observed color and count rate (solid line, best value; dotted lines, 1σ errors). We have obtained colors and the STIS count rate in the redshift range $0 < z < 4$ for each synthetic galaxy spectra in two ways. First, we have redshifted the spectra, which corresponds to applying a $K$-correction (thick lines).

We have also redshifted the spectra, evolving them back in time with a star-forming history prescription that reproduces the observed colors at $z = 0$, which correspond to an evolutionary + $K$-correction (thin lines). From the top panel

![Fig. 5. WFPC2 colors for synthesized SEDs vs. redshift. The models presented are the same as in Fig. 5. An $A_V = 0.86$ would produce SEDs that are 0.185 bluer.](image)

![Fig. 6. $(V - I)_{ST} - H$ color for synthesized SEDs vs. redshift. The models presented are the same as in Fig. 5. An $A_V = 0.86$ would produce SEDs that are 0.17 bluer.](image)

![Fig. 7. $(V - I)_{ST} - K$ color for synthesized SEDs vs. redshift. The models presented are the same as in Fig. 5. An $A_V = 0.86$ would produce SEDs that are 0.185 bluer.](image)

![Fig. 8. STIS count rates for synthesized SEDs vs. redshift. The models presented are the same as in Fig. 5 but are normalized to a $(V - I)_{ST} = 26.03$ mag, as observed in the combined WFPC2 images.](image)
of Figure 5, we can check that an S$\alpha$ galaxy is only consistent with the observed $V_{606} - I_{814}$ color if it is at $z \approx 1.5$; an S$c$, if $z \approx 0.4$ or $z \approx 1.2$, and the constraint on irregulars depend strongly on their assumed formation time. The top panel of Figure 8 shows that the STIS count rate [when normalized to give the observed $(V_{606} K_S} = 26.03$ magnitude] provides roughly the same constraints. However, when we add the optical–near infrared colors (Figs. 6 and 7, top), the constraints are much stronger on the type of galaxy allowed. As can be seen, no galaxy showing a spectrum equal to the local “canonical” types (that is, only allowing $K$-corrections) is consistent with the observed data. When evolutionary corrections are included, different galaxy types intersect the observed colors at different redshifts. The exact fitting redshifts are uninformative, since they are highly dependent on the assumed stellar formation prescription of the galaxy.

In order to clarify the galaxy stellar contents allowed by the observed colors, we plot in the bottom panels of Figures 5–8 the prediction of a 1 Gyr (solid line), a 100 Myr (dotted line), and a 20 Myr (dashed line) burst of star formation observed at redshift $z$ at the termination of the burst. That is, the burst starts 1 Gyr, 100 Myr, or 20 Myr, respectively, before it is observed at redshift $z$. We also show a 1 Gyr burst model that is observed at redshift $z$, 200 Myr after the end of the burst (dot-dashed line), in order to understand the effect of the truncation of star formation. As Figure 5 (bottom) shows, ongoing bursts of star formation of durations shorter than 1 Gyr produce acceptable $V_{606} - I_{814}$ colors; longer duration bursts begin to be unacceptable at around redshift $z \sim 0.8$. This is because for bursts of longer duration, the contribution to the total light of evolved stars increases with respect to that of the most massive stars (O and B) that are continuously formed. When the A stars start to dominate the total emitted light, there is a significant flux decrement in the region of the most energetic Balmer lines (3645–4000Å). This decrement passes between the F606W and F814W filters around $z \sim 0.8$, explaining the redder $V_{606} - I_{814}$ color in the bottom panel of Figure 5. Older stellar populations would produce even redder colors as late-type stars contribute more and more to the integrated light (see Fig. 5, top). Another important conclusion comes from the truncated star formation model (dot-dashed line). In this case, after 200 Myr without star formation, all hot stars (O and B) have evolved off the main sequence, and there is not enough ultraviolet flux to explain the observed colors if the redshift is $z \gtrsim 0.5$.

The constraints arising from the STIS count rate (Fig. 8, bottom) are almost the same as those derived from the WFPC2 $V_{606} - I_{814}$ color. However, the STIS count rate is more difficult to interpret in terms of specific features of the stellar composition, due to the width of the wavelength coverage. The addition of near-infrared magnitudes (Figs. 6 and 7) provides much tighter constraints on the stellar composition, although not on the redshift. It is obvious from the $V_{606} - H$ and $V_{606} - K$ observed colors that the age of the burst needs to be roughly between 100 Myr and 1 Gyr. Moreover, a truncation in the star formation, that is, a galaxy that no longer forms hot stars and whose stellar population thereafter starts to be dominated by A or later type stars, is strongly rejected by the observed optical–near infrared colors.

To better visualize the constraints that the available data place on the allowed stellar population and redshift, we have calculated the $\chi^2$ distribution for synthetic SEDs, computed for an age range from 10 Myr to 10 Gyr and a redshift range from 0 to 4,

$$\chi^2(\text{age}, z) = \sum_{i=1}^{n} \frac{[C_i^{\text{obs}} - C_i^{\text{SED}}(\text{age}, z)]^2}{\sigma_i^{\text{obs2}}},$$

where $C_i^{\text{obs}}$ are the observed colors, $\sigma_i^{\text{obs}}$ are their errors, and $C_i^{\text{SED}}(\text{age}, z)$ are the computed colors from the SED at that age and redshift.

Figure 9 presents the 1, 2, and 3 $\sigma$ allowed regions given the observed colors and count rate. The top panel of Figure 9 shows bursts of star formation of the age given in the plot observed at the redshift shown in the plot. The corresponding SEDs have been synthesized assuming a constant star formation rate up to the age of observation. The bottom panel of Figure 9 shows the effect of star formation cessation. In this panel, there is a constant formation rate up to 1 Gyr (as in the top panel), but then it stops and no further stars are formed. It is clear that when star formation stops,
the synthesized spectra are largely inconsistent with the observed colors. Only at redshifts \(z < 0.5\) is some passive evolution of the stellar population allowed. However, the galaxy would have to be unusually faint for its size (at least \(4 \text{ mag fainter}\) than an \(I^\prime\) with a semimajor axis \(\leq 2.5 \text{ h}^{-1} \text{kpc}\) if the redshift were \(z < 0.5\).

Although we have made quantitative comparisons between synthesized SEDs and observed colors, we want to stress that our intention is only to give a qualitative description of the stellar population content. Given that we are using spectral synthesis codes in which we have changed some parameters but not explored the whole range of possible star formation rates, initial mass functions, and metallicities, by no means can we provide an exact estimate of the stellar population age. However, our main conclusion is robust against spectral synthesis code subtleties: the stellar component is young and dominated by early-type, O and B, stars. Star formation should be taking place in this object; otherwise, the observed optical–near infrared colors would be much redder. The redshift is, however, unconstrained by the observed colors.

A possible source of uncertainty in our conclusion, in addition to the SEDs used, is the assumed value of the local Galactic extinction. We have used the best value obtained in CL99 (\(A_V = 1.09^{+0.10}_{-0.20}\)), which is the result of the combination of several estimates. This value is pulled high by the extinction measured from the colors of a star in the vicinity of GRB 970228. If in CL99 we had not used the extinction estimate from this star, we would have obtained a weighted best value of \(A_V = 0.86 \pm 0.14\) (see CL99’s Table 2). This extinction value, \(A_V = 0.86\), produces \(V_{606} - I_{814}\), \(V_{606} - H\), and \(V_{606} - K\) colors that are 0.07, 0.17, and 0.19 bluer than for \(A_V = 1.09\) (Figs. 5–7). Such color changes would not modify our conclusions.

In our analyses of magnitudes and colors of the extended component so far, we have assumed no intrinsic extinction at the source. If the extended component is a galaxy with ongoing star formation, it is likely that it will contain dust and will therefore absorb part of the optical radiation emitted (e.g., Calzetti, Kinney, & Storchi-Bergmann 1994). Should any intrinsic extinction be present, our conclusion of a galaxy with ongoing star formation would be strengthened. In fact, if we add the internal intrinsic extinction as another free parameter, in addition to the age and redshift, when we compute the \(\chi^2\) (see eq. [1]), the age–z distributions obtained by marginalizing over the intrinsic extinction do not differ much from the ones shown in Figures 9. The best-fit age obtained by minimizing the \(\chi^2\) with respect to the three free parameters (age, intrinsic extinction, and \(z\)) is somewhat lower than when doing so with only two (age and \(z\), as expected. The best estimate of the intrinsic extinction is relatively low, \(A_V \sim 0.1–0.2\).

4. Conclusions

We have reanalyzed the images of the GRB 970228 field taken with the HST WFPC2 and STIS instruments. Tables 1 and 2 summarize our photometric measurements. As previously reported, we find that the point-source component has faded in the time elapsed between these observations, while the extended component shows no significant variation. Although a possible reddening of the GRB 970228 OT colors has been reported (Galama et al. 1998), no significant color change is detected for the point-source component between the two WFPC2 images.

Analyzing the two WFPC2 images together, we find for the extended source \(V_{606} = 26.03^{+0.19}_{-0.16}\) and \(I_{814} = 26.21^{+0.45}_{-0.32}\) which we transform (see above) into \(R_e = 25.48^{+0.20}_{-0.22}\). This magnitude is significantly fainter than that reported by Galama et al. (1998). Ground-based optical observations of the pointlike optical transient suffered some contamination from the extended component. This contamination was negligible during the first days after the onset of the burst, but became substantial after the first week. Our measured \(R_e\) magnitude implies that the total OT + extended magnitudes compiled by Galama et al. (1998) were overcorrected for the extended source by these authors in obtaining the magnitude of the OT. With our new correction, the temporal behavior of the OT appears to have changed from a steep early decline to a shallower power-law decay after the first week. Some of this spectral slope change could be due to intrinsic reddening of the source. However, the light curve is open to multiple interpretations because the number of observations is sparse.

The WFPC2 magnitudes and STIS count rate of the extended-source component are consistent with no variation, within the errors. Several considerations indicate that this object is most likely a galaxy and possibly the host of GRB 970228. If this object were a galaxy, its colors, \(V_{606} - I_{814}\) and \(V_{606} - K\), are remarkably blue when we take into consideration the measured extinction. Using synthetic spectra, we conclude that the observed emission from this object is dominated by hot stars and therefore is most likely a galaxy undergoing star formation. We cannot constrain its redshift using the available color information.

We acknowledge valuable discussions with Daniel Reichart, Mark Metzger, Andrew Fruchter, Carlo Graziani, Jean Quashnock, Cole Miller, and Dave Cole. Part of this work is based on NASA/ESA Hubble Space Telescope archival data retrieved from the archive maintained at STScI. We acknowledge support from NASA grants NAGW-4690, NAG5-1454, and NAG5-4406.

REFERENCES

Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1987, ApJ, 345, 245
Castander, F. J., & Lamb, D. Q., 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts: Proc. 4th Huntsville Symp., ed. C. A. Meegan, R. Preece, & T. Koshut (Woodbury: AIP), 520
Costa, E., et al. 1997a, IAU Circ. 6572
Djorgovski, S. G., Kulkarni, S. R., Gal, R. R., Odewahn, S. C., & Frail, D. A. 1997, IAU Circ. 6732
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Frontera, A., Livo, M., Macchetto, D., Petro, L., Sahu, K., Pian, E., Frontera, F., Thorsett, S., & Tavani, M. 1997, IAU Circ. 6747
Frontera, A., et al. 1997, IAU Circ. 6637
Frontera, F., Greiner, J., Antonelli, L. A., Costa, E., Fiore, F., Parmar, A. N., Piro, L., Boller, T., & Woges, W. 1999, A&A, in press (preprint astro-ph/9804270)
Fruchter, A., Livio, M., Macchetto, D., Petro, L., Sahu, K., Pian, E., Frontera, F., Thorsett, S., & Tavani, M. 1997, IAU Circ. 6747
Fruchter, A., et al. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts: Proc. 4th Huntsville Symp., ed. C. A. Meegan, R. Preece, & T. Koshut (Woodbury: AIP), 509
—. 1999, ApJ, 516, 683
Galama, T., et al. 1997, Nature, 387, 479
Galama, T., Groot, P., van Paradijs, J., Kouveliotou, C., Sahu, K. C., Livio, M., Petro, L., Macchetto, F. D., & Fruchter, A. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts: Proc. 4th Huntsville Symp., ed. C. A. Meegan, R. Preece, & T. Koshut (Woodbury: AIP), 478
González, R. A., Fruchter, A. S., & Dirsch, B. 1999, ApJ, 515, 69
Groot, P., et al. 1997a, IAU Circ. 6584
———. 1997b, IAU Circ. 6588
Guarnieri, A., et al. 1997, A&A, 328, L13
Holtzman, J., et al. 1995a, PASP, 107, 156
Holtzman, J., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995b, PASP, 107, 1065
Klose, S., Stecklum, B., & Tuffs, R. 1997, IAU Circ. 6611
Livio, M., et al. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts: Proc. 4th Huntsville Symp., ed. C. A. Meegan, R. Preece, & T. Koshut (Woodbury: AIP), 483
Margon, B., Deutsch, E. W., Lamb, D. Q., & Castander, F. J. 1997, IAU Circ. 6618
Metzger, M. R., Cohen, J. L., Blakeslee, J. P., Kulkarni, S. R., Djorgovski, S. G., Steidel, C. C., & Frail, D. A. 1997a, IAU Circ. 6631
Metzger, M. R., Kulkarni, S. R., Djorgovski, S. G., Gal, R., & Steidel, C. C. 1997b, IAU Circ. 6588
O'Donnell, J. E. 1994, ApJ, 422, 158
Pedichini, F., et al. 1997a, IAU Circ. 6635
———. 1997b, A&A, 327, L32
Reichart, D. E. 1998, ApJ, 485, L57
Sahu, K. C., Livio, M., Petro, L., & Macchetto, F. 1997a, IAU Circ. 6606
Sahu, K. C., Livio, M., Petro, L., Macchetto, F., van Paradijs, J., Kouveliotou, C., Fishman, G., & Meegan, C. 1997b, IAU Circ. 6619
Sahu, K. C., et al. 1997c, Nature, 387, 476
Soifer, B., Neugebauer, G., Armus, L., Metzger, M., Kulkarni, S., Djorgovski, S., Steidel, C., & Frail, D. 1997, IAU Circ. 6619
van Paradijs, J., et al. 1997, Nature, 386, 686
Wijers, R. M. A. J., Rees, M. J., & Meszaros, P. 1997, MNRAS, 288, L51
Yoshida, A., et al. 1997, IAU Circ. 6593

Note added in proof.—While this paper was in press, Djorgovski et al. (1999; GCN 289, available http://lheawww.gsfc.nasa.gov/docs/gamcosray//egt/bacodine/gcn3/289.gcn3) reported a redshift for the GRB 970228 host galaxy of $z = 0.695 \pm 0.002$. 