AN HST SEARCH FOR SUPERNOVAE ACCOMPANYING X-RAY FLASHES

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ABSTRACT

We present the results from a Hubble Space Telescope ACS search for supernovae associated with X-ray flashes 020903, 040701, 040812, and 040916. We find strong evidence that XRF 020903 (z = 0.25) was associated with a SN 1998bw-like supernova and confirm this using optical spectroscopy at t ~ 25 days. We find no evidence, however, for SN 1998bw-like supernovae associated with the other three events. In the case of XRF 040701 (z = 0.21), we rule out even a faint supernova similar to SN 2002ap, using template light curves for several local Type Ic supernovae. For the two cases in which the redshift is not known, XRFs 040812 and 040916, we derive robust redshift limits, assuming that they were accompanied by supernovae similar to SN 1998bw, and compare these limits with photometric redshift constraints provided by their host galaxies. We supplement this analysis with results for three additional events (XRFs 011030, 020427, and 030723) and discuss the observed diversity of supernovae associated with X-ray flashes and gamma-ray bursts. We conclude that XRF-SNe exist but can be significantly fainter than SN 1998bw, possibly consistent with the observed spread in local Type Ibc supernovae.

Subject heading: gamma rays: bursts — radiation mechanisms: nonthermal — X-rays: bursts

1. INTRODUCTION

Observational evidence for a connection between gamma-ray bursts (GRBs) and supernovae (SNe) was first established with the discovery of the highly luminous type Ic SN 1998bw in spatial and temporal coincidence with GRB 980425 (Pian et al. 2000; Galama et al. 1998a). In the 7 years since this extraordinary event, several possible GRB-SN associations have been reported on the basis of red “bumps” observed in optical afterglow light curves (e.g., Bloom et al. 1999). Moreover, in two cases (GRBs 030329 and 031203) there is unambiguous spectroscopic evidence of high-redshift SN features (Hjorth et al. 2003; Stanek et al. 2003; Matheson et al. 2003; Malesani et al. 2004). These observations provide conclusive evidence that at least some gamma-ray bursts are produced in the explosions of massive stars.

In recent years, a new class of high-energy transients has been identified, characterized by an emission spectrum peaking in the X-ray band, an order of magnitude softer than the peak energies observed for GRBs (Heise et al. 2001). These so-called X-ray flashes (XRFs) are thought to be related to GRBs since the two classes share several observational properties, including prompt emission profiles (Sakamoto et al. 2005 and references therein), broadband afterglows (Butler et al. 2005; Soderberg et al. 2004; Fynbo et al. 2004), and star-forming host galaxies at cosmological distances (Bloom et al. 2003; Levan et al. 2002, 2005).

Several hypotheses on the physical connection between XRFs and GRBs have been proposed. One popular model posits that XRFs are simply GRBs viewed away from the jet collimation axis (Yamazaki et al. 2003; Zhang et al. 2004; Granot et al. 2005). In this scenario, the observed prompt emission is dominated by the mildly relativistic material in the “wings” of the jet, rather than the highly relativistic (Γ ~ 100) ejecta beamed away from the line of sight. Another popular model suggests that XRFs are produced in a “dirty fireball,” where the ejecta carry a more substantial baryonic load (and hence less relativistic material) than typical GRBs (Zhang et al. 2004). In both scenarios XRFs are expected to be associated with SNe, whose properties and detectability should not be affected by the viewing angle or baryonic load.

The discovery of a SN in association with an XRF would therefore conclusively associate XRFs with the death of massive stars and hence GRBs. Motivated thus, we undertook a systematic search for SNe associated with XRFs using the Hubble Space Telescope (HST). As part of our XRF-SN analysis, we synthesized supernova light curves at various redshifts utilizing as templates the well-sampled optical light curves of several local SNe (§ 2). Comparison of the synthesized SNe with our HST observations enabled us to study the diversity of XRF-associated SNe. Details on the individual HST targets and observations follow in § 3. By including results from other XRF-SN searches, we compile an extended sample of seven
events (XRFs 011030, 020427, 020903, 030723, 040701, 040812, and 040916) and present a global summary of XRF-SN detection limits in § 4. A discussion on the observed spread in the peak optical luminosities of GRB- and XRF-associated SNe follows as § 5.

2. SUPERNova LIGHT CURVE SYNTHESIS

In modeling the XRF-associated SNe, we adopted optical data for the local SNe 1994I, 1998bw, and 2002ap as templates. These three SNe were selected on the basis of their well-sampled optical light curves, which represent an overall spread in the observed properties of Type Ibc supernovae. To produce synthesized light curves for each of these template SNe, we compiled optical $UBVRI$ observations from the literature and smoothed the extinction-corrected (foreground plus host galaxy) light curves. We then redshifted the light curves by interpolating over the photometric spectrum and stretching the arrival time of the photons by a factor of $(1 + z)$. Since observed spectra of local $(d \leq 100$ Mpc) Type Ibc SNe show a steep drop-off in flux blueward of $\sim 4000 \AA$ due to heavy line blanketing, and since good-quality UV data are currently not available below 3000 $\AA$, we do not attempt to extrapolate the rest-frame spectra blueward of the rest-frame $U$-band observations. This limits the synthesized light curves to $z \leq 0.80$ and $z \leq 1.20$ for the observed $R$ and $I$ bands, respectively. Below we discuss the compiled optical data sets for each of the template SNe.

2.1. SN 1998bw

The well-sampled $UBVRI$ light curves for SN 1998bw were taken from Galama et al. (1998a) and McKenzie & Schaefer (1999) and corrected for Galactic extinction $(A_V = 0.19$; Schlegel et al. 1998). We assume negligible host galaxy extinction, consistent with the spectroscopic analysis Patat et al. (2001). The broadband optical data set spans a timescale from $t \approx 0.7$ to 417 days. Here, the explosion time is set by the $BeppoSAX$ detection of GRB 980425 on 1998 April 25.91 UT (Pian et al. 2000). In calculating optical luminosities for SN 1998bw, we assume a distance, $d_L \approx 36.1$ Mpc $(H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$), based on the observed redshift to the host galaxy, ESO 184–G82 (Galama et al. 1998b).

2.2. SN 1994I

Richmond et al. (1996) provide a large compilation of multicolor light curves for SN 1994I. We adopt a large host galaxy extinction of $A_V = 1.4$ and negligible Galactic extinction as derived through the spectroscopic analysis (Richmond et al. 1996). Using an explosion date of 1994 March 30 UT from radio light-curve modeling (Stockdale et al. 2005), the $BVRI$ data span from $t \approx 1.4$ to 130 days, while the $U$-band data extend only as far as $t \approx 47.4$ days. In an effort to extend the $U$-band light curve, we scale the late-time linear decay of the $B$-band light curve to match the last epoch of $U$-band observations and assume that the $U - B$ color is constant thereafter. We note that this scaling introduces a source of uncertainty in our late-time $[t \approx 47(1 + z)]$ high-$z$ synthesized light curves of SN 1994I. In calculating optical luminosities, we adopt a distance of $d_L \approx 8.5$ Mpc for the host galaxy, M51, as given by Richmond et al. (1996).

2.3. SN 2002ap

$UBVRI$ light curves were taken from Foley et al. (2003) and scaled to an explosion date of 2002 January 28.9 UT (Mazzali et al. 2002). We adopt the spectroscopic derived total extinction (foreground plus host galaxy) of $A_V = 0.26$ (Foley et al. 2003). Data span $t \approx 1.3$ to 317.3 days after the explosion in $BVRI$ filters, while the $U$-band data extend only to $t \sim 35.2$ days. In a manner similar to that for SN 1994I, we extend the $U$-band light curve by scaling the late-time $B$-band data and note that this introduces uncertainty in the synthesized light curves at high-$z$. We assume that the distance to the host galaxy, M74, is $d_L \approx 7.3$ Mpc (Sharina et al. 1996; Sohn & Davidge 1996).

We emphasize the striking differences between the three SN light curves when the extinction-corrected rest-frame $V$-band light curves are compared. With regard to the luminosity at peak time, SN 1998bw is a factor of $\sim 2.2$ more luminous than SN 1994I and $\sim 6$ times more luminous than SN 2002ap. Moreover, the time of $V$-band peak varies by a factor of 2: while SN 1998bw peaks at $t \sim 16$ days, SN 1994I and SN 2002ap both peak at just $t \sim 9$ days. Such early peak times present a challenge for GRB-SN searches, since the optical afterglow typically dominates on these timescales.

3. Hubble Space Telescope XRF-SN Search

Since the activation of our Cycle 13 HST program to study the supernovae associated with X-ray flashes and gamma-ray bursts (GO-10135; PI: Kulkarni), three XRFs have been discovered and localized by their afterglow emission: XRFs 040701, 040812, and 040916. In an effort to study the SNe possibly associated with these XRFs, we observed each of these objects with HST at late-time, when an associated supernova is most likely to dominate the optical emission. To supplement our sample of XRF observations, we investigated archival HST images of XRF 020903 (GO-9405; PI: Fruchter). We describe our data analysis techniques below.

Using the Wide-Field Camera (WFC) of the Advanced Camera for Surveys (ACS) on board HST, we imaged the fields of XRFs 040701, 040812, and 040916. For each target we undertook observations at two epochs, $t \sim 30$ and $\sim 60$ days, in order to search for optical emission associated with an underlying supernova. Each epoch consisted of two orbits, during which we imaged the field in two filters, F625W and F775W, corresponding to Sloan Digital Sky Survey $r'$ and $i'$ bands, respectively.

We retrieved archival images of XRF 020903 from the HST archive. Similar to the other bursts in our sample, the XRF 020903 data were obtained with HST ACS using WFC. We analyze the images from two epochs at $t \sim 91$ and $\sim 300$ days to search for the signature of an associated supernova. These data were taken in the broad $V$-band filter, F606W.

The $HST$ data were processed using the `multidrizzle` routine within the `stsdas` package of IRAF (Fruchter & Hook 2002). Images were drizzled using `pixfrac = 0.8` and `pixscale = 1.0`, resulting in a final pixel scale of 0.05 arcsec pixel$^{-1}$. Drizzled images were then registered to the first epoch using the `xregister` package within IRAF.

To search for source variability, we used the ISIS subtraction routine by Alard (2000), which accounts for temporal variations in the stellar point-spread function (PSF). Residual images (epoch 1 – epoch 2) were examined for positive sources positionally coincident with the afterglow error circle. To test our efficiency at recovering transient sources, false stars with a range of magnitudes were inserted into the first-epoch images using the IRAF task `mkobject`. An examination of the false stellar residuals provided an estimate of the magnitude limit ($3 \sigma$) to which we could reliably recover transients.

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15 See http://archive.stsci.edu/hst/search.php.
Photometry was performed on the residual sources within a 0.5 arcmin aperture. We converted the photometric measurements to infinite aperture and calculated the corresponding AB magnitudes within the native HST filters using the aperture corrections and zero points provided by Sirianni et al. (2005). For comparison with ground-based data, we also converted the photometric measurements to Johnson R- and I-band (Vega) magnitudes using the transformation coefficients derived by Sirianni et al. (2005) and assuming a flat $F_0$ source spectrum.

In the following sections we summarize the afterglow properties for each of the targets and the photometry derived from our HST SN search. A log of the HST observations for the four XRFs follows in Table 1.

### 3.1. XRF 020903

#### 3.1.1. Prompt Emission and Afterglow Properties

XRF 020903 was detected by the Wide-Field X-Ray Monitor (WXM) on board the High Energy Transient Explorer (HETE-2) satellite on 2002 September 3.421 UT. With a spectral energy distribution peaking below 5 keV, XRF 020903 is the softest burst detected during the lifetime of the instrument (Sakamoto et al. 2004). Despite the large $4' \times 31'$ localization region, an optical afterglow was discovered (Soderberg et al. 2004) at $\alpha = 22^h48^m42.3^s, \delta = -20^\circ 46'09''3 (J2000.0). At $t \approx 0.9$ days, the afterglow had $R \approx 19.5$ mag and continued to fade as $F_{\nu} \propto t^{-1.1}$ until $t \approx 30$ days, when the decay flattened to a plateau. Optical spectroscopy showed the transient source to be associated with a galaxy complex at $z = 0.251$ (Soderberg et al. 2002).

#### 3.1.2. HST Observations

XRF 020903 was observed using HST ACS on 2002 December 3.79 and 2003 June 30.65 UT, corresponding to $t \approx 91$ and 300 days after the burst. Imaging was carried out in the broad F606W filter for total exposure times of 1840 s (epoch 1) and 1920 s (epoch 2). Relative astrometry was performed using an early-time ($t \sim 0.9$ day) image from the Palomar 200 inch (5 m) telescope (Soderberg et al. 2004). Using 42 unsaturated, unconfused stars in common between the two images, we registered the HST data with a systematic uncertainty of 0".12 (2 $\sigma$).

The HST images reveal that the afterglow localization circle coincides with the southwest knot of the host galaxy complex (Fig. 1). Through image subtraction, we find a positive

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**TABLE 1**

| Target   | Observation Date (UT) | $\Delta t$ (days) | Exposure Time (s) | Filter    | $HST$ Magnitude$^a$ (AB) | Extinction$^b$ ($A_k$) | Johnson Magnitude (Vega)$^c$ |
|----------|-----------------------|-------------------|-------------------|-----------|--------------------------|------------------------|-----------------------------|
| XRF 020903 | 2002 Dec 3.8         | 91.4              | 1840              | F606W     | 24.53 ± 0.03             | $A_k = 0.09$          | $R = 24.23 ± 0.03$        |
|          | 2003 Jun 30.6        | 300.2             | 1920              | F606W     | ...                      | ...                    | ...                         |
| XRF 040701 | 2004 Aug 9.6         | 39.1              | 1820              | F625W     | >27.81                   | $A_k = 0.13$          | $R > 27.48$               |
|          | 2004 Aug 30.5        | 60.0              | 1820              | F625W     | ...                      | ...                    | ...                         |
|          | 2004 Aug 9.7         | 39.1              | 1940              | F775W     | >26.83                   | $A_j = 0.09$          | I > 26.30                  |
|          | 2004 Aug 30.5        | 60.0              | 1940              | F775W     | ...                      | ...                    | ...                         |
| XRF 040812 | 2004 Sep 13.3        | 32.0              | 2000              | F625W     | >26.99                   | $A_k = 3.61$          | R > 23.18                  |
|          | 2004 Oct 4.8         | 53.5              | 2000              | F625W     | ...                      | ...                    | ...                         |
|          | 2004 Sep 13.4        | 32.1              | 2120              | F775W     | >26.38                   | $A_j = 2.62$          | I > 23.32                  |
|          | 2004 Oct 4.8         | 53.5              | 2120              | F775W     | ...                      | ...                    | ...                         |
| XRF 040916 | 2004 Oct 18.4        | 32.4              | 1930              | F625W     | >27.89                   | $A_k = 0.15$          | $R > 27.54$               |
|          | 2004 Nov 30.3        | 75.3              | 1928              | F625W     | ...                      | ...                    | ...                         |
|          | 2004 Oct 18.4        | 32.4              | 2058              | F775W     | >27.19                   | $A_j = 0.64$          | I > 26.64                  |
|          | 2004 Nov 30.4        | 75.4              | 2056              | F775W     | ...                      | ...                    | ...                         |

$^a$ From residual image. Observed magnitude, not corrected for foreground extinction.

$^b$ Galactic extinction from Schlegel et al. (1998).

$^c$ From residual image. Corrected for foreground extinction using $A_k$ given in the seventh column.

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**Fig. 1.** Three-panel frame showing HST ACS imaging for XRF 020903 at $t \approx 91$ days (epoch 1) and $t \approx 300$ days (epoch 2) in the F606W filter. By subtracting the epoch 2 image from epoch 1, we produced the residual image, above. We apply the same stretch to all frames. As clearly shown in this residual image, a transient source is detected coincident with the 0''12 (2 $\sigma$) optical afterglow position (circle), lying on the southwest knot of the host galaxy complex.
residual coincident with the optical afterglow position at $\alpha = 22^h 48^m 42^s 293, \delta = -20^\circ 46' 08'' 47' (J2000.0)$. Photometry of the residual source gives $F_{606W} \approx 24.53 \pm 0.03$ mag ($R \approx 24.32 \pm 0.03$ mag). Correcting for Galactic extinction ($A_R = 0.09; \text{Schlegel et al.
1998}$), the true magnitude of the source is $R \approx 24.23 \pm 0.03$ mag. To estimate our photometric uncertainty, we placed random apertures near other galaxy residuals and calculated the standard deviation of the resulting values.

Figure 2 shows the extinction-corrected $HST$ photometry along with ground-based $R$-band data for the optical afterglow associated with XRF 020903. Ground-based data have been compiled from the GCN circulars (GCNs; Covino et al. 2002; Gorosabel et al. 2002), as well as from Table 1 of Soderberg et al. (2004). We have numerically subtracted the host galaxy contribution from the ground-based data, assuming an extinction-corrected host galaxy brightness of $R \approx 20.90$ mag based on late-time observations (Gorosabel et al. 2002; Levan et al. 2002). From the compiled $R$-band afterglow light curve, it is evident that the temporal decay flattens significantly around $t \sim 30$ days and subsequently steepens toward the $HST$ measurement at $t \sim 91$ days. This flattening (or plateau phase) occurs on the same timescale that a SN 1998bw–like supernova at $z = 0.25$ would reach maximum light (see also Bersier et al. 2004).

### 3.1.3. Associated Supernova

Overplotted in Figure 2 are the synthesized light curves of SNe 1998bw, 1994I, and 2002ap at a redshift of $z = 0.25$. It is clear that an associated SN 1998bw–like supernova would be $\sim 1$ mag brighter than the $HST$ observation at $t \sim 91$ days, while SN 1994I– and SN 2002ap–like light curves are each fainter by 1.4 mag. By taking the weighted average of the ground-based data between $t \sim 20$–40 days, we predict that the supernova was $0.6 \pm 0.5$ mag fainter than SN 1998bw at maximum light. We note that this uncertainty is dominated by “aperture effects” (see Price et al. 2003) that cause variable contribution from the host galaxy complex in different epochs.

We obtained optical spectroscopy of the transient source using the Magellan 6.5 m telescope equipped with the Low Dispersion Survey Spectrograph (LDSS2) on 2002 September 28.06 UT ($t \approx 24.6$ days), during the observed plateau phase. The data were reduced and calibrated using standard techniques. The spectrum is characterized by a faint continuum dominated by narrow, bright emission lines typical of star-forming galaxies (Fig. 3; Soderberg et al. 2002; Chornock & Filippenko 2002).

To search for high-velocity SN features within the observed spectrum, we utilized the supernova classification techniques of Howell et al. (2005), designed for identification of SNe in the presence of host galaxy contamination. Host galaxy light must be subtracted from the observed spectrum to reveal the SN flux. We fit a range of starburst host galaxy templates from Kinney et al. (1993), consistent with the continuum shape and narrow lines in the observed spectrum. After sigma-clipping the narrow emission lines and subtracting the best-fit galaxy template (model SB1), the residual spectrum shows broad features resembling those of SN 1998bw near maximum light. Figure 3 presents a comparison of our galaxy subtracted spectrum with SN 1998bw at $t \approx 20.5$ days (rest frame; Patat et al. 2001), redshifted to $z = 0.25$ and dimmed by $\sim 0.3$ mag. The resemblance is striking.

Taken together, the spectroscopic and photometric data strongly suggest that XRF 020903 was associated with a supernova that is $\sim 0.6 \pm 0.5$ mag fainter than SN 1998bw at maximum light. Moreover, the SN light curve fades faster than SN 1998bw, falling $\sim 1$ mag below the synthesized SN 1998bw light curve $1.4$ days.}

![Figure 2](image1.png)

**Figure 2.** Constraints on a supernova associated with XRF 020903. Extinction-corrected ground-based $R$-band observations of the optical afterglow have been compiled from Soderberg et al. (2004) and the GCNs (Covino et al. 2002; Gorosabel et al. 2002), and are shown as diamonds and gray circles, respectively. The temporal decay of the (host-galaxy–subtracted) optical afterglow is described by $t^{-1.1}$ (dashed gray line) at early time, followed by a plateau phase at $t \sim 30$ days. The weighted mean of the points between $t \sim 20$–40 days (black cross) indicates that at peak the supernova was $0.6 \pm 0.5$ mag fainter than the synthesized SN 1998bw light curve (thick line). At $t \approx 91$ days, however, the $HST$ transient (encircled dot) is $\sim 1$ mag fainter than the synthesized curve, implying the supernova faded faster than SN 1998bw. SN 1994I– and 2002ap–like supernovae (medium and thin lines, respectively) would be significantly fainter than the $HST$ residual.

![Figure 3](image2.png)

**Figure 3.** Magellan LDSS2 spectrum of XRF 020903, taken at $t \approx 24.6$ days. Host galaxy emission lines were sigma-clipped (top) and we remove the host galaxy contribution using a starburst template (bottom, light gray). The galaxy subtracted spectrum has broad SN features, in clear resemblance to SN 1998bw at $t \sim 20$ days (rest frame), redshifted to $z = 0.25$ and dimmed by $0.3$ mag (bottom, black). The telluric band is marked with a circled cross.
curve at late-time. A dimmer, faster fading supernova was also interpreted for SN 2003dh/GRB 030329 (Lipkin et al. 2004; Deng et al. 2005; cf. Matheson et al. 2003) and is consistent with the luminosity-stretch relation for GRB SNe (Bloom et al. 2002; Deng et al. 2005; cf. Matheson et al. 2003) and is consistent with the observed X-ray photons. Utilizing the $N_{\text{H}}$ to $A_v$ conversion of Predehl & Schmitt (1995), this limit corresponds to a rest-frame host galaxy extinction of $A_{V,\text{host}} \lesssim 2.8$ mag.

Despite deep searches, no optical afterglow candidate was discovered through ground-based monitoring of the Chandra error circle (de Ugarte Postigo et al. 2004; Berger et al. 2004b; Pian et al. 2004). This nondetection could be the result of the large host galaxy extinction, consistent with the observed X-ray afterglow absorption.

3.2. XRF 040701

3.2.1. Prompt Emission and Afterglow Properties

XRF 040701 was localized on 2004 July 1.542 UT by the HETE-2 WXM to an 8' radius error circle centered at $\alpha = 20^h47^m46^s, \delta = -40^\circ 14' 13''$ (J2000.0; Barraud et al. 2004).

We observed the error circle with the Chandra X-Ray Observatory using the AXAF CCD Imaging Spectrometer (ACIS) for 22.3 ks beginning at 2004 July 9.32 UT ($t \approx 7.9$ days) and 20.4 ks on 2004 July 18.05 ($t \approx 16.6$ days). Comparison of the two epochs revealed the most variable source to be at position $\alpha = 20^h48^m01^s, \delta = -40^\circ 11' 08''$ (J2000.0), with an uncertainty of 0.5 in each coordinate (2 $\sigma$; Fox 2004), which we interpret as the X-ray afterglow. Assuming Galactic absorption, the X-ray flux of the source was $7.75 \times 10^{-14}$ and $4.06 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ ($2$–$10$ keV), in the first and second epochs, respectively. This implies a temporal decay, $F_X \sim t^{-\alpha}$ with $\alpha = -1.15$, between the two observations, comparable to the typical observed values of GRB X-ray afterglows, $\alpha \sim -1.1$ (Berger et al. 2003a and references therein).

Inspection of Digitized Sky Survey (DSS) images revealed that the X-ray afterglow is associated with a resolved galaxy complex whose redshift we determined to be $z = 0.2146$ (Kelson et al. 2004). At this relatively low redshift, the X-ray afterglow is sensitive to absorption within the host galaxy. We fit an absorbed power-law model to the afterglow spectrum where the column density, $N_{\text{H}}$, was a combination of foreground and host galaxy extinction. We find that the column density within the host galaxy must be $N_{\text{H}} \lesssim 5 \times 10^{21}$ cm$^{-2}$ (90% confidence) in order to reproduce the observed low-energy ($<1$ keV) X-ray photons. Despite deep searches, no optical afterglow candidate was discovered through ground-based monitoring of the Chandra error circle (de Ugarte Postigo et al. 2004; Berger et al. 2004b; Pian et al. 2004). This nondetection could be the result of the large host galaxy extinction, consistent with the observed X-ray afterglow absorption.

3.2.2. HST Observations

HST ACS imaging was carried out on 2004 August 9.66 and 30.52 UT ($t \approx 39.1$ and 60.0 days after the burst). Each epoch had a total exposure time of 1840 and 1920 s in the F625W and F775W filters, respectively. We astrometrically tied the HST and Chandra images by first registering the X-ray source list to our I-band images from the Las Campanas Observatory (LCO) 40 inch (1 m) telescope (Berger et al. 2004b) using three sources in common. We then tied the LCO images to those from HST resulting in a final positional uncertainty of 1706 (2 $\sigma$).

Our HST observations reveal that the afterglow error circle coincides with the northeast galaxy of the host complex. Inspection of the images reveals that there are no transient sources within this localization region. Figure 4 shows the images from both epochs in addition to the residual images produced from the subtraction routine. We found that the false stellar residuals recovered at our detection threshold correspond to limits of F625W $> 27.8$ and F775W $> 26.8$ mag ($R > 27.6$ and $I > 26.4$ mag). Correcting for Galactic extinction ($A_R = 0.13$; Schlegel et al. 1998), the actual limits are $R > 27.5$ and $I > 26.3$ mag. We note that the slightly elevated flux of the bipolar galaxy residual are consistent with these limits.
3.2.3. Supernova Limits

Overplotted in Figure 5 are synthesized light curves for SNe 1998bw, 1994I, and 2002ap at $z = 0.21$. From the figure, it is clear that a SN 1998bw–like supernova would have been $\sim 6$ mag brighter than our $HST$ limits. A faint supernova similar to SN 2002ap would still be $\sim 3.4$ mag above our detection threshold. Our constraints on the column density imply that host galaxy extinction cannot account for this difference; even in an extreme scenario, given by $A_V^\text{host} \approx 2.8$ mag, our limits are still $\sim 3.2$ mag fainter than SN 1998bw. We conclude that an XRF 040701–associated supernova must be $\sim 3$ mag fainter than SN 1998bw, making it significantly fainter than all GRB-SNe known to date.

3.3. XRF 040812

3.3.1. Prompt Emission and Afterglow Properties

XRF 040812 was discovered on 2004 August 12.251 UT by the Imager on board the INTEGRAL satellite (IBIS). Preliminary analysis indicated a spectrum that was X-ray–rich. The event was localized to a 2° radius circle centered at $\alpha = 16^h 26^m 05^s, \delta = -44^\circ 44' 32"$ (J2000.0; Gotz et al. 2004).

Patel et al. (2004a) observed the field of XRF 040812 with Chandra ACIS beginning on 2004 August 17.30 UT ($t \approx 5$ days) and on 2004 August 22.41 UT ($t \approx 10$ days) for 10 ks each. Comparison of the two epochs revealed a variable source at position $\alpha = 16^h 26^m 25^s, \delta = -44^\circ 43' 49"$ (J2000.0) which faded as $F_X \propto t^{-1.4}$ between the observations (Patel et al. 2004b). The unabsorbed flux in the first and second epochs was $2.5 \times 10^{-13}$ and $9.3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–10 keV), respectively (Campana & Moretti 2004a, 2004b).

Due to high Galactic extinction in the direction of the burst ($A_R = 3.6$ mag; Schlegel et al. 1998) and the presence of an extremely bright star $\sim 20''$ from the Chandra position, optical/IR campaigns could neither observe the optical afterglow nor obtain spectroscopy of the host galaxy (Berger 2004; Berger et al. 2004a; Cobb & Bailyn 2004; D’Avanzo et al. 2004). As a result, a spectroscopic redshift is not available for XRF 040812.

3.3.2. HST Observations

HST ACS imaging for XRF 040812 was carried out on 2004 September 13.4 and October 4.8 UT ($t \approx 32.1$ and 53.6 days after the burst). Each epoch had a total exposure time of 2000 and 2120 s in the F625W and F775W filters, respectively. Observations were taken with orientation angles chosen to minimize contamination from diffraction spikes and saturated columns resulting from the bright foreground star. Using the Chandra source list provided by Patel et al. (2004a), we identified five unconfused, unsaturated sources in common between the Chandra observations and our $F$-band Las Campanas Observatory (LCO) 40 inch observations (Berger et al. 2004a) and used these to tie the X-ray afterglow position to ground-based images. The LCO and HST images were then registered, resulting in a final positional uncertainty of $0''.91 (2 \sigma)$.

Through examination of the HST images, we find an extended source $\sim 0''.3 (<1 \sigma)$ from the nominal Chandra position and interpret it as the host galaxy of XRF 040812. We find the galaxy to be relatively bright, F625W $\approx 24.50 \pm 0.06$ mag,
corresponding to $R \approx 20.68 \pm 0.05$ mag after correcting for the large foreground extinction. Comparison with the set of GRB host galaxy magnitudes compiled by E. Berger et al. (2005, in preparation) suggests that XRF 040812 is at a relatively low redshift, $z \approx 0.5$. At this redshift, the host galaxy extinction is constrained to be $A_V,_{\text{host}} \lesssim 6.1$ (90% confidence), based on our independent analysis of the lowest energy X-ray afterglow emission.

Image subtraction reveals no transient sources that could be attributed to an optical afterglow or associated supernova within the Chandra localization circle (Fig. 6). We find 3 $\sigma$ detection limits on the residual image of F625W $> 27.0$ and F775W $> 26.4$ mag ($R > 26.8$ and $I > 25.9$ mag). Due to the large Galactic extinction, however, the true limits are significantly shallower, $R > 23.2$ and $I > 23.3$ mag.

Figure 7 displays the Galactic extinction–corrected HST limits along with the predicted optical afterglow extrapolated from the X-ray flux in a manner similar to that for XRF 040701 (§ 3.2.2). Given the observed X-ray decay, we extrapolate with $\beta \approx -0.96$ for $p \approx 2.92$ and $\beta \approx -1.29$ for $p \approx 2.59$. As evident from the figure, the HST $I$-band limit is 1.9 mag fainter than the predicted optical afterglow, assuming the flux continued evolving as $F_{\text{opt}} \propto t^{-1.4}$ to the HST epoch. If, instead, a jet break occurred at the second Chandra epoch, the predicted optical afterglow could be consistent with the HST nondetection.

### 3.3.3. Supernova Limits

Since the redshift of XRF 040812 is not known, we overplot synthesized light curves for SNe 1998bw, 1994I, and 2002ap at the appropriate redshift such that the SN curves match the residual-image HST detection limit. Supernovae placed above these redshift limits would not be detected. Due to the heavy foreground extinction toward XRF 040812, the $I$-band limits provide deeper constraints on an associated supernova. As shown in Figure 7, a SN 1998bw–like supernova is ruled out for $z \lesssim 0.90$, while SN 1994I– and SN 2002ap–like SNe are ruled out for $z \lesssim 0.34$ and $z \lesssim 0.35$, respectively. To be consistent with the estimated low-$z$ inferred from the host galaxy brightness, an associated SN must be significantly fainter than SN 1998bw or suppressed due to host galaxy extinction.

### 3.4. XRF 040916

#### 3.4.1. Prompt Emission and Afterglow Properties

On 2004 September 16.002 UT the HETE-2 satellite discovered XRF 040916. Preliminary spectral analysis revealed a dearth of photons at $\approx 10$ keV suggestive that the event was an X-ray flash (Yamazaki et al. 2004a). The initial localization error region was 18′ in radius centered at $\alpha = 23^h01^m44^s$, $\delta = -05^\circ37'43''$ (J2000.0). A refined error box with half the original size (545 arcmin$^2$) was released later (Yamazaki et al. 2004b). Using SuprimeCam mounted on the Subaru 8.2 m telescope, Kosugi et al. (2004) discovered a faint optical afterglow at $\alpha = 23^h00^m55^s1, \delta = -05^\circ38'43''$ (J2000.0) with a magnitude of $R_C \approx 22.3 \pm 0.2$ at $t \approx 0.23$ days. The afterglow subsequently decayed as $F_{\text{opt}} \propto t^{-1.0}$. In comparison to GRB optical afterglows compiled by Fox et al. (2003) and Berger et al. (2005), XRF 040916 is the faintest optical afterglow ever detected on this timescale. We note that no spectroscopic redshift has been reported for this event.

#### 3.4.2. HST Observations

XRF 040916 was imaged with HST ACS on 2004 October 18.38 and November 30.30 UT ($t \approx 32.4$ and 75.3 days after the burst) for a total exposure time of 1930 (2058) s in epoch 1 and 1928 (2056) s in epoch 2 in the F625W (F775W) filter. For astrometry, we used early-time ($t \approx 0.16$ day) $R$- and $I$-band data from the Palomar robotic 60 inch (1.5 m) telescope (P60;
S. B. Cenko et al. 2005, in preparation) in which the optical afterglow is clearly detected. Twelve stars in common between the Palomar and HST images provided an astrometric uncertainty of 0.29\(^{\circ}2\) (2\(\sigma\)). Within the afterglow position error circle, we find a faint source near the detection limit of our first epoch F625W and F775W images at \(\alpha = 23^\text{h}00^\text{m}55^\text{s}141, \delta = -05^\circ38^\prime42^\prime70\) (J2000.0). Figure 8 shows that the source is too faint to be recovered in the residual images, implying that it is just below our 3\(\sigma\) detection threshold of F625W > 27.9 mag and F775W > 27.2 mag (\(R > 27.7\) and \(I > 26.7\) mag). Correcting for Galactic extinction (\(A_R = 0.15\); Schlegel et al. 1998), the true limits are \(R > 27.5\) and \(I > 26.6\) mag.

In Figure 9 we show the HST limits along with early-time data from P60 and from the GCNs (Kosugi et al. 2004; Klotz et al. 2004; Henden 2004), all corrected for Galactic extinction. The early data are well fit with a \(F_{opt} \propto t^{-1.0}\) decay. We note that the early detection by Henden (2004) is inconsistent with our \(I\)-band data. The HST limits are consistent with the extrapolated optical afterglow, assuming that the flux decayed without steepening until the epoch of HST observations.

3.4.3. Supernova Limits

Since the redshift of XRF 040916 is not known, we overplot synthesized light curves for SNe 1994I and 2002ap each at the appropriate redshift such that the SN curves match the residual image HST detection limit. Supernovae with light curves similar to SNe 1994I and 2002ap would not be detected above \(z = 1.02\) and \(z = 0.82\), respectively. Synthesized light curves for SN 1998bw at \(z = 0.8\) and \(z = 1.2\) represent the limits to which we can confidently extrapolate the rest-frame SN spectrum. These light curves are \(\sim 3\) and \(\sim 1.5\) mag brighter than the observed HST limits in the \(R\) and \(I\) bands, and therefore suggest that either XRF 040916 is at higher redshift (e.g., \(z > 1.2\)) or it is associated with a lower luminosity SN.

We note that XRF 040916 is the only event within our HST survey for which we do not detect the host galaxy. Given our

![Figure 7](image1.png)

**Fig. 7.**—Constraints on a supernova associated with XRF 040812 are shown for the \(R\) and \(I\) bands. By extrapolating the observed X-ray afterglow to the optical bands, we predict a range of magnitudes for the optical afterglow on these same timescales (dark-shaded polygon). Assuming that the temporal decay can be extrapolated outside the X-ray observation window produces the light-shaded bands. Dashed lines represent the case where a jet break occurs at the second Chandra epoch. The marked arrows show the (Galactic extinction–corrected) HST constraints derived from image subtraction techniques described in §3.3.2. Synthesized light curves for SNe 1998bw (thick line), 1994I (medium line), and 2002ap (thin line), are shown each at the redshift limit to which they could be detected within our residual HST observations (circled dots).

![Figure 8](image2.png)

**Fig. 8.**—Six-panel frame showing HST ACS imaging for XRF 040916 at \(t \sim 32.4\) days (epoch 1) and \(t \sim 75.3\) days in the F625W and F775W filters. By subtracting epoch 2 images from epoch 1, we produced the residual images. We apply the same stretch to all frames. As shown in the residual images, a faint source is detected in epoch 1, coincident with the astrometrically derived optical afterglow position (2\(\sigma\); circle).
In the case of XRF 040701, our foreground extinction–corrected \textit{HST} detection limit is \(-6\) mag fainter than SN 1998bw at this redshift. Our analysis of the X-ray afterglow spectra reveals that the rest-frame host galaxy extinction is constrained to \(A_V, \text{host} \leq 2.8\), implying a conservative upper limit on the brightness of the associated SN to be \(\sim 3.2\) mag fainter than SN 1998bw and fainter than all of the GRB SNe studied to date. Taken together, XRFs 020903 and 040701 (the only two XRFs with redshifts in our sample) imply that at least some of the XRF-associated SNe are considerably fainter than SN 1998bw.

Due to the heavy foreground extinction toward XRF 040812, our ability to detect a SN 1998bw–like event would only be possible for \(z \leq 0.7\). In this case, analysis of the X-ray afterglow does not provide a strong constraint on the host galaxy extinction, since the lowest energy photons are absorbed by the Galaxy. Our limits are more constraining for the case of XRF 040916, where we would be sensitive to a SN 1998bw–like supernova beyond \(z \approx 1.2\). The lack of a SN detection, however, is consistent with a high redshift, as possibly suggested by the faintness of the host galaxy and optical afterglow.

Deeper constraints have previously been reported based on \textit{HST} STIS data for two additional XRFs without known redshifts, XRFs 011030 and 020427 (Levan et al. 2005). Thanks to the broad throughput of the STIS Clear filter, the sensitivity extends redward of \(B\) band, thereby enabling SN detection to \(z \approx 1.5\) before UV blanketing suppresses the observed emission. Levan et al. (2005) showed that a SN 1998bw–like supernova would be detectable to \(z \sim 1.5\) for both XRFs 011030 and 020427. Using the X-ray afterglow data for these two bursts, Levan et al. (2005) estimated their host galaxy extinction to be \(A_V \leq 1.7\) and \(A_I \leq 2.5\), respectively, assuming a moderate redshift of \(z \gtrsim 0.5\). At lower redshift, the host galaxy extinction required to suppress a SN 1998bw–like supernova is inconsistent with the X-ray limits, suggesting that these two bursts are either located at higher redshift or associated with low-luminosity SNe. We note that a firm redshift limit of \(z \lessgtr 2.3\) has been reported for XRF 020427 based on the lack of Ly\(\alpha\) absorption down to 3800 \AA\ within the optical spectrum (van Dokkum & Bloom 2003).

While there were no \textit{HST} observations taken for XRF 030723, we utilize the deep ground-based afterglow observations reported by Fynbo et al. (2004) to constrain the emission from an underlying supernova. Despite claims that the optical rebrightening at \(t \sim 10\) days is due to an associated supernova (Tominaga et al. 2004; Fynbo et al. 2004), we conclude that the observed optical/near-IR (NIR) variability is dominated by afterglow emission since neither the \(R\)–\(K\) color nor the optical to X-ray spectral index vary on this timescale (D. B. Fox et al. 2005, in preparation; Butler et al. 2005). We therefore adopt the \(R\)-band afterglow light curve as an effective upper limit on the flux of an accompanying SN. We derive the most robust constraint from an observation at \(t = 24.78\) days with \(R = 25.08 \pm 0.09\). This limit is sufficiently deep to rule out a SN 1998bw–like supernova at \(z \lessgtr 0.8\). We note that while the redshift of XRF 030723 is not known, the lack of Ly\(\alpha\) absorption in optical spectra limits the redshift to \(z \lessgtr 2.3\) (Fynbo et al. 2004).

We summarize the limits on XRF-associated supernovae for these seven XRFs in Figure 10. Also shown are the peak SN magnitudes (relative to SN 1998bw) for limits (GRB 010921; Price et al. 2003) and secure detections of GRB-associated supernovae compiled from the literature (GRBs 970228, 980703, 990712, 991208, 000911, 011121, 020405, 021211 [Zeh et al. 2004]; GRB 030329 [Lipkin et al. 2004; Deng et al. 2005]; GRB 031203 [Malesani et al. 2004]; and GRB 041006 [Stanek et al. 2004].)
5. DISCUSSION

We presented results from our *HST* ACS search for the supernovae associated with the XRFs 020903, 040701, 040812, and 040916, and extended this sample by including published results for SN searches in XRFs 011030, 020427, and 030723. We find strong evidence (photometric and spectroscopic) for a SN 1998bw–like supernova (dimmed by \(\lesssim 1\) mag) in association with XRF 020903 \((z = 0.25)\). This finding conclusively associates XRFs with the death of massive stars for the first time. In the case of XRF 040701 \((z = 0.21)\), our *HST* limit is ~6 mag fainter than SN 1998bw, which cannot be accounted for by host galaxy extinction. Based on these two events (XRFs 020903 and 040701), we conclude that at least some XRF-associated SNe exist but can be significantly fainter than SN 1998bw.

In Figure 11 we compile peak magnitudes for local Type Ibc supernovae and GRB-associated SNe. While the GRB-SN population tends to lie at the bright end of the local SN luminosity distribution, there is a pronounced ~2 mag spread in their observed peak brightness, which produces significant overlap with the local SNe. We emphasize that the SN associated with XRF 020903 is consistent with this observed spread; however, a supernova associated with XRF 040701 would be considered faint even in the context of the local SN population.

Since peak luminosity correlates roughly with the mass of \(^{56}\text{Ni}\) synthesized in the explosion, these observations imply a significant spread in the nickel yield from GRB and XRF explosions. Most importantly, as revealed from low-luminosity GRB/XRF SNe, engine-driven relativistic explosions do not necessarily produce more \(^{56}\text{Ni}\) than local SNe Ibc, which are not associated with relativistic ejecta (Berger et al. 2003b). This result is bracketed by two extremes: events with a large nickel output can be associated with weak engine-driven explosions harboring only a small amount of relativistic ejecta (e.g., SN 1998bw/GRB 980425), and those with a low nickel yield can be produced in strong engine-driven explosions characterized by copious amounts of energy coupled to highly relativistic jetted material. In conclusion, we find evidence that nickel production and engine activity represent independent parameters of the GRB/XRF explosion mechanism, each of which can be individually tuned.

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