We present the optical discovery and subarcsecond optical and X-ray localization of the afterglow of the short GRB 120804A, as well as optical, near-IR, and radio detections of its host galaxy. X-ray observations with Swift/XRT, Chandra, and XMM-Newton extending to $\delta t \approx 19$ days reveal a single power-law decline. The optical afterglow is faint, and comparison to the X-ray flux indicates that GRB 120804A is “dark,” with a rest-frame extinction of $A_{V,\text{rest}} \approx 2.5 \text{ mag}$ at $z = 1.3$. The intrinsic neutral hydrogen column density inferred from the X-ray spectrum, $N_{\text{HI, int}}(z = 1.3) \approx 2 \times 10^{22} \text{ cm}^{-2}$, is commensurate with the large extinction. The host galaxy exhibits red optical/near-IR colors. Equally important, JVLA observations at $\approx$0.9–11 days reveal a constant flux density of $F_\nu(5.8 \text{ GHz}) = 35 \pm 4 \mu\text{Jy}$ and an optically thin spectrum, unprecedented for GRB afterglows, but suggestive instead of emission from the host galaxy. The optical/near-IR and radio fluxes are well fit with the scaled spectral energy distribution of the local ultraluminous infrared galaxy (ULIRG) Arp 220 at $z \approx 1.3$, with a resulting star formation rate of $\dot{M}_{\star} \approx 300 M_{\odot} \text{ yr}^{-1}$. The inferred extinction and small projected offset (2.2 $\pm$ 1.2 kpc) are also consistent with the ULIRG scenario, as is the presence of a companion galaxy at the same redshift and with a separation of about 11 kpc. The limits on radio afterglow emission, in conjunction with the observed X-ray and optical emission, require a circumburst density of $n \sim 10^{-3} \text{ cm}^{-3}$, an isotropic-equivalent energy scale of $E_{\gamma, \text{iso}} \approx E_{K, \text{iso}} \approx 7 \times 10^{45} \text{ erg}$, and a jet opening angle of $\theta_j \gtrsim 11^\circ$. The expected fraction of luminous infrared galaxies in the short GRB host sample is $\sim$0.01 and $\sim$0.25 (for pure stellar mass and star formation weighting, respectively). Thus, the observed fraction of two events in about 25 hosts (GRBs 120804A and 100206A) appears to support our previous conclusion that short GRBs track both stellar mass and star formation activity.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB120804A)

Online-only material: color figures

1. INTRODUCTION

Short-duration gamma-ray bursts (GRBs) occur in a wide range of environments that include elliptical and star-forming galaxies in the field and in clusters (e.g., Berger 2011 and references therein). These galaxies have redshifts of $z \approx 0.1$ to $\gtrsim 1$ (Berger et al. 2007; Rowlinson et al. 2010), star formation rates of SFR $\lesssim 0.01$ to $\approx 40 M_{\odot} \text{ yr}^{-1}$ (Berger 2009; Perley et al. 2012), and stellar masses of $M_{\star} \approx 10^9$–$10^{11} M_{\odot}$ (Leibler & Berger 2010). These properties are suggestive of a progenitor population that tracks both stellar mass and star formation activity (though with a significant delay of $\sim 0.3 \text{ Gyr}$; Leibler & Berger 2010), in agreement with the popular compact object coalescence model (e.g., Eichler et al. 1989; Narayan et al. 1992).

In a similar vein, short GRBs also exhibit a range of explosion properties, with isotropic-equivalent energies of $E_{\gamma, \text{iso}} \sim E_{K, \text{iso}} \sim 10^{49}$–$10^{52} \text{ erg}$ (Berger 2007; Nakar 2007; Nysewander et al. 2009), jet opening angles of $\theta_j \approx \text{few} \gtrsim 20^\circ$ in a few cases (Burrows et al. 2006; Grupe et al. 2006; Soderberg et al. 2006; Watson et al. 2006; Fong et al. 2012), and circumburst densities of $n \lesssim 1 \text{ cm}^{-3}$ (Berger et al. 2005; Soderberg et al. 2006; Fong et al. 2012). The distribution of opening angles is of particular importance since it impacts the true energy scale and event rate. To date, all measurements or limits on $\theta_j$ have relied on X-ray observations thanks to the relative brightness and high detection fraction of the afterglow in the X-ray band compared to the optical and radio bands (Nysewander et al. 2009; Berger 2010). Here we present the optical discovery and subarcsecond localization of the optical and X-ray afterglow of the short GRB 120804A, as well as optical, near-IR, and radio detections of its host galaxy. The afterglow data constrain the burst properties ($E_{K, \text{iso}}$, $\theta_j$, $n$). The host galaxy observations identify it as an ultraluminous infrared galaxy (ULIRG) at a photometric redshift of $z \approx 1.3$, making GRB 120804A one of the most distant short bursts known to date. This is the first ULIRG host in the short GRB sample, exceeding even the luminous infrared galaxy (LIRG) likely host of GRB 100206A (Perley et al. 2012). We present the afterglow and host galaxy observations in Section 2, extract the explosion properties in Section 3, and determine the host galaxy photometric redshift and properties in Section 4. Throughout the paper we report magnitudes in the AB system (unless otherwise noted), use a Galactic extinction value of $E(B-V) \approx 0.204 \text{ mag}$ (Schlafly & Finkbeiner 2011), and employ the standard cosmological parameters: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda} = 0.73$, and $\Omega_M = 0.27$. 

ABSTRACT

We present the optical discovery and subarcsecond optical and X-ray localization of the afterglow of the short GRB 120804A, as well as optical, near-IR, and radio detections of its host galaxy. X-ray observations with Swift/XRT, Chandra, and XMM-Newton extending to $\delta t \approx 19$ days reveal a single power-law decline. The optical afterglow is faint, and comparison to the X-ray flux indicates that GRB 120804A is “dark,” with a rest-frame extinction of $A_{V,\text{rest}} \approx 2.5 \text{ mag}$ at $z = 1.3$. The intrinsic neutral hydrogen column density inferred from the X-ray spectrum, $N_{\text{HI, int}}(z = 1.3) \approx 2 \times 10^{22} \text{ cm}^{-2}$, is commensurate with the large extinction. The host galaxy exhibits red optical/near-IR colors. Equally important, JVLA observations at $\approx$0.9–11 days reveal a constant flux density of $F_\nu(5.8 \text{ GHz}) = 35 \pm 4 \mu\text{Jy}$ and an optically thin spectrum, unprecedented for GRB afterglows, but suggestive instead of emission from the host galaxy. The optical/near-IR and radio fluxes are well fit with the scaled spectral energy distribution of the local ultraluminous infrared galaxy (ULIRG) Arp 220 at $z \approx 1.3$, with a resulting star formation rate of $\dot{M}_{\star} \approx 300 M_{\odot} \text{ yr}^{-1}$. The inferred extinction and small projected offset (2.2 $\pm$ 1.2 kpc) are also consistent with the ULIRG scenario, as is the presence of a companion galaxy at the same redshift and with a separation of about 11 kpc. The limits on radio afterglow emission, in conjunction with the observed X-ray and optical emission, require a circumburst density of $n \sim 10^{-3} \text{ cm}^{-3}$, an isotropic-equivalent energy scale of $E_{\gamma, \text{iso}} \approx E_{K, \text{iso}} \approx 7 \times 10^{45} \text{ erg}$, and a jet opening angle of $\theta_j \gtrsim 11^\circ$. The expected fraction of luminous infrared galaxies in the short GRB host sample is $\sim$0.01 and $\sim$0.25 (for pure stellar mass and star formation weighting, respectively). Thus, the observed fraction of two events in about 25 hosts (GRBs 120804A and 100206A) appears to support our previous conclusion that short GRBs track both stellar mass and star formation activity.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB120804A)

Online-only material: color figures
2. OBSERVATIONS AND ANALYSIS

GRB 120804A was discovered with the Swift Burst Alert Telescope (BAT) on 2012 August 4 at 00:55:47.8 UT (Baumgartner et al. 2012) and was also detected with Konus-WIND (Sakamoto et al. 2012). The burst duration is $T_{90} = 0.81\pm0.08\text{ s (15–350 keV)}$ with a fluence of $F_p = (8.8\pm0.5)\times10^{-7}\text{ erg cm}^{-2} (15–150\text{ keV})$ and $(1.45\pm0.30)\times10^{-6}\text{ erg cm}^{-2}$ (15–1000 keV). The 16 ms peak flux is $(6.0\pm2.7)\times10^{-6}\text{ erg cm}^{-2}\text{ s}^{-1} (15–1000\text{ keV})$. A joint analysis of the BAT and Konus-WIND data indicates a peak energy of $E_p = 135^{+66}_{-29}\text{ keV}$ (Sakamoto et al. 2012). The spectral lags are $16\pm12\text{ ms (15–25 to 50–100 keV)}$ and $-5\pm6\text{ ms (25–50 to 100–350 keV)}$.

Recently, Bromberg et al. (2012) suggested, based on prompt-emission properties alone, that the 50% probability dividing line for Swift long and short GRBs is about 0.8 s, similar to the duration of GRB 120804A. At the redshift of $z \approx 1.3$, which we infer in Section 4, the resulting rest-frame values of $E_p (\approx 310\text{ keV})$ and the spectral lag ($\approx 9\text{ ms}$) along with the isotropic-equivalent $y$-ray energy ($\approx 6\times10^{51}\text{ erg}$) and the peak luminosity ($\approx 3\times10^{52}\text{ erg s}^{-1}$) are generally intermediate between the correlations exhibited by short and long GRBs (e.g., Figures 3 and 4 of Zhang et al. 2009). However, the combination of lag and duration most closely matches the short-burst distribution. In the absence of a specific analysis of GRB 120804A along the lines of Bromberg et al. (2012) that can argue for a long-burst origin, we consider GRB 120804A to be in the short-duration category.

Swift/X-ray Telescope (XRT) observations commenced about 78 s after the burst and led to the identification of a fading source, located at R.A. = $15^h35^m47^s51$, decl. = $-28^\circ46'56''/9$ with an uncertainty of 1\' radius (90% containment, UVOT-enhanced; Osborne et al. 2012). Observations with the UV/Optical Telescope (UVOT) began about 97 s after the burst, but no counterpart was detected to a 3\sigma limit of $\lesssim 21.4\text{ mag in the white filter (at}\delta t \approx 97–247\text{ s; Chester & Lien 2012)}$. Optical and near-IR observations with GROND starting at $\delta t \approx 1.5\text{ hr also led to non-detections with } \lesssim 22\text{ mag (griz) and } \lesssim 20.6\text{ mag (the J band; Sudilovsky et al. 2012).}$

2.1. X-Ray Observations

We analyze the Swift/XRT data using the HEASOFT package (v6.11) and latest calibration files with the standard filtering and screening criteria. We generate the 0.3–10 keV count-rate light curve following the procedure described in Margutti and screening criteria. We generate the 0

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We further obtained an XMM-Newton observation on 2012 August 22.91 UT ($\delta t \approx 18.9\text{ days}$; PI: Margutti) to search for the signature of a jet break at late time. We analyze the EPIC data with the XMM Science Analysis System (SAS v11.0.0), selecting events with PATTERN $\leq 12$ for the MOS cameras, PATTERN $\leq 4$ for the pn camera, and FLAG = 0 for both. To reduce the contamination by soft proton flares, we screen the original event files using a sigma-clipping algorithm. The remaining good science time is 29.5 ks for MOS1 and MOS2 and 25.5 ks for pn. The X-ray afterglow is detected in the MOS1 and MOS2 images with $(1.0\pm0.3)\times10^{-3}\text{ counts s}^{-1}$ (0.2–10 keV) and in the pn image with $(4.3\pm0.7)\times10^{-3}\text{ counts s}^{-1}$ (0.2–10 keV). We perform spectral analysis using the evselect tool, with the response files generated with the rmfgen and arfgen tools. The resulting inter-calibration factor of MOS1 and MOS2 relative to pn is 0.9–1. We adopt the value of $N_{\text{hit}}$ from the XRT analysis, leading to a pn unabsorbed 0.3–10 keV flux of $(2.4\pm0.5)\times10^{-14}\text{ erg s}^{-1}\text{ cm}^{-2}$.

2.2. Optical Afterglow Discovery and Relative X-Ray Astrometry

We obtained two epochs of i-band imaging with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on the Gemini-North 8 m telescope on 2012 August 4.27 and 7.30 UT ($\delta t \approx 0.23\text{ days and } \approx 3.26\text{ days, respectively}$). The observations consisted of 1980 s and 2880 s, respectively, in $0''/65$ seeing. We process the data using the gemini1 package in IRAF and perform photometry using a zero point of 28.46 $\pm$ 0.10 mag measured on the nights of August 2–8 UT. We perform digital image subtraction of the two epochs with the ISIS package (Alard 2000) and recover a fading source with $m_i = 26.2\pm0.2\text{ AB mag (with an additional systematic uncertainty of } \pm 0.1\text{ mag due to the zero-point uncertainty),}$ which we consider to be the optical afterglow of GRB 120804A. Corrected for Galactic extinction, the resulting flux density is $F_i = 0.17\pm0.05\text{ \mu Jy at } \delta t \approx 0.23\text{ days.}$ We note that for a typical power-law decline rate in the optical band, $F_i \propto t^{-1}$, the expected flux density at $\delta t \approx 3.26\text{ days is less than 1/10th of the flux density at } \delta t \approx 0.23\text{ days, and we can therefore safely approximate the flux density in the second epoch as zero.}$ Images of the two epochs and the resulting subtraction are shown in Figure 1.

We determine the absolute position of the afterglow by astrometrically matching the images to the 2MASS reference frame using 45 common sources. The resulting astrometric uncertainty is 0.15 in each coordinate. The afterglow position in the residual image is R.A. = $15^h35^m47^s79$, decl. = $-28^\circ46'56''/17$ (J2000), with a centroid uncertainty of about 0.05 in each coordinate.

To locate the Chandra X-ray afterglow on the optical images, we perform differential astrometry using four common sources.
We find a relative offset between the two coordinate frames (Chandra to Gemini) of \( \delta \text{RA} = -0.06 \pm 0.21 \) and \( \delta \text{decl.} = -0.01 \pm 0.17 \), leading to a refined X-ray afterglow position of R.A. = 15\(^{h}\)35\(^{m}\)47.478, decl. = -28\(^{\circ}\)46\(^{\prime}\)36\(^{\prime\prime}\)30 with an uncertainty of about 0.35 radius that takes into account a centroid uncertainty of about 0.06; see Figure 1. The Chandra position is in excellent agreement with the optical afterglow position.

2.3. Optical/Near-IR Host Galaxy Observations

In the second Gemini observation, we detect an extended source near the afterglow position with \( m_r = 24.80 \pm 0.15 \text{ mag} \) (including zero-point uncertainty and corrected for Galactic extinction) located at R.A. = 15\(^{h}\)35\(^{m}\)47.477, decl. = -28\(^{\circ}\)46\(^{\prime}\)36\(^{\prime\prime}\)44, with a centroid uncertainty of about 0.10. We consider this source to be the host galaxy of GRB 120804A. Given the brightness of the galaxy, the probability of chance coincidence using a radius of 1\(^{\prime\prime}\) (e.g., Bloom et al. 2002; Berger 2010) is \( P_{cc} \approx 0.02 \). We investigate potential association with brighter galaxies (\( \approx 19–21 \text{ mag} \)) at larger offsets (\( \approx 0.2–1 \)) but find chance coincidence probabilities of \( P_{cc} \approx 0.2–0.7 \), indicating that these are not likely to be associated with GRB 120804A.

We also observed GRB 120804A with GMOS on the Gemini-North telescope on 2012 August 4.24 UT (\( \delta t \approx 0.20 \text{ days} \)) in the \( r \) band with a total exposure time of 2340 s. We process the data using the Gemini package in IRAF and perform photometry using a zero point of 28.41 \( \pm 0.02 \text{ mag} \) measured on the nights of July 27–August 9 UT. Photometry at the position of the host galaxy reveals a faint source with \( m_r = 26.2 \pm 0.2 \text{ mag} \), corresponding to a flux density of \( F_r = 0.19 \pm 0.04 \mu \text{Jy} \) (corrected for Galactic extinction). Since this was an early observation, the measurement may be contaminated by afterglow emission. However, taking into account a spectral shape of \( F_v \propto v^{-0.8} \) and the large rest-frame extinction (see Section 3), we conclude that the afterglow contribution is sub-dominant, \( \approx 0.03 \mu \text{Jy} \).

We observed the host galaxy in the \( J \) band with the FourStar near-IR camera on the Magellan/Baade 6.5 m telescope on 2012 August 28.98 UT with a total on-source time of 2390 s. We analyze the data using a custom pipeline in python and perform photometry using common sources with the 2MASS catalog. The host galaxy has a measured brightness of \( m_J = 23.05 \pm 0.20 \text{ mag} \) (corrected for Galactic extinction).

We obtained \( Y \) - and \( K_s \)-band observations with the High Acuity Wide-field \( K \)-band Imager (HAWK-I) on the Very Large Telescope (VLT) starting on 2012 September 7.96 UT, with a total exposure time of 1320 s in each filter. We produce dark-subtracted and flat-fielded images of the field using the HAWK-I pipeline within {	extit{esorex}} and perform photometry on the \( K_s \)-band image relative to the 2MASS catalog. We determine the \( Y \)-band calibration using the instrumental zero point (appropriate for our observations, which were obtained in good conditions) and confirm that this is appropriate by extrapolating 2MASS \( J \)-band photometry to observations taken in the \( i \) band. The host galaxy is detected in the \( K_s \) band with \( m_{K_s} = 22.0 \pm 0.1 \text{ mag} \) and weakly in the \( Y \) band with \( m_Y = 23.7 \pm 0.3 \text{ mag} \) (both values are corrected for Galactic extinction).

Finally, we obtained spectroscopic observations of the host galaxy with the FOCal Reducer and low dispersion Spectrograph (FORS2) on the VLT on 2012 August 19.01 UT. The observations consisted of 4 \( \times \) 600 s exposures, covering the wavelength range 4300–9300 Å. We set the slit position angle to 149\(^{\circ} \) to cover the host and nearby galaxy (see Figure 1). We detect no continuum or line emission at the position of the host galaxy and only a faint continuum from the nearby galaxy.

The host galaxy photometry is summarized in Table 1. We also provide photometry for the extended source located \( \approx 1\prime\prime.4 \) to the southeast of the host galaxy position (Figure 1).
for flux and bandpass calibration and interleaved observations of J0238+1636 for gain calibration. There is a bright, contaminating source in the field (27 mJy at 4.9 GHz and 9 mJy at 6.7 GHz), located about 4′5 from the position of GRB 100206A. We therefore image the field utilizing self-calibration techniques on this bright source, leading to a non-detection of radio emission with a conservative 5σ limit of $F_\nu (5.8 \text{ GHz}) \lesssim 80 \mu \text{Jy}$. The synthesized beam size of $1.7' \times 0.8'$ is well matched to the angular size of the host galaxy (Perley et al. 2012).

### 3. Afterglow Properties

We model the X-ray data, optical detection, and radio upper limits using the standard afterglow synchrotron model (Granot & Sari 2002). We follow the standard assumptions of synchrotron emission from a power-law distribution of electrons ($N(\gamma) \propto \gamma^{-p}$) with constant fractions of the post-shock energy density imparted to the electrons ($\epsilon_e$) and magnetic fields ($\epsilon_B$). The additional free parameters of the model are the isotropic-equivalent blast-wave kinetic energy ($E_{K,\text{iso}}$) and the circumburst density ($n$ for a constant density medium).

We note three key observational facts to guide the afterglow modeling. First, the X-ray light curve is best fit with a single decline rate of $\alpha_X = -0.93 \pm 0.06$, which, coupled with the spectral index of $\beta_X \approx -0.9 \pm 0.1$ (Section 2.1), indicates that the synchrotron cooling frequency is $v_c \approx v_X$ and that $p \approx 2.2$. Second, the peak of the X-ray afterglow is $\approx 20 \mu \text{Jy}$ at $\delta t \approx 200$ s. This suggests that the radio light curve will eventually reach a similar peak flux density if the synchrotron peak frequency is $v_m \approx v_X$ at $\delta t \approx 200$ s (i.e., $F_\nu, m \approx 20 \mu \text{Jy}$ at 200 s). Such a peak flux density is consistent with our inferred radio upper limits. On the other hand, if $v_m$ is located well below the X-ray band at $\delta t \approx 200$ s, this would imply that $F_{\nu, m} \gtrsim 20 \mu \text{Jy}$, thereby violating the radio limits at later time. Finally, the optical and X-ray flux densities at $\delta t \approx 5.5$ hr are comparable, indicating that the optical to X-ray spectral index is $\beta_{OX} \approx 0.03 \pm 0.06$, compared to an expected slope of $\approx 0.6$ (for $p = 2.2$ and $v_c \approx v_X$). This shallow slope indicates that GRB 120804A can be classified as a “dark” burst, following the definition of Jakobsson et al. (2004).

To guide the reader, we use the constraints listed above along with the synchrotron emission equations in Granot & Sari (2002) to find the following rough constraints on the burst parameters:

\begin{align*}
\nu_m(200 \text{ s}) & \approx \nu_X \Rightarrow E_{K,\text{iso},52} \epsilon_e^2 \epsilon_B^2 \approx 1.1 \times 10^{-3}, \\
\nu_c(200 \text{ s}) & \approx \nu_X \Rightarrow E_{K,\text{iso},52} n_0 \epsilon_B^3 \approx 6.9 \times 10^{-5},
\end{align*}

\begin{equation}
F_{\nu, m}(200 \text{ s}) \approx 20 \mu \text{Jy} \Rightarrow E_{K,\text{iso},52} n_0^{1/2} \epsilon_B^2 \approx 3.0 \times 10^{-5}.
\end{equation}

Combining these equations with the constraint that $\epsilon_e, \epsilon_B \lesssim 1/3$ indicates that $E_{K,\text{iso}} \approx 3 \times 10^{51} \text{ erg}$ and $n_0 \approx 10^{-3} \text{ cm}^{-3}$.

Using the full model from Granot & Sari (2002), we find that the entire data set can be fit with the following parameters (using $z = 1.3$; see Section 4): $E_{K,\text{iso}} \approx 8 \times 10^{51} \text{ erg}$, $n \approx 10^{-3} \text{ cm}^{-3}$, $\epsilon_e \approx 0.3$, $\epsilon_B \approx 0.1$, and $p \approx 2.2$, in good agreement with the basic constraints discussed above. The inferred blast-wave energy is comparable to the isotropic-equivalent $\gamma$-ray energy, $E_{\gamma,\text{iso}} \approx 6 \times 10^{50} \text{ erg}$. To explain the suppressed optical emission, we also require $A_{\text{opt}} \approx 2.5 \text{ mag}$ (at $z = 1.3$). The resulting light curves are shown in Figure 2. Models with higher values of $E_{K,\text{iso}}$ and/or $n$ violate the radio limits (e.g., dotted line in Figure 2).
In addition, the lack of a break in the X-ray light curve to at least $\approx 46$ days (Burrows et al. 2012) places a lower bound on the jet collimation angle, with $\theta_j \gtrsim 11^\circ$, where we use the values of $E_{\text{iso}}$ and $\eta$ indicated above. This indicates a beaming correction factor of $f_{\text{beam}}^{-1} \equiv [1 - \cos(\theta_j)]^{-1} \lesssim 55$ and hence a beaming-corrected energy scale of $E_{\nu} + E_K \approx 2.5 \times 10^{50} - 1.4 \times 10^{52}$ erg, with the upper bound set by isotropy.

Since, in the afterglow model above, the X-ray light curve sets the overall flux density scale, an alternative explanation for the radio non-detections and the low optical flux density is that the X-ray emission is dominated by a different emission mechanism. One possibility is contribution from inverse Compton emission (Sari & Esin 2001), but this requires a large density of $n \gtrsim 10^{23}$ cm$^{-3}$. Another possibility is emission from a newly born rapidly spinning magnetar (e.g., Zhang & Meszaros 2001), but the expected evolution in this case is a relatively constant brightness for a duration similar to the spin-down timescale, followed by $F_{\nu} \propto t^{-2}$ at later time (for a typical braking index of 3). This is quite distinct from the observed single power law of $F_{\nu} \propto t^{-1}$ at $\delta t \gtrsim 200$ s.

4. A ULIRG HOST GALAXY

The observed optical/near-IR spectral energy distribution (SED) of the host galaxy exhibits a red color of $i - K = 2.8 \pm 0.25$ mag ($=4.3$ Vega mag); the $r - K$ color is $3.9 \pm 0.3$ mag ($=5.6$ Vega mag). There is also noticeable steepening between the $i$- and $Y$-band filters, with $i - Y = 1.1 \pm 0.45$ mag. These properties are indicative of a Balmer/4000 Å break at $z \approx 1.3$ and either an evolved or dusty stellar population. Using the Maraston (2005) evolutionary stellar population synthesis models to fit the $riYJK_s$-band data, we infer a photometric redshift of $z = 1.3^{+0.2}_{-0.1}$ (1$\sigma$ uncertainties); see Figure 3.

Taken in conjunction with the radio detection, the SED is reminiscent of ULIRGs ($L_{\text{FIR}} \gtrsim 10^{12} L_\odot$). To investigate this possibility, we compare the host galaxy fluxes to the SED$^9$ of the local ULIRG Arp 220. As shown in Figure 4, at $z = 1.3$ a simple scaling of Arp 220 provides a remarkable fit to the data. An elliptical galaxy template (2 Gyr old population; Polletta et al. 2007) at $z = 1.3$ provides a reasonable fit in the optical/near-IR (although it underestimates the observed $r$- and $K_s$-band fluxes) but cannot explain the radio emission (Figure 4).

At $z = 1.3$, the rest-frame $B$-band absolute magnitude is $M_B \approx -20.2$ mag, or $L_B \approx 0.2 L^*$ in comparison to the $B$-band luminosity function at $z \sim 1.3$–2 (Ilbert et al. 2005). The rest-frame $K$-band absolute magnitude inferred from the model is $M_K \approx -22.1$ mag ($-24.0$ Vega mag, or $L_K \approx 0.4 L^*$; Caputi et al. 2006b). This luminosity corresponds to a stellar mass of $M_* \approx 5 \times 10^{10} M_\odot$ (using a characteristic mass-to-light ratio of $M_*/L_K \approx 0.3$; Drory et al. 2004). The infrared bolometric luminosity scaled using the SED of Arp 220 is $L_{\text{FIR}} \approx 10^{12} L_\odot$.

The unobscured star formation rate is inferred from the observed $r$ band ($\lambda_0 \approx 2700$ Å) to be $\approx 1 M_\odot$ yr$^{-1}$. However, from the observed radio emission we estimate the total star formation rate to be much larger (Yun & Carilli 2002): 

$$
\text{SFR} \approx \frac{F_{\nu,\text{obs}} d_L^2}{25 v_{\nu,\text{GHz}}^2 + 0.7 v_{\nu,\text{GHz}}^{1.3}} \approx 300 M_\odot \text{yr}^{-1},
$$

where $v_0 = (1 + z) v_{\text{obs}}$ is the rest frequency and $d_L$ is the luminosity distance. Assuming that the host stellar mass has been assembled with this star formation rate gives a characteristic age of about 0.15 Gyr. Using the limit on radio emission from GRB 100206A in Equation (4), we find $\text{SFR} \lesssim 50 M_\odot \text{yr}^{-1}$.

The large star formation rate in the host of GRB 120804A is also expected to produce X-ray emission, with $L_X \approx 7 \times 10^{39} \times \text{SFR \ erg s}^{-1}$ (Watson et al. 2004; Vattakunnel et al. 2012). For the values inferred above we find an expected luminosity of $L_X \approx 2 \times 10^{42}$ erg s$^{-1}$, corresponding to a flux of $F_X \approx 4.5 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. This is about 55 times lower than the afterglow flux measured with $XMM$-Newton at

Figure 3. Photometric redshift constraints for the host galaxy of GRB 120804A (black) and the nearby galaxy (gray) using the optical and near-IR flux densities (Table 1) along with the Maraston (2005) evolutionary stellar population synthesis models. The best-fit value for the host galaxy is $z = 1.3^{+0.2}_{-0.1}$, while for the nearby galaxy it is $z = 1.25 \pm 0.10$ (1$\sigma$ uncertainties). (A color version of this figure is available in the online journal.)

Figure 2. X-ray light curve, optical $i$-band detection, and radio 5.8 GHz upper limits for the afterglow of GRB 120804A. The solid lines are an afterglow model fit using the formulation of Granot & Sari (2002), with $E_{\text{iso}} \approx 8 \times 10^{51}$ erg, $n \approx 10^{-3}$ cm$^{-3}$, $\eta_i \approx 0.3$, $\eta_B \approx 0.1$, and $p \approx 2.2$. The low observed flux density in the optical band is suggestive of extinction and can be explained with $A_V^\text{host} \approx 2$ mag (dashed red line). The dotted blue line indicates the predicted radio light curve for a model with fixed parameters of $n = 1$ cm$^{-3}$ and $E_{\text{iso}} = 6 \times 10^{51}$ erg (i.e., matched to $E_{\nu,\text{iso}}$), which produces an indistinguishable fit in the X-rays (this model requires $\eta_i \approx 0.25$, $\eta_B \approx 0.1$, and $p \approx 2.1$). Clearly, such a high density can be ruled out. The arrows mark the $\text{Chandra}$ and $\text{XMM-Newton}$ observations, including the time of a late $\text{Chandra}$ observation, which indicates continued decline with a single power law (Burrows et al. 2012).

(A color version of this figure is available in the online journal.)

9 Obtained from the SWIRE Template Library (Polletta et al. 2007). We note that ULIRG templates exhibit some variability, but this will have little effect on the resulting photometric redshift.
Figure 4. Left: spectral energy distribution of the host galaxy of GRB 120804A (black circles: optical, near-IR, and radio) compared to a scaled SED of Arp 220 (blue line) and an elliptical galaxy with a 2 Gyr stellar population (red line) at $z = 1.3$. Both SEDs are scaled to match the optical/near-IR photometry of the host galaxy. The inset shows a zoom-in on the optical/near-IR range, highlighting that both SEDs provide a reasonable fit in this wavelength range (with a somewhat better fit in the $K_s$-band for the Arp 220 SED). The gray symbols mark the photometry of the nearby galaxy, along with an elliptical galaxy model at $z = 1.3$. In both cases, the apparent steepening between the $i$- and $y$-band filters points to a similar redshift. Right: comparison to the scaled SEDs of radio-quiet (red line) and radio-loud (red line) AGNs at $z = 1.3$, as well as the SED of an elliptical galaxy with a 2 Gyr stellar population (green line). The AGN SEDs are scaled to match the observed radio flux density of the host galaxy. The radio-quiet AGN scenario overpredicts the optical, near-IR, and X-ray fluxes. On the other hand, the radio-loud scenario matches the radio flux density without violating the other measurements; the optical/near-IR emission is dominated by stellar emission. (A color version of this figure is available in the online journal.)

$\delta t \approx 19$ days and hence consistent with a star formation origin for the radio emission.

An alternative interpretation of the radio detection is emission from an active galactic nucleus (AGN). Matching the standard template of a radio-quiet AGN (Shang et al. 2011) to the observed radio flux density (using $z = 1.3$) leads to a substantial overestimate of the optical/near-IR brightness and a much bluer color (Figure 4). Similarly, the expected X-ray flux in this scenario is $F_X \approx 6.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, several times brighter than the XMM-Newton detection of the afterglow. Thus, we can rule out a radio-quiet AGN origin. If we instead use the standard radio-loud AGN template (Shang et al. 2011) matched to the radio flux density, we find that the expected optical/near-IR and X-ray fluxes are $\sim 1$--2 orders of magnitude fainter than measured (Figure 4). Indeed, the observed lower bound on the ratio of radio to X-ray luminosity, $\nu L_\nu / L_X \gtrsim 2 \times 10^{-4}$, along with an upper bound of $L_X \lesssim 5 \times 10^{42}$ erg s$^{-1}$ are in good agreement with samples of low-luminosity AGNs (e.g., Terashima & Wilson 2003). In this scenario, the optical/near-IR emission is instead dominated by a stellar component, from either an old population or a redborn young population with a modest star formation rate of a few $M_\odot$ yr$^{-1}$.

For the radio luminosity and stellar mass of the host galaxy, the fraction of galaxies with radio-loud AGNs is about $2 \times 10^{-3}$ (e.g., Heckman & Kauffmann 2002). Since the presence of a putative AGN should be unrelated to the GRB, this result indicates that the AGN hypothesis has a low likelihood. Similarly, while both a ULIRG and an AGN origin can explain the observed radio emission, we note that the former also offers a natural explanation for the inferred extinction and fits the broadband host SED with a single component. We therefore consider a ULIRG as the more likely explanation for the host galaxy of GRB 120804A.

The offset between the optical afterglow position and host galaxy centroid is $0\farcs27 \pm 0\farcs15$, corresponding to $2.2 \pm 1.2$ kpc at $z \approx 1.3$. This is a relatively small offset for short GRBs (with a median of $\approx 5$ kpc; Fong et al. 2010; Berger 2010), though not unprecedented. Still, in the context of a ULIRG origin, the small offset is consistent with the inferred afterglow extinction.

Finally, we determine a photometric redshift for the galaxy located $\approx 1\arcmin 4$ from the host galaxy position and find $z = 1.25 \pm 0.10$, consistent with that of the host galaxy (Figures 3 and 4). Thus, it appears likely that these galaxies, with a projected separation of about 11 kpc, are interacting or merging. This is not unexpected since at least some ULIRG activity is triggered by galaxy mergers (e.g., Sanders & Mirabel 1996).

5. SUMMARY AND CONCLUSIONS

We presented the discovery and subarcsecond localization of the optical and X-ray afterglow of the short GRB 120804A. A comparison of the observed fluxes points to substantial rest-frame extinction of $A_V \approx 2.5$ mag, commensurate with the large neutral hydrogen column density, $N_{H,\text{int}} \approx 2 \times 10^{22}$ cm$^{-2}$. In conjunction with deep radio limits, we infer an energy of $E_{\gamma,\text{iso}} \approx E_{K,\text{iso}} \approx 7 \times 10^{51}$ erg and a low circumburst density of $n \sim 10^{-3}$ cm$^{-3}$. The lack of a break in the X-ray afterglow at $\approx 46$ days leads to $\theta_j \gtrsim 11\arcsec$, in line with existing measurements of short GRB jets (Fong et al. 2012). The prompt-emission properties of GRB 120804A, combined with its low circumburst density, point to a genuine short-duration origin.

We also detect the host galaxy of GRB 120804A, which exhibits red optical/near-IR colors and radio emission that are well matched by the SED of a ULIRG (Arp 220) at $z \approx 1.3$. The inferred total star formation rate is $\approx 300 M_\odot$ yr$^{-1}$. A low-luminosity radio-loud AGN in an elliptical galaxy cannot be definitively ruled out, but the ULIRG interpretation, combined with the small projected offset of 2.2 $\pm$ 1.2 kpc, more naturally explains the inferred afterglow extinction. The host galaxy is part of an interacting/merging system, which is not unexpected for ULIRGs. Observations with the Atacama Large Millimeter/submillimeter Array (ALMA) will be able to robustly distinguish the two scenarios. At 240 GHz (ALMA
band), the expected flux densities are about 0.3 mJy and 1 μJy, for the ULIRG \(^{10}\) and AGN cases, respectively. The former can be detected with high significance in a short observation. The host galaxy of the short GRB 100206A at \(z = 0.407\) is also a luminous infrared galaxy, \(L_{\text{IR}} \approx 4 \times 10^{11}L_\odot\) with SFR \(\sim 30–40 M_\odot\) yr\(^{-1}\) inferred from SED fitting of data at \(\sim 0.3–10 \mu m\) (Perley et al. 2012). Here we find SFR \(\lesssim 60 M_\odot\) yr\(^{-1}\) from radio observations. Of the \(\approx 25\) short GRBs with robust host galaxy associations (Fong et al. 2013), the hosts of GRBs 120804A and 100206A are the only galaxies with clear LIRG/ULIRG properties. At \(z \sim 1\), the population of ULIRGs and bright LIRGs accounts for \(\sim 25\%\) of the total star formation rate density (Le Floc’h et al. 2005; Caputi et al. 2007), but their contribution to the stellar mass density is small, \(\sim 1\%\) to few percent (e.g., Caputi et al. 2006a). Thus, the fraction of \(\sim 5\%–10\%\) in the short GRB host population appears to be intermediate between the star formation and mass weighted fractions. This is expected for a progenitor population that tracks both star formation and stellar mass, consistent with previous findings for short GRBs (Leibler & Berger 2010).

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Facilities: Swift (XRT), CXO (ACIS-S), XMM, Gemini:Gillett (GMOS), Magellan:Baade (FourStar), VLT:Yepun (HAWK-I), EVLA

\(^{10}\) This flux density is relevant for the scaled SED of Arp 220. Variations in the dust temperature would lead to a range of potential flux densities (e.g., Yun & Carilli 2002; Michalowski et al. 2008).