THE HOST GALAXIES OF SHORT-DURATION GAMMA-RAY BURSTS: LUMINOSITIES, METALLICITIES, AND STAR FORMATION RATES

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ABSTRACT

The association of some short-duration gamma-ray bursts (GRBs) with elliptical galaxies established that their progenitors, unlike those of long GRBs, belong to an old stellar population. However, the majority of short GRBs appear to occur in star forming galaxies, raising the possibility that some progenitors are related to recent star formation activity. Here, we present optical spectroscopy of these hosts and measure their luminosities, star formation rates, and metallicities. We find luminosities of \( L_B \approx 0.1–1.5 \, L_\odot \), star formation rates of \( SFR \approx 0.2–6 \, M_\odot \, yr^{-1} \), and metallicities of \( 12 + \log(O/H) \approx 8.5–8.9 \left( Z \approx 0.6–1.6 \, Z_\odot \right) \). A detailed comparison to the hosts of long GRBs reveals systematically higher luminosities, lower specific star formation rates (SFR/L\(_B\)) by about an order of magnitude, and higher metallicities by about 0.6 dex. The Kolmogorov–Smirnov probability that the short and long GRB hosts are drawn from the same underlying galaxy distribution is only \( \approx 10^{-3} \). Short GRB hosts exhibit excellent agreement with the specific star formation rates and the luminosity–metallicity relation of field galaxies at \( z \approx 0.1–1 \). We thus conclude that short GRB hosts are not dominated by young stellar populations like long GRB hosts. Instead, short GRB hosts appear to be drawn uniformly from the underlying field galaxy distribution, indicating that the progenitors have a wide age distribution of several Gyr.

Key words: gamma rays: bursts

1. INTRODUCTION

The properties of gamma-ray burst (GRB) host galaxies provide important insight into the nature of the burst progenitors. In the case of the long-duration GRBs (\( T_{90} \gtrsim 2 \, s \)), the hosts are blue star forming galaxies with high specific star formation rates (SFRs) and sub-\( L_\odot \) luminosities (e.g., Hogg & Fruchter 1999; Chary et al. 2002; Berger et al. 2003; Le Floc’h et al. 2003; Christensen et al. 2004; Savaglio et al. 2008). Moreover, the bursts themselves trace the star formation activity within their hosts (Bloom et al. 2002; Fruchter et al. 2006). At low redshift, \( z \lesssim 0.3 \), long GRBs appear to occur preferentially in low luminosity and metallicity galaxies (Stanek et al. 2006; Savaglio et al. 2008), although it remains unclear whether this is a causal connection or a byproduct of the intense star formation activity (Berger et al. 2007a). Taken together, these properties provided an early indication that the progenitors of long GRBs are massive stars, and ultimately they may shed light on the conditions (if any) that favor the formation of the progenitors.

The more recent discovery of afterglow emission from short-duration GRBs led to associations with both star forming and elliptical host galaxies (Berger et al. 2005; Fox et al. 2005; Gehrels et al. 2005; Bloom et al. 2006). The association with elliptical galaxies demonstrates unambiguously that the progenitors of at least some short GRBs are related to an old stellar population, consistent with the popular model of compact object mergers (NS–NS or NS–BH—NS, neutron star; BH, black hole; e.g., Eichler et al. 1989; Narayan et al. 1992). In addition, Hubble Space Telescope imaging of the star forming host galaxy of GRB 050709 revealed that, unlike in the case of the long GRBs, the burst was not associated with a region of active star formation (Fox et al. 2005).

Subsequent to the discovery of the first short GRB afterglows and hosts, we have shown that a substantial fraction of these events (1/3–2/3) reside at higher redshifts than previously suspected, \( z \gtrsim 0.7 \) (Berger et al. 2007c; Cenko et al. 2008). Spectroscopic observations indicate that a substantial fraction of these galaxies are undergoing active star formation. Indeed, of the current sample of short GRBs localized to better than a few arcseconds (23 bursts), \( \approx 45\% \) reside in star forming galaxies compared to only \( \approx 10\% \) in elliptical galaxies.\(^1\) This result raises the question of whether some short GRBs are related to star formation activity rather than an old stellar population, and if so, whether the star formation properties are similar to those in long GRB host galaxies. The answer will shed light on the diversity of short GRB progenitors, in particular their age distribution and the possibility of multiple progenitor populations.

Here, we present optical spectroscopy of short GRB host galaxies and measure their luminosities, metallicities, and star formation rates (Sections 2 and 3). We then assess their specific SFRs and luminosity–metallicity relation, and compare these results with the properties of long GRB hosts and field star forming galaxies (Section 4). Finally, we use these comparisons to draw conclusions about the progenitor population, and outline future host galaxy studies that will provide continued constraints on the progenitors (Section 5).

Throughout the paper, we use the standard cosmological parameters, \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_m = 0.27 \), and \( \Omega_\Lambda = 0.73 \).

2. OBSERVATIONS

In Table 1, we summarize the properties of all short GRBs with Swift X-Ray Telescope (XRT) localizations, and their host galaxies. All references for the burst and host properties are provided in Table 1, including in particular Berger et al. (2007c) and Cenko et al. (2008) for the details of our spectroscopic observations. We present the flux-calibrated spectra of the host galaxies of GRBs 060801, 061006, 061210, 061217, and 070724 in Figure 1. Spectra of the hosts of GRBs 070429b and 070714b...

\(^1\) The other \( \approx 45\% \) remain currently unclassified due to their faintness, a lack of obvious spectral features, or the absence of deep follow-up.
The nature of the host galaxy remains unclear, given the location of an Abell cluster at the location of GRBs 050709 and 051221a are provided in Fox et al. (2005) and a faint galaxy of unknown redshift \( z < 1\) away (Berger 2007), a galaxy at \( z = 0.111\) about 17\(^{\prime}\) away (Berger 2006a; Stratta et al. 2007), and a faint galaxy of unknown redshift \( z \leq 1\) away. All three associations have a statistical significance of about 10\%. We note that the galaxy at \( z = 0.111\) has a specific SFR of 1.2 \( M_{\odot} \) yr\(^{-1}\) \((\text{Stratta et al. 2007})\), in good agreement with the host sample presented in this paper. In addition, we measure for this galaxy a luminosity of \( M_B \approx -19.1\) mag and a metallicity of \( 12 + \log(O/H) = 8.8 \pm 0.2\), in excellent agreement with the luminosity–metallicity relation.

References.
(1) Gehrels et al. 2005; (2) Bloom et al. 2006; (3) Villasenor et al. 2005; (4) Fox et al. 2005; (5) Hjorth et al. 2005; (6) Barthelmy et al. 2005; (7) Berger et al. 2005; (8) Gupte et al. 2006; (9) Ferrero et al. 2007; (10) Berger 2006b; (11) Prochaska et al. 2006; (12) La Parola et al. 2006; (13) Berger et al. 2007c; (14) Burrows et al. 2006; (15) Soderberg et al. 2006; (16) Arimoto et al. 2006; (17) Mangano et al. 2006; (18) Roming et al. 2006; (19) Sato et al. 2006a; (20) Troja et al. 2006; (21) Bloom et al. 2007; (22) Sato et al. 2006b; (23) Sato et al. 2006c; (24) Butler et al. 2006; (25) Krimm et al. 2006; (26) Golenetskii et al. 2006; (27) Troja et al. 2006; (28) Stratta et al. 2007; (29) Cannizzo et al. 2006; (30) Ziaeepour et al. 2006; (31) Cenko et al. 2008; (32) Gotz et al. 2007; (33) D’Avanzo et al. 2007b; (34) Barthelmy et al. 2007; (35) Barbier et al. 2007; (36) Graham et al. 2008; (37) Parsons et al. 2007; (38) Bloom & Butler 2007; (39) Cucchiara et al. 2007; (40) Guidorzi et al. 2007; (41) Berger & Kaplan 2007; (42) Marshall et al. 2007; (43) Perley et al. 2007; (44) Sato et al. 2007; (45) D’Avanzo et al. 2007a; (46) Berger et al. 2007b and (47) Ukawa et al. 2008.

are presented in Cenko et al. (2008), while spectra of the hosts of GRBs 050709 and 051221a are provided in Fox et al. (2005) and Soderberg et al. (2006), respectively. Below we summarize our new spectroscopic observations of GRB 070724.

2.1. GRB 070724

A putative host galaxy was identified within the 2\(^{\prime}\)2 radius XRT error circle of this short burst in archival Digital Sky Survey images (Bloom & Butler 2007). No coincident variable optical, near-IR, or radio source was detected (Levan et al. 2007; Cucchiara et al. 2007; Covino et al. 2007; Chandra & Frail 2007).

We obtained imaging and spectroscopy of the likely host galaxy using the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) mounted on the Gemini-South 8-m telescope. We confirm the presence of the galaxy and measure its brightness to be \( r_{AB} = 20.56 \pm 0.03\) mag. The probability of chance coincidence for a galaxy of this brightness within the XRT error circle is only \( 8 \times 10^{-3}\) (Beckwith et al. 2006).

The spectroscopic observations lasted a total of 3600 s, using the GMOS R400 grating at central wavelengths of 7000 and 7050 Å with a 1\(^{\prime}\) slits (resolution of about 7 Å). The data were reduced using the gemini package in IRAF. Wavelength calibration was performed using CuAr arc lamps, and air-to-vacuum and heliocentric corrections were applied. We identify several emission lines corresponding to \( [O\text{II}] \lambda 3727, [O\text{III}] \lambda 4959, 5007\) and \( H\beta \) at a redshift of \( z = 0.4571 \pm 0.0003\) (Figure 1).
3. HOST GALAXY PROPERTIES

The sample of short GRBs presented in this paper is comprised of all events with Swift/XRT positions (23 bursts), with typical uncertainties of $\sim$2–5$''$ (Butler 2007; Goad et al. 2007). Of these events, nine bursts have been further localized to sub-arcsecond precision based on detections in the optical, near-IR, radio, and/or X-rays. In eight of these nine cases a host galaxy has been identified, and in six cases its redshift has been measured. These are the most secure host galaxy associations in the sample, with a redshift range of $z$ = 0.16–0.92, an optical magnitude range of $r$ = 18–25 mag, and a ratio of late- to early-type of 5:1 (hereafter Sample 1). The additional two bursts with sub-arcsecond positions and no current redshift measurements have faint hosts with $r$ = 24.8 and 26.3 mag. As discussed in Berger et al. (2007c), these events are likely located at $z > 0.7$.

Of the 14 short bursts with only XRT positions, 12 have deep follow-up observations that led to the identification of galaxy counterparts, with $r$ = 17–26 mag; the chance coincidence probabilities for these galaxy associations range from $\sim$10$^{-3}$ to 0.1 (for a detailed discussion see Berger et al. 2007c). Six of these 12 hosts have spectroscopically measured redshifts, $z = 0.23$–1.13 (hereafter Sample 2). These are the brighter hosts, $r = 17$–23 mag, and their probabilities of chance coincidence are thus the lowest (Berger et al. 2007c). Their ratio of late- to early-type is again 5:1. The remaining, fainter hosts likely reside at $z > 0.7$ (Berger et al. 2007c).

We focus here on the two samples of host galaxies with measured spectroscopic redshifts. As we stress below, our results remain unaffected even if we use only the events with sub-arcsecond positions (Sample 1).

3.1. Luminosities

We infer the host galaxy absolute magnitudes in the rest-frame $B$ band, $M_B$, using their observed $r$-band magnitudes (Table 1). At $z = 0.5$ the observed $r$ band directly samples the rest-frame $B$ band, but for the hosts at $z = 1$ it provides a measure of the rest-frame $U$ band. To transform the latter to the $B$ band, we use the typical rest-frame $U - B$ colors of blue galaxies, appropriate for our star forming galaxy sample, as measured from the DEEP2 galaxy survey, $U - B = 0.75$ mag (Coil et al. 2008). The observed dispersion in $U - B$ color results in an $\sim$30% uncertainty in $M_B$.

For the hosts in Sample 1 we find $M_B = -18$ to $-21$ mag or $L_B = 0.1$–1.5 $L_\odot$; the highest luminosity belongs to the elliptical host galaxy of GRB 050724 (Berger et al. 2005).

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2 The single exception is GRB 070707 for which our deepest limit is $r > 24.4$ mag.
Figure 2. The distribution of B-band absolute magnitudes for the hosts of short (black) and long (dark gray) GRBs, as well as field star forming galaxies from the GOODS-N survey (light gray; Kobulnicky & Kewley 2004). A K-S test of the cumulative distributions (top) indicates a probability of only 10% that the short GRB hosts are drawn from the same distribution of long GRB hosts, and 60% that they are drawn from the field galaxy distribution.

We use the appropriate value of $L_\star$ as a function of redshift determined from the DEEP2 survey (Willmer et al. 2006). For the star forming hosts in Sample 2 we find $M_B \approx -20$ to $-21$ mag, or $L_B \approx 0.4\text{–}1.4 L_\star$; the elliptical host galaxy of GRB 050509b has $L_B \approx 5 L_\star$ (Bloom et al. 2006). The distribution of $M_B$ values is shown in Figure 2.

3.2. Star Formation Rates

We next use the $\lambda 3727$ line luminosities to infer the host SFRs (Figure 1). We use the standard conversion, $\text{SFR} = (1.4 \pm 0.4) \times 10^{-44} L_{\lambda 3727} M_\odot$ yr$^{-1}$ (Kennicutt 1998). For the star forming hosts in Sample 1 we find $\text{SFR} \approx 0.2\text{–}1 M_\odot$ yr$^{-1}$, while the elliptical host of GRB 050724 has $\text{SFR} \lesssim 0.05 M_\odot$ yr$^{-1}$ (Berger et al. 2005). For the galaxies in Sample 2 we infer $\text{SFR} \approx 1\text{–}6 M_\odot$ yr$^{-1}$, with a limit of $\lesssim 0.1 M_\odot$ yr$^{-1}$ for the elliptical host of GRB 050509b (Bloom et al. 2006). The SFR for each host galaxy is provided in Table 1.

Using the absolute magnitudes inferred above, we find that the specific SFRs are $\text{SFR}/L_B \approx 1\text{–}10 M_\odot$ yr$^{-1}$ L$_B^{-1}$ for the star forming hosts (see Figure 3). For the two elliptical host galaxies the upper limits are $\text{SFR}/L_B \lesssim 0.03 M_\odot$ yr$^{-1}$ L$_B^{-1}$.

3.3. Metallicities

For five of the 12 host galaxies we have sufficient spectral information to measure the metallicity.\footnote{The relevant emission lines are $\lambda 3727$, H$\beta$, $\lambda 4959$, 5007, H$\alpha$, and $\lambda 6584$.} We use the standard metallicity diagnostic, $R_{23} = (F_{\lambda 3727} + F_{\lambda 4959,5007})/F_{\lambda H\alpha}$ (Pagel et al. 1979; Kobulnicky & Kewley 2004) and $F_{\lambda N\alpha} / F_{\lambda H\alpha}$. The value of $R_{23}$ depends on both the metallicity and the ionization state of the gas, which we determine using the ratio of oxygen lines, $O_{32} = F_{\lambda 4959,5007}/F_{\lambda 3727}$.

We note that the $R_{23}$ diagnostic is double-valued with low- and high-metallicity branches (e.g., Kewley & Dopita 2002). This degeneracy can be broken using $\lambda 6584$ to infer $\lambda 3727$. For the previously published host of GRB 051221a we use the $\lambda 3727$ line fluxes provided in Soderberg et al. (2006), and derive similar values to those for the host of GRB 070724. Finally, for the host galaxy of GRB 050709 we lack a measurement of the $\lambda 3727$ emission line, and we thus rely on $\lambda 5007$ to infer $R_{23}$. The value of $R_{23}$ depends on both the metallicity and the ionization state of the gas, which we determine using the ratio of oxygen lines, $O_{32} = F_{\lambda 4959,5007}/F_{\lambda 3727}$.

We note that Prochaska et al. (2006) infer a metallicity of $12 + \log(O/H) \approx 8.2$ for GRB 050709, but their value is based on a different calibration of $\lambda 5007$ to $\lambda H\alpha$. Our inferred value allows for a self-consistent comparison with field galaxies and long GRB hosts.
A comparison of the B-band absolute magnitude distributions of short and long GRB hosts in the same redshift range (\(z \lesssim 1.1\)) is shown in Figure 2. The long GRB hosts range from \(M_B \approx -15.9\) to \(-21.9\) mag, with a median value of \((M_B) \approx -19.2\) mag (\(\langle L_B\rangle \approx 0.2 L_\odot\); Berger et al. 2007a). Thus, the long GRB hosts extend to lower luminosities than the short GRB hosts, with a median value that is about 1.1 mag fainter. A Kolmogorov–Smirnov (K-S) test indicates that the probability that the short and long GRB hosts are drawn from the same underlying distribution is 0.1. A comparison to the GOODS-N sample (with \((M_B) \approx -20.0\) mag) reveals more significant overlap, and the K-S probability that the short GRB hosts are drawn from the field sample is 0.6.

A clearer distinction between the hosts of short and long GRBs is evident from their specific SFRs. For long GRBs, the inferred SFRs range from about 0.2 to 50 \(M_\odot\) yr\(^{-1}\), and their specific SFRs are about 0.3–40 \(M_\odot\) yr\(^{-1}\) L\(^{-1}\)_\odot\), with a median value of about 0.1 \(M_\odot\) yr\(^{-1}\) L\(^{-1}\)_\odot\) (Christensen et al. 2004). As shown in Figure 3, the specific SFRs of short GRB hosts are systematically lower than those of long GRB hosts, with a median value that is nearly an order of magnitude lower. Indeed, the K-S probability that the short and long GRB hosts are drawn from the same underlying distribution is only \(3.5 \times 10^{-3}\). This is clearly seen from the cumulative distributions of specific SFRs for each sample (inset of Figure 3).

On the other hand, a comparison to the specific star formation rates of the GOODS-N field galaxies reveals excellent agreement (Figure 3). The K-S probability that the short GRB hosts are drawn from the field galaxy distribution is 0.6. This result remains unchanged even if we use only the host galaxies in Sample 1. Thus, short GRB hosts are drawn from the normal population of star-forming galaxies at \(z \lesssim 1\), in contrast to long GRB hosts, which have elevated specific star formation rates, likely as a result of preferentially young starburst populations (Christensen et al. 2004; Savaglio et al. 2008).

Finally, the metallicities measured for short GRB hosts are in excellent agreement with the luminosity–metallicity relation for field galaxies at \(z \sim 0.1–1\) (Figure 4; Kobulnicky & Kewley 2004; Tremonti et al. 2004). The two hosts with \(M_B \approx -18\) mag have \(12 + \log(O/H) \approx 8.6\), while those...
with $M_R \approx -20$ to $-21$ mag have $12 + \log(O/H) \approx 8.8$–8.9, following the general trend. However, the short GRB host metallicities are systematically higher than those of long GRB hosts, which have been argued to have lower than expected metallicities (Stanek et al. 2006). The median metallicity of short GRB hosts is about 0.6 dex higher than for long GRB hosts, and there is essentially no overlap between the two host populations.

5. SUMMARY AND CONCLUSIONS

We present optical spectroscopy of several short GRB host galaxies, and a complete compilation of all short GRBs with Swift/XRT positions (23 bursts). About one half of the sample has spectroscopically identified host galaxies, with $z \approx 0.1$–1.1. The ratio of star forming to elliptical galaxies in this spectroscopic sample is 5:1, regardless of whether we use only the objects with sub-arcsecond positions, or include those with XRT positions. We note that the maximum allowed fraction of elliptical galaxies in the Swift/XRT positions, assuming that all of the currently unclassified hosts turn out to be ellipticals, is 55%. In the formulation of Zheng & Ramirez-Ruiz (2007), which considered the ratio of host types as a function of a progenitor power-law age distribution, $P(\tau) \propto \tau^a$ (where $\tau$ is the time delay between formation and merger), the range of early- to late-type ratios allowed by the data leads to $n \lesssim 1$; if the ratio is indeed $\sim 20\%$ then $n$ is further constrained to $\lesssim 1$.

Despite the fact that most short GRBs occur in star forming galaxies, their properties are strongly distinct from those of long GRB hosts. The rest-frame $B$-band luminosity distribution of the short GRB hosts is systematically brighter than for long GRB hosts in the same redshift range. An even stronger difference is apparent in the specific SFRs, with a median value for short GRB hosts that is nearly an order of magnitude lower than for long GRB hosts. Similarly, the metallicities of the short GRB hosts are about 0.6 dex higher than those of long GRB hosts, and unlike the long GRB hosts they follow the luminosity–metallicity relation of field galaxies. To the extent that the mean properties of the host galaxies reflect the identity of the progenitors, this clearly indicates that the progenitors of long and short GRBs are themselves distinct, supporting additional lines of evidence such as the lack of supernova associations in short GRBs.

On the other hand, a comparison to a large sample of star forming field galaxies in a similar redshift range reveals excellent agreement in terms of specific SFRs and the luminosity–metallicity relation. Indeed, the K-S probability that the short GRB hosts are drawn from the field galaxy population is high, $\approx 0.6$. Thus, short GRBs select galaxies that are representative of the average stellar populations at least to $z \sim 1$.

These comparisons, along with the presence of some short GRBs in elliptical galaxies, indicate that the progenitor ages span a wide range of $\sim 0.1$–10 Gyr. The rough lower bound is inferred from the overall dissimilarity to the hosts of long GRBs, which appear to be dominated by young stellar populations of $\lesssim 0.1$ Gyr (Christensen et al. 2004). We stress that regardless of the exact minimum age, the dissimilarity to the hosts of long GRBs indicates that only a small fraction of short GRBs ($\lesssim 1/3$) are likely to arise from a prompt population of progenitors.

Our conclusions about the mix of host galaxy types and the wide range of progenitor ages provide additional constraints on short GRB progenitor models. In the context of coalescence models (NS–NS and NS–BH), several authors have made predictions for these properties based on population synthesis models (e.g., Fryer et al. 1999; Belczynski et al. 2002, 2006; O’Shaughnessy et al. 2008), fits to the burst redshift and luminosity distributions (e.g., Guetta & Piran 2006; Nakar et al. 2006), and models of the star formation history in different galaxy types (Zheng & Ramirez-Ruiz 2007). We stress that while there is still a diversity of predictions between the various models, those that predict a wide range of merger timescales, with the bulk beyond $\sim 0.1$ Gyr, and a mix of host galaxy types (e.g., Guetta & Piran 2006; Zheng & Ramirez-Ruiz 2007; O’Shaughnessy et al. 2008), are favored by the observations presented here.

Similarly, the wide age distribution as inferred from the host galaxy properties is at odds with young progenitor populations such as magnetars. However, even in this context, a delayed channel for magnetar formation via accretion-induced collapse of a white dwarf has been proposed (Metzger et al. 2008), which may account for some short GRBs.

We finally note that while nearly half of the short GRB hosts remain unclassified at present, the overall qualitative conclusion of our study—that short and long GRB hosts and hence the progenitors have a different distribution of properties—is robust. In particular, even if future spectroscopic observations of the unclassified hosts reveal that they are more similar to those of long GRBs, the overall dispersion in short GRB host properties will still be significantly larger than for long GRB hosts, in terms of both metallicities and specific star formation rates. Naturally, any population of short GRB hosts that is found to be similar to long GRB hosts may lead to the conclusion that some of the progenitors are related to a young stellar population (e.g., promptly merging binaries or magnetars); to reiterate, our current limit on such a population is $\lsim 1/3$.

Looking forward, we expect to advance our understanding of the progenitors from these primary lines of host galaxy investigations. First, with a growing sample of short GRB hosts we will be able to assess whether the progenitor population is uniform, or perhaps exhibits a bimodal distribution, with a contribution from prompt (proportional to star formation) and delayed (proportional to stellar mass) components, as appears to be the case for Type Ia supernovae (e.g., Sullivan et al. 2006). We expect the sample to grow both from new events and from continued optical and near-IR spectroscopy of the existing hosts. Second, high angular resolution imaging with the Hubble Space Telescope can be used to investigate in detail the location of short GRBs within their host galaxies. This has already been done for GRB 050709, indicating that, unlike for long GRBs, the burst was not associated with a region of active star formation (Fox et al. 2005). Finally, absorption spectroscopy of short GRB afterglows, still unavailable in the present sample, will directly reveal the type of environment (disk, halo, intergalactic medium) in which the bursts explode. Taken together, these studies promise to shed light on the short GRB progenitor population(s), at least until the advent of sensitive gravitational wave detectors in the next decade.

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REFERENCES

Arimoto, M., et al. 2006, GRB Coordinates Network, 4550, 1
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco, CA: ASP), 25
Barbieri, L., et al. 2007, GRB Coordinates Network, 6623, 1
Barthelmy, S. D., et al. 2007, GRB Coordinates Network, 6622, 1
Barthelmy, S. D., et al. 2005, Nature, 438, 994
Beckwith, S. V. W., et al. 2006, ApJ, 132, 1729
Belczynski, K., Bulik, T., & Rudak, B. 2002, ApJ, 571, 394
Belczynski, K., et al. 2006, ApJ, 648, 1110
Berger, E. 2005, Nature, 438, 95
Berger, E. 2006a, GRB Coordinates Network, 5952, 1
Berger, E. 2006b, in AIP Conf. Ser., 836, Gamma-Ray Bursts in the Swift Era, ed. S. S. Holt, N. Gehrels, & J. A. Nousek (Secaucus, NJ: Springer), 33
Berger, E. 2007, GRB Coordinates Network, 5995, 1
Berger, E., Cowie, L. L., Kulkarni, S. R., Frail, D. A., Aussel, H., & Barger, A. J. 2003, ApJ, 588, 99
Berger, E., Fox, D. B., Kulkarni, S. R., Frail, D. A., & Djorgovski, S. G. 2007a, ApJ, 660, 504
Berger, E., & Kaplan, D. L. 2007, GRB Coordinates Network, 6680, 1
Berger, E., Morrell, N., & Roth, M. 2007b, GRB Coordinates Network, 7154, 1
Berger, E., et al. 2005, Nature, 438, 988
Berger, E., et al. 2007c, ApJ, 664, 1000
Bloom, J. S., & Butler, N. R. 2007, GRB Coordinates Network, 6661, 1
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., et al. 2006, ApJ, 638, 354
Bloom, J. S., et al. 2007, ApJ, 654, 878
Burrows, D. N., et al. 2006, ApJ, 653, 468
Butler, N. 2006, GRB Coordinates Network, 5389, 1
Butler, N. R. 2007, AJ, 133, 1027
Cannizzo, J. K., et al. 2006, GCN, 20, 1
Cenko, S. B., et al. 2008, arXiv:0802.0874
Chandra, P., & Frail, D. A. 2007, GRB Coordinates Network, 6667, 1
Chary, R., Becklin, E. E., & Armus, L. 2002, ApJ, 566, 229
Christensen, L., Jørgensen, I., Allington-Smith, J. R., Davies, R. L., Metcalfe, N., Murowinski, R. G., & Crampton, D. 2004, PASP, 116, 425
Kenneicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35
Kobulnicky, H. A., & Kewley, L. J. 2004, ApJ, 617, 240
Krimm, H., et al. 2006, GRB Coordinates Network, 5704, 1
La Parola, V., et al. 2006, A&A, 454, 753
Le Floc’h, E., et al. 2003, A&A, 400, 499
Levan, A. J., Tanvir, N. R., & Davis, C. 2007, GRB Coordinates Network, 6662, 1
Mangano, V., La Parola, V., Mineo, T., O’Brien, P., Romano, P., Burrows, D. N., Chester, M., & Angelini, L. 2006, GRB Coordinates Network, 4565, 1
Marshall, F. E., Barthelmy, S. D., Burrows, D. N., Chester, M. M., Cummings, J., Evans, P. A., Roming, P., & Gehrels, N. 2007, GCN, 80, 1
Metzger, B. D., Quataert, E., & Thompson, T. A. 2008, MNRAS, 385, 1455
Nakar, E., Gal-Yam, A., & Fox, D. B. 2006, ApJ, 650, 281
Narayan, R., Paczynski, B., & Piran, T. 1992, ApJ, 395, L83
O’Shaughnessy, R., Belczynski, K., & Kalogera, V. 2008, ApJ, 675, 566
Pagel, B. E. J., Edmunds, M. G., Blackwell, D. E., Chun, M. S., & Smith, G. 1979, MNRAS, 189, 95
Parsons, A., et al. 2007, GRB Coordinates Network, 6656, 1
Perley, D. A., Thoece, C. C., & Bloom, J. S. 2007, GRB Coordinates Network, 6774, 1
Prochaska, J. X., et al. 2006, ApJ, 642, 989
Racusin, J., Barbier, L., & Landsman, W. 2007, GCN, 70, 1
Roming, P. W. A., et al. 2006, ApJ, 651, 985
Sato, G., et al. 2006a, GRB Coordinates Network, 5064, 1
Sato, G., et al. 2006b, GRB Coordinates Network, 5381, 1
Sato, G., et al. 2007, GRB Coordinates Network, 7148, 1
Savaglio, S., Glazebrook, K., & Le Borgne, D. 2008, arXiv:0803.2718
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Soderberg, A. M., et al. 2006, ApJ, 650, 261
Stanek, K. Z., et al. 2006, Acta Astron., 56, 333
Stratta, G., et al. 2007, A&A, 474, 827
Sullivan, M., et al. 2006, ApJ, 648, 868
Tremonti, C. A., et al. 2004, ApJ, 613, 898
Troja, E., Burrows, D. N., & Gehrels, N. 2006, GRB Coordinates Network, 5063, 1
Troja, E., Page, K. L., Gehrels, N., & Burrows, D. N. 2006, GRB Coordinates Network, 5723, 1
Ukwatta, T. N., et al. 2008, GCN, 111, 1
Villasenor, J. S., et al. 2005, Nature, 437, 855
Willmer, C. N. A., et al. 2006, ApJ, 647, 853
Zheng, Z., & Ramirez-Ruiz, E. 2007, ApJ, 665, 1220
Ziaeepour, H., et al. 2006, GCN, 111, 1
No. 1, 2009