1. INTRODUCTION

From the earliest associations between gamma-ray bursts (GRBs) and host galaxies, burst environments have revealed many important clues to the nature of GRB progenitors (e.g., Sokolov et al. 2001; Bloom et al. 2002; Fynbo et al. 2003; Le Floc’h et al. 2003). As Swift (Gehrels et al. 2004) accurately localizes hundreds of GRBs, statistical studies of GRB host galaxies are becoming increasingly critical to understanding GRB formation mechanisms (e.g., Christensen et al. 2004; Wainwright et al. 2007).

A GRB host galaxy is identified by the superposition in the plane of the sky of a GRB afterglow and a galaxy. With only visual associations between afterglows and galaxies used to identify GRB host galaxies, the possibility always exists for an incorrect association. Some afterglow and galaxy associations may be chance superpositions, with the galaxy being either a foreground or background galaxy that is not physically associated with the GRB. These mistaken associations could cause confusion when analyzing data on GRB environments. When dealing with a statistical sample of GRBs, rather than a single case study, results will only be impacted if a relatively significant number of the host galaxies have been mistakenly identified. Understanding the likelihood of galaxy misidentification in a given sample of GRBs is, therefore, imperative when conducting such studies. However, even a single mistaken association might generate confusion if the combination of GRB and galaxy characteristics are anomalous. For example, the potentially paradigm-shifting object GRB 060614 (e.g., Cobb et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Schaefer & Xiao 2006), a burst identified as low-redshift for which no supernova (SN) was detected, could be a typical object of no special interest if the burst’s purported host galaxy is actually just a random galaxy along the line of sight to the GRB.

When an optical afterglow is detected, afterglow localization is precise to significantly less than an arcsecond. The superposition between a galaxy and an optical afterglow is, therefore, generally taken as proof that the galaxy in question is the host galaxy of the GRB. Since the optical afterglow position can be determined to within subpixel accuracy, the probability of the optical afterglow falling randomly on any galaxy-covered pixel is determined by dividing the number of pixels covered by galaxies in each field by the total number of pixels in that field. If only an X-ray afterglow is detected, the GRB can only be localized to within an error region of radius ~2”. If a galaxy is detected within this error region, it is generally assumed to be the host galaxy of the GRB, although confusion can arise when two or more sources are detected within or around a single X-ray afterglow error region (e.g., Ferrero et al. 2007).

In this paper we investigate a uniform set of 72 GRB fields in order to examine the general issue of associations between GRBs and host galaxies. In § 2 we describe our data and analysis techniques. In § 3 the probability of chance coincidence between optical afterglows and galaxies is determined by measuring the fractional area covered by galaxies. In § 4 localizations based on X-ray afterglows are considered by measuring the probability of galaxies falling within randomly placed X-ray error regions. Afterglow-associated galaxies are compared to field galaxies in § 5. We discuss our results in § 6 along with some strategies for recognizing false hosts, and conclude in § 7.

2. DATA

Our J-band optical images were obtained using the ANDICAM instrument mounted on the 1.3 m telescope at the Cerro Tololo Inter-American Observatory (CTIO). This telescope is operated as part of the Small and Moderate Aperture Research Telescope System (SMARTS) consortium.

2.1. GRB Selection

The 72 bursts included in these analyses were, in general, selected based on their observability from CTIO, limited to those bursts with declination $\leq +35^\circ$. Observations were also limited by each burst’s right ascension because all observations began...
| GRB   | R.A. (2) | Decl. (3) | Arcsec | Optical AG? | Limiting I_mag (6) | Optical I (7) | X-Ray (8) | GRB Redshift (9) | Galaxy/AG Overlap (10) |
|-------|----------|-----------|--------|-------------|---------------------|--------------|-----------|-----------------|------------------------|
| 050128 | 14 38 17.66 | –34 45 54.7 | 2.7    | ...         | 22.4                | 0.012        | 0.118     | ...             | ...                    |
| 050219a| 11 05 39.13 | –40 41 02.6 | 3.5    | ...         | 22.5                | 0.010        | 0.154     | ...             | X-ray (18.9)            |
| 050223 | 20 05 32.66 | –62 28 20.4 | 3.2    | ...         | 22.3                | 0.017        | 0.194     | 0.584*         | X-ray (21.1)            |
| 050315 | 03 18 51.04 | –46 23 43.5 | 2.7    | ...         | 22.4                | 0.010        | 0.088     | 1.44           | ...                    |
| 050401 | 16 31 28.84 | +02 11 14.5 | 1.8    | ...         | 22.6                | 0.009        | 0.088     | ...             | ...                    |
| 050408 | 12 02 17.36 | +10 51 10.5 | 1.2    | ...         | 22.4                | 0.011        | 0.048     | 1.236          | ...                    |
| 050412 | 12 04 25.18 | –01 12 00.8 | 6.9    | ...         | 22.6                | 0.011        | 0.322     | ...             | X-ray (21.7)            |
| 050416a | 12 33 54.57 | +21 03 26.9 | 0.6    | ...         | 22.7                | 0.012        | 0.036     | 0.6355*        | X-ray + optical (22.2) |

*Note: X-ray = X-ray AG Coordinates and Radius, R.A. = Right Ascension, Decl. = Declination, Arcsec = Arcseconds, Optical AG? = Optical AG? Coordinates, Overlap Probability = Overlap Probability, X-Ray = X-Ray AG Coordinates and Radius, GRB Redshift = GRB Redshift, Galaxy/AG Overlap = Galaxy/AG Overlap, and (1) = X-Ray AG Coordinates and Radius.
with Galactic latitude and short-hard bursts (7) were observed. Due to large and uncertain telescope scheduling time limitations. Both long-soft bursts (6) within days postburst. Bursts were occasionally not observed due to 5, depending on an uncertain amount of extinction.

within days postburst. Bursts were occasionally not observed due to telescope scheduling time limitations. Both long-soft bursts (65) and short-hard bursts (7) were observed. Due to large and uncertain values of Galactic reddening near the Galactic plane, no GRBs with Galactic latitude |b| < 10° are included in this sample.

The redshifts, or redshift upper limits, of 37 bursts in our sample have been determined through either optical afterglow observations or observations of possible host galaxies. If only the 23 redshifts that are measured directly from GRB afterglow absorption are considered, then the median redshift is z = 2.0. For the entire sample of bursts, the median redshift is z ~ 1.3 with a range from 0.089 to 6.6. The median redshift is understandably reduced when including GRB redshifts obtained from associated galaxies, because galaxies are generally easier to detect and observe spectrally when at low redshift. The GRBs included in this sample are listed in Table 1.

2.2. Observations and Data Reduction

The nightly data set for each burst consisted of six individual 360 s I-band observations, taken at slightly offset telescope positions. Each individual image was reduced in the typical manner, with bias and dark subtraction, flat fielding, and cosmic-ray removal using the L.A. Cosmic program5 (van Dokkum 2001). The individual images were median combined with maximum pixel rejection to produce a source-free initial fringe correction image. This background image was scaled and subtracted from the original images—only this time masking the sources in each image, rather than using minimax rejection. This new background was scaled and subtracted from the individual images, which were then aligned and combined to produce the final nightly science frame.

For each GRB, between one and 11 usable nightly images were obtained (the mode being four images). Particularly shallow images or nights with relatively poor seeing were excluded. Some images taken at early times postburst were also excluded, as they contained optical afterglow light. All usable nightly images were aligned and combined to produce a final deep frame for each GRB. The frame edges were cropped so that each final frame is of uniform depth over the entire field. Field size varied slightly but is typically 5.4' × 5.4'. A few fields contained saturated stars with diffraction spikes; the area immediately surrounding these stars is excluded from all of the following analyses.

Secondary standard stars in each field were photometrically calibrated by comparison, on photometric nights, with Landolt standard stars (Landolt 1992). Photometric calibration is typically accurate to 0.05 mag. No photometric observations were obtained for four GRBs, and those fields are calibrated using USNO-B1.0 I2 magnitudes (Monet 2003), with typical calibration errors of 0.2 mag. The reddening-corrected (Schlegel et al. 1998) 3 σ I-band limiting magnitudes for point sources in these images ranges from I = 21.2 to 23.3 mag, with a median of 22.4 mag. All magnitudes are given in the Vega system.

The fields are astrometrically calibrated using USNO-B1.0 stars, with a statistical error of < 0.26. The CCD pixel scale is 0.37 arcsec pixel−1, so that the astrometry is accurate to within a single pixel. X-ray afterglow coordinates and 90% confidence error radii for all bursts are taken from Butler (2007). Error region radii vary from 0.5° to 6.9°, with a median of 1.9°. The data are summarized in Table 1.

2.3. Galaxy Detection

All objects in the field were cataloged using SExtractor (Bertin & Arnouts 1996) with a 2 σ detection threshold. The SExtractor

| GRB   | X-Ray AG Coordinates and Radius | Optical | X-Ray | Redshift | Galaxy/AG Overlaps |
|-------|--------------------------------|--------|-------|----------|-------------------|
|       | R.A.                  | Decl.  | Arcsec| Optical? | Limiting I Mag  |
| 061201f | 22 08 32.09          | −74 34 48.2 | 3.6             | Yes       | 22.1              |
| 061202f | 07 02 05.54          | −74 41 54.6 | 1.5              |         | 22.2              |
| 061217f | 10 41 39.32          | −21 07 22.1 | 3.8              |         | 22.5              |
| 070224f | 11 56 05.77          | −13 19 49.4 | 1.7              | Yes      | 22.7              |
| 070306f | 09 52 23.32          | +10 28 55.4 | 1.1              | Yes      | 22.4              |
| 070318f | 03 13 56.79          | −42 56 47.7 | 1.4              | Yes      | 21.8              |
| 070330f | 17 58 10.53          | −63 47 35.0 | 2.4              | Yes      | 22.2              |
| 070419b | 21 02 49.91          | −31 15 47.2 | 1.7              |         | 22.5              |
| 070429a | 19 50 48.71          | −32 24 15.1 | 1.9              |         | 22.2              |
| 070508a | 20 51 12.10          | −78 23 03.4 | 2.1              | Yes      | 22.2              |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

5 Possible galaxy/AG overlaps based on the ISOAREAF_IMAGE area of each galaxy.
6 Redshift references: 050223 (Pellizza et al. 2006); 050315 (Kelson & Berger 2005); 050318 (Berger & Mulchaey 2005); 050408 (Berger et al. 2005); 050416a (Cenko et al. 2005); 050509a (Prochaska et al. 2005a); 050525 (Foley et al. 2005); 050724 (Prochaska et al. 2005b); 050730 (Chen et al. 2005); 050801 (de Pasquale et al. 2007); 050826 (Halpern & Mirabal 2006); 060115 (Piranomonte et al. 2006a); 060116 (Piranomonte et al. 2006b); 060313 (Roming et al. 2006); 060505 (Ofek et al. 2006); 060526 (Berger & Gladmer 2006); 060602a (Jakobsson et al. 2007a); 060604a (Castro-Tirado et al. 2006); 060615a (Piranomonte et al. 2006a); 060740a (van Dokkum 2001).
parameter CLASS_STAR was then used to distinguish the galaxies from the stars in the field. This parameter is determined by a neural network and ranges from CLASS_STAR = 0.0 for extended objects to CLASS_STAR = 1.0 for pointlike objects. We consider objects with CLASS_STAR > 0.8 to be stars, and these objects are not included in the following analyses. This value is chosen to avoid contaminating the sample with stars that are mistakenly classified as galaxies. Adopting a less strict value results in more galaxy identifications. Defining galaxies to have CLASS_STAR < 0.9, for example, increases chance coincidence probabilities by ~10%. In crowded star fields, SExtractor’s ability to differentiate between stars and galaxies is reduced. This effect is minimized in our analyses, however, as none of the fields considered here are within 10° of the Galactic plane. Galaxy I-band magnitudes are given by MAG_AUTO, with zero points appropriately adjusted for each field. These magnitudes are generally accurate to within a few tenths of a magnitude.

Only galaxies detected by SExtractor are considered in these analyses. At the position of a few afterglows there are low-significance galaxies that are not identified by SExtractor. For consistency, these visual identifications are not included.

Since our observations are limited to galaxies brighter than ~23 mag, we would not expect to be able to detect all the potential host galaxies in our images. Galaxies go undetected primarily because of their large redshifts, although dwarf galaxies might be missed even at low redshifts. Examination of galaxies brighter than the median limiting magnitude of our sample ($I < 22.4$) in the VIMOS VLT Deep Survey–Chandra Deep Field–South (VVDS-CDFS) galaxy catalog (Le Fèvre et al. 2004) suggests that nearly all of the galaxies detected in our fields are likely to be at a redshift lower than $z = 1.5$, and about 65% have redshift $z \leq 0.7$.

To understand our ability to detect GRB host galaxies, it would be useful to know the characteristics of a typical GRB host. In pre-Swift GRB samples, however, galaxies associated with GRBs have been noted to be a rather heterogeneous group (e.g., Conselice et al. 2005; Le Floc’h et al. 2003) covering a wide range of galaxy types and absolute magnitudes ($M_B \sim -16$ to $-21$; Sokolov et al. 2001; Conselice et al. 2005; Wainwright et al. 2007), although there is a tendency for GRBs to occur in faint galaxies (Jaunsen et al. 2003; Le Floc’h et al. 2003; Fruchter et al. 2006). Assuming a typical galaxy color of $B - I = 2$ (Fukugita et al. 1995), the brightest host galaxies could have $I = -23$ and might be detected in our images to $z \sim 1$. Observed galaxy brightness would, of course, depend on the necessary $k$-correction, which depends strongly on galaxy morphology. The star-forming galaxies of long-duration bursts would be favored for detection at higher redshifts because of their strong rest-frame UV emission. Unfortunately, redshift limits for detecting the dimmest host galaxies are much more severe. These dwarf hosts may be common in the local universe, but many could not be detected in our images to even moderate redshifts given our magnitude limits.

3. OPTICAL AFTERGLOW AND GALAXY COINCIDENCE

There is no exact projected distance at which a GRB and a galaxy become associated, and galaxies lack clear “edges.” Therefore, we calculate the probability of a chance optical afterglow/galaxy association below using two slightly different definitions of galaxy area.

3.1. ISOAREAF_IMAGE Area

One measure of the pixel area of each galaxy is given by the isophotal SExtractor parameter ISOAREAF_IMAGE. This value disregards the lower significance outskirts of each galaxy, so it is a conservative estimate of galaxy area. If an optical afterglow were to fall within the ISOAREAF_IMAGE area of a galaxy, that galaxy would be regarded as a strong host galaxy candidate. This excludes cases in which GRBs fall at the outskirts of galaxies—which are bound to occur. Hence these figures serve strictly as a lower limit.

The ISOAREAF_IMAGE area covered by galaxies in each field ranges from 0.2% to 3.5% (see Fig. 2 and Table 1), with a median of 1.0% (see Table 2). Summing the overlap probability over all 72 fields yields an expectation of 0.86 observed galaxy/optical afterglow coincidences—including even those fields for which no optical afterglow detection was made. For the 47 fields in which optical afterglow was detected from either short- or long-duration bursts, there is an expectation of 0.54 observed galaxy/optical afterglow coincidences. In fact, this sample contains seven such coincidences (GRBs 050416a, 050724, 050826, 060505, 060614, 061021, and 061121). Based on Monte Carlo simulations, the chance of having randomly observed that many coincidences is less than 0.004%. These results are summarized in Table 2.

Since the total galaxy-covered area in each field depends on limiting magnitude, which varies from field to field, it is useful to consider a more homogeneous selection of galaxies. As deeper observations are obtained, more galaxies will be detected. Therefore, deeper imaging increases the chance for a correct identification, but also increases the chance for spurious associations because the fractional area covered by galaxies is increased. By imposing a magnitude cutoff, therefore, we produce a minimum value for the possibility of chance superposition. For the homogeneous sample, we limit our analysis to galaxies with Galactic extinction corrected magnitudes brighter than $I = 21.5$. This value is determined by producing a magnitude histogram of all the galaxies being used in this analysis, with bin size of half a magnitude, and selecting the midvalue of the bin containing the maximum number of galaxies (see Fig. 2). Beyond this magnitude, our galaxy sample is significantly affected by incompleteness. In individual fields, this galaxy completeness “turnover” value ranges from
20 to 22, with a median and mode of 21.5. In the fields that are incomplete at 21.5 mag, there will be “missing” galaxies. This means that the probability of chance superposition with a $I \leq 21.5$ galaxy will be slightly underestimated.

Not surprisingly, the exclusion of all $I > 21.5$ galaxies reduces the field coverage of galaxies by only a small amount (see Table 2). The most significant change is that only four of the seven observed optical afterglow/galaxy associations in this sample occur with galaxies brighter than 21.5 mag (GRBs 050724, 050826, 060505, and 061021). However, Monte Carlo simulations indicate that the chance of having observed these four at random in the 47 fields in which optical afterglow was detected is $<1\%$. So even in this reduced sample, there remains a meaningful overdensity of galaxy/optical afterglow coincidences. However, it is plausible that one or more of these associations could be a coincidence.

### 3.2. Ellipse Area

Without fully understanding how all GRBs are produced, the exact placement of GRBs within their galaxies cannot be accurately predicted. Long-duration GRBs, for example, may require the kind of rapid star formation regions often found in galactic spiral arms (Conselice et al. 2005; Fruchter et al. 2006), while short-duration GRBs may favor the fringes of galaxies if they are formed by the mergers of compact remnants (Bloom et al. 2006b; Berger et al. 2007b). We have, therefore, been somewhat too restrictive in assuming that a galaxy will only be identified as a host if the GRB occurs within the galaxy’s ISOAREAF_IMAGE area.

To consider the more general situation of a optical afterglow at a given observed position relative to a nearby galaxy, we define galaxy area as an ellipse having major and minor axes of length $v \times A_{\text{IMAGE}}$ and $v \times B_{\text{IMAGE}}$, where $A_{\text{IMAGE}}$ and $B_{\text{IMAGE}}$ are SExtractor parameters that represent the maximum and minimum spatial r.m.s. of each galaxy profile and $v$ is a simple scaling factor. In general, an ellipse with $v = 3$ is visually coincident with the extent of the galaxy (see Fig. 3). When the shape of each galaxy is defined in this way, galaxy area is equal to $v^2 \pi \times A_{\text{IMAGE}} \times B_{\text{IMAGE}}$.

In Figure 4 we plot the probability of chance alignment for an afterglow contained within a galaxy ellipse with scale factor $v$. The $v$ values of the seven GRBs with optical afterglow/galaxy coincidences are marked with arrows. The probability of chance alignment rises quadratically with $v$ until $v$ is so large that the galaxies significantly overlap with one another. We plot both the entire sample of galaxies and only those galaxies with $I \leq 21.5$. Excluding the dimmer galaxies only changes the random overlap probability by a few tenths of a percent at large $v$. On the right-hand side of the graph, the number of expected chance coincidences in our sample of 72 GRBs is shown.

Setting the scale factor to $v = 3$, we use the ellipse galaxy area to repeat the analyses that were done in § 3.1 with the ISOAREAF_IMAGE area. These results are shown in Table 2. For individual galaxies the ellipse area is generally larger than the ISOAREAF_IMAGE area, so using the ellipse area results in a slightly increased probability of chance coincidence.

### 3.3. Comparing Short- and Long-Duration GRB Fields

A comparison of short- and long-duration fields is of interest, although the sample of short-duration bursts in this sample is limited to only seven fields (vs. 65 long-duration bursts). The galaxy area coverage spans a similar range of values between the two samples. The median area (ISOAREAF_IMAGE area) covered by all galaxies in short GRB fields ($\sim 0.009$) is only slightly lower than the median area covered in long GRB fields ($\sim 0.01$). Since short bursts may occur farther outside their galaxies than...
long-duration bursts, the galaxy area over which a true association would be physically plausible may be larger for short bursts than for long bursts.

In this sample, three short GRBs had detected optical afterglows, but there is only one short burst galaxy/optical afterglow association. This association frequency (1 of 3) is somewhat larger than that of the long GRBs (6 of 44), but this may be an artifact of the limited short burst sample. While the exact nature of short bursts is not yet clear, if short bursts are associated with early-type galaxies, they may be preferentially located in local galaxy clusters (e.g., Pedersen et al. 2005; Bloom et al. 2006b). In that case, a higher frequency of associations might be expected for short bursts than long bursts. However, the correlation between short bursts and clusters is not yet confirmed. The observations presented here are consistent with recent evidence that suggests that not all short bursts are limited to local clusters (Berger et al. 2007a, 2007b).

4. X-RAY AFTERGLOW AND GALAXY COINCIDENCE

For a nonnegligible population of Swift GRBs (nearly 50%), no optical afterglow is detected. Underluminous optical afterglows and heavy line-of-sight extinction may account for many “dark” bursts. An optical afterglow might also go undetected due to observing constraints, such as the relative position of the Sun or the moon to the burst’s coordinates or poor weather conditions at optimum observing sites. Regardless of the reason, such a nondetection generally means that the burst will only by localized to within a few arcseconds by X-Ray Telescope (XRT) observations of the burst’s X-ray afterglow. XRT observations comprise a data set that is significantly more uniform than deep,
ground-based optical afterglow observations that, by necessity, are obtained from a large number of different instruments at varying times postburst. This homogeneity, combined with the fact that the X-ray localized data set contains nearly double the number of optically localized GRBs, makes it tempting to analyze GRB host galaxies based exclusively on X-ray afterglow positions. We, therefore, examine our data to determine how significantly such an analysis might be impacted by the presence of falsely identified hosts.

Each X-ray afterglow error region of the GRBs in this sample was examined for coincident galaxies, and 14 are found to overlap with one or more SExtractor galaxies. Any overlap between the circle defined by the X-ray afterglow error region and a galaxy ellipse with \( v = 3 \) is considered to be a coincidence (see Fig. 3). This definition of galaxy area is used instead of the ISOAREAF_IMAGE area because an ellipse defines a clear “edge” to the galaxy, while SExtractor does not output the exact boundaries of a galaxy.

We then investigated the probability that one or more galaxies will fall within any random region that is the same size as a burst’s X-ray afterglow error region. For each GRB field, 500 random positions were selected and each position was assigned a region with a radius equivalent to the X-ray afterglow error radius of the corresponding GRB. All region/galaxy overlaps were then counted. Only a handful of overlaps occur in some fields, while in others more than a quarter of all random regions contain a galaxy. The median overlap probability is 6.9%. The probability of one or more galaxies overlapping any region the size of the burst’s X-ray afterglow error region is given in column (8) of Table 1. The overlap probability in each field strongly depends on both the radius of the random regions and the galaxy population density. The burst with the largest X-ray error region is GRB 050412, with a radius of 6.9°. In this field, any randomly placed region of that size has a 32% chance of overlapping with a galaxy. Note that the density of the galaxy population is dependent on image depth, as shallower images will contain fewer dim galaxies. Chance probabilities will, therefore, increase with image depth. Figure 5 shows a histogram of the probability of

![Figure 4](image1.png)

![Figure 5](image2.png)

![Figure 6](image3.png)

---

6 The X-ray afterglow error region of GRB 060505 overlaps with two galaxies.
region/galaxy overlap in the 72 GRB fields examined. Arrows on the graph indicate the fields in which the X-ray afterglow error region did coincide with one or more galaxies.

The expected number of observed overlaps created by chance in this GRB sample is 6.7, which is obtained by summing the overlap probability over all fields. This is significantly less than the 14 actually observed. Using a Monte Carlo simulation (see Fig. 6), the probability of having observed 14 overlaps in this sample is found to be only 0.5%. Thus, there is a clear overdensity of galaxies in GRB X-ray afterglow error regions. But the galaxies associated with the X-ray afterglow error regions do not have to be the true host galaxies of the GRBs. In fact, of the X-ray afterglow error regions in this sample that contain a galaxy, it is likely that approximately half contain a galaxy that is not associated with the GRB. This does not appear to be an artifact of images in our sample with large X-ray afterglow error region radii.

When we consider only fields with small error radii, ≤2", we observed five overlaps when only two are expected.

Approximately 250 Swift bursts have been detected and well localized by their X-ray afterglows using the XRT. Based simply on the median probability of overlap in these fields, there is only a 10^{-8} chance that no “false hosts” have been detected. In fact, if our sample represents a typical distribution, then there could be over 20 such detections in the entire Swift sample. Improving the limiting magnitudes in each field would only serve to significantly increase the number of galaxy detections. Indeed, as image depth increases, the detection of one or several galaxies within a given X-ray afterglow error region is inevitable. Clearly, caution is required when identifying a galaxy in a X-ray afterglow error region as the host galaxy of the GRB. Note, in particular, that relatively few optical afterglows have been associated with short-duration bursts, yet many claims as to the nature of short-duration bursts have recently been made on the basis of their X-ray afterglow and galaxy associations (e.g., Pedersen et al. 2005; Bloom et al. 2006b). The likelihood of misidentified hosts is, therefore, of particular concern when considering short bursts.

5. FIELD GALAXIES VERSUS AFTERGLOW-ASSOCIATED GALAXIES

Having collected the observable properties of all the galaxies in these 72 fields, we can determine if the galaxies associated
with either X-ray or optical afterglows represent an anomalous sample of the field galaxies. The observable properties considered are magnitude, pixel area (either ISOAREAF_IMAGE area or ellipse area), and ellipticity ($e$, where $e = 1 - (B_{\text{IMAGE}} / A_{\text{IMAGE}}$). These observable properties are, of course, a function of intrinsic size, shape, brightness, and redshift.

Figure 7a shows galaxy ellipse area, with $e = 3$, versus magnitude. Monte Carlo simulations show that the galaxies associated with X-ray afterglow error regions are a typical sample of all the galaxies in the field over this dimension. This result is not surprising, since nearly half these galaxies could actually be just field galaxies, rather than GRB-associated galaxies. The galaxies associated with optical afterglow, however, do appear slightly different than the field galaxies at the $\sim 2\sigma$ level. This seems to be due to the fact that these galaxies are somewhat brighter than typical field galaxies: $\sim 30\%$ of optical-afterglow-associated galaxies have $I < 18$ mag, while this is true of only $\sim 3\%$ of field galaxies. To test this, we split the entire sample of galaxies into three magnitude bins: bright: $I < 18$, intermediate: $18 \leq I < 22$, and faint: $I \geq 22$. Of the seven galaxies associated with optical afterglow, two are bright, three are intermediate, and two are faint. We then repeat the Monte Carlo simulation but require that for each run the seven galaxies randomly picked from the entire sample include two bright, three intermediate, and two faint galaxies. With the addition of this magnitude selection, the optical-afterglow-associated galaxy sample becomes indistinguishable from the field galaxies.

Similar analyses are performed for galaxy ISOAREAF_IMAGE area versus magnitude, ellipticity versus magnitude, galaxy ellipse area versus ellipticity, and galaxy ISOAREAF_IMAGE area versus ellipticity (see Figs. 7b–7e). The X-ray afterglow error regions are a typical sample of all the galaxies in the field over these dimensions. The optical-afterglow-associated galaxies are atypical on the $\sim 2\sigma$ level when comparing ISOAREAF_IMAGE area versus magnitude and ellipticity versus magnitude. Again, this seems to be due to the fact that these galaxies are somewhat brighter than the average field galaxies.

6. DISCUSSION

Unlike the fairly uniform images considered here, most observations of GRB fields are obtained with a wide range of depth and resolution. Improving depth and resolution will result in the detection of more galaxies, in which case the values calculated here serve only as a lower limit to the probability of chance association. While increased resolution may seem to make the “edge” of a galaxy more defined, we would caution that knowing the exact optical extent of the galaxy is not helpful for identifying a GRB’s host without first fully understanding how GRBs trace light.

An additional complication is lensing, which will always occur when a background GRB is observed through a foreground galaxy. Lensing will increase the brightness of the GRB and its afterglow and shift the observed position of the GRB’s afterglow relative to the lensing galaxy (Paczynski 1986; Mao 1992; Grossman & Nowak 1994). The magnification produced by this lensing, of course, depends strongly on galaxy mass, observer to lens distance, lens to source distance, and the extent of the alignment. This lensing effect actually increases the likelihood of detecting a chance association because it increases the observed brightness of a GRB’s optical afterglow. Host galaxy/optical afterglow associations, by definition, require the detection of an optical afterglow, and brighter optical afterglows are more likely to be detected than dim afterglows.

If pseudoredshifts derived from GRB luminosity relationships eventually become accurate enough to use in evaluating afterglow/galaxy coincidences, lensing would present a complication because lensed GRBs might not follow expected luminosity relationships. The Amati relationship (Amati et al. 2002; Amati 2006), for example, correlates gamma-ray spectral peak energy with a burst’s isotropic equivalent radiated energy. From measurements of peak spectral energy and gamma-ray flux, therefore, a GRB’s redshift can be estimated. Lensing should not alter the gamma-ray burst spectral shape so that peak energy remains unchanged. The increase in gamma-ray flux produced by lensing, however, would result in an underestimated burst distance ($z \propto$ luminosity/flux). This is problematic for detecting inconsistent GRB and galaxy redshifts because lensing will move the pseudoredshift of the GRB toward the redshift of the foreground galaxy.

Treating the lensing galaxy as a single isothermal sphere, the strongest lensing effect would be produced by a low-redshift galaxy lying directly along the line of sight to a high-redshift GRB (angular offset between source and lens $\lesssim 0.3\arcsec$). Random chance, however, favors less exact alignments. At greater angular separations ($>0.3\arcsec$, where magnification depends only weakly on angular separation), only very large galaxies ($L_\ast$ or $\sigma > 100$ km s$^{-1}$) can produce more than a factor of 2 in magnification of the source. Consider a scenario in which a $0.1L_\ast$ galaxy at $z = 0.3$ lenses a GRB at $z = 3$, with an angular separation of $0.5\arcsec$. This produces only a $15\%$ increase in brightness. Lensing, therefore, only becomes a concern when a burst aligns very closely with a $\sim L_\ast$ galaxy. However, there is only a $10^{-4}$ chance that the line of sight to a GRB at redshift $z = 5$ would pass within $0.3\arcsec$ of the gravitational center of a $\sim L_\ast$ galaxy. For bursts that occur at lower redshift, this probability only decreases. Hence, while lensing will always occur with chance alignments, the effects will generally be of little consequence.

Currently, there are only a few situations in which any kind of mismatch between a GRB and proposed host is likely to be noted. One example of this would be when no SN is detected in a low-redshift galaxy associated with a long-duration GRB. A second example would be the association of a long-duration burst with an elliptical galaxy with little to no ongoing star formation. In either event, it is difficult to make a firm conclusion because of the possibility that not all GRBs are produced in the canonical fashion. One can question the cause of a GRB as easily as question its redshift.

To avoid contaminating host galaxy samples with false hosts, it would be useful to have a way to separate true and false hosts. Unfortunately, no exact method of doing so exists. Some strategies are as follows:

**Gamma-ray luminosity indicators.**—While luminosity indicators (e.g., Amati et al. 2002; Ghirlanda et al. 2004; Liang & Zhang 2005) cannot currently produce accurate redshifts for individual bursts, they may eventually be able to be used in such a manner. In that case, however, a discrepancy could either indicate a chance superposition or a very unusual GRB, so that interpretation of such a mismatch is unclear. Lensing effects could also invalidate this method.

**Detection (or nondetection) of SNe.**—This is only meaningful if long-duration bursts are all formed in core-collapse SNe and are similar in brightness to GRB 980425/SN 1998bw, which is assumed to be the archetypal GRB-related SN. This is further
limited to GRBs that occur at relatively low redshifts ($z \lesssim 0.7$). Host galaxy extinction is also a complicating factor that may obscure an underlying SN.

**Optical afterglow spectral absorption features.**—A GRB must occur behind the absorbing material, so line detection actually only gives a lower limit on redshift (although this is generally taken to be the GRB’s redshift). Redshifts derived in this manner can be compared to redshift measurements of the proposed host galaxy after the afterglow has faded. Only a very bright afterglow could possibly show absorption features independent of the superimposed galaxy, however. The exception is proposed host galaxy after the afterglow has faded. Only a very low redshift can be compared to redshift measurements of the GRB (outflows, disks, etc.) so they could serve as accurate redshift indicators. This is a very unproven method, however, because line identification is inexact, reported lines have been at low significance, and few GRB X-ray spectra contain these lines (e.g., Sako et al. 2005).

**Strong lensing of GRB afterglows.**—This would be extremely unlikely for a single foreground galaxy, but could potentially be caused by a foreground galaxy cluster.

7. **CONCLUSIONS**

We have studied the galaxy population surrounding a sample of 72 GRBs. Typically 1% of the sky near the positions of GRBs is covered by galaxies with $I \lesssim 21.5$. With ~125 Swift GRBs with detected optical afterglows, the probability that no chance alignments have been detected is $(0.99)^{125} = 28\%$. Indeed, approximately one superposition between the GRB and a foreground galaxy is expected. While it is possible that no such chance alignments have yet been observed, as Swift detects more and more GRBs with optical afterglows, the likelihood of such an event only increases. While most GRB/galaxy associations noted in the literature are almost certainly correct, caution is required when making sweeping conclusions from only one or two GRB/host galaxy associations.

We have also considered galaxies associated with X-ray afterglows. Over 250 X-ray afterglows, with typical error radii of ~2", have been detected by Swift. These numbers guarantee that some galaxies associated with X-ray afterglow will be falsely identified as hosts. In fact, approximately half of the 14 X-ray afterglow error region/galaxy coincidences in our sample may exist only by chance. Even with large samples, therefore, using X-ray afterglow-identified host galaxies to draw conclusions about GRBs causes confusion.

We thank SMARTS observers D. Gonzalez, J. Espinoza, and A. Pasten for their dedication, and S. Tourrelotte for assistance with optical data reduction. We are also grateful to P. G. van Dokkum and P. Natarajan for useful discussions about galaxies and lensing. This work is supported by NSF Graduate Fellowship DGE0202738 to B. E. C. and NSF/AST grants 04-07063 and 07-07627 and Swift grant NNG 05GM63G to C. D. B.
No. 2, 2008

GRBs AND HOST GALAXIES

1167

Paczynski, B. 1986, ApJ, 308, L43
Pedersen, K., et al. 2005, ApJ, 634, L17
Pelliza, L. J., et al. 2006, A&A, 459, L5
Piranomonte, S., et al. 2006a, GCN Circ. 4520, http://gcn.gsfc.nasa.gov/gen/gcn3/4520.gcn3
———. 2006b, GCN Circ. 4583, http://gcn.gsfc.nasa.gov/gen/gcn3/4583.gcn3
Price, P. A., Berger, E., & Fox, D. B. 2006, GCN Circ. 5275, http://gcn.gsfc.nasa.gov/gen/gcn3/5275.gcn3
Prochaska, J. X., et al. 2005a, GCN Circ. 3390, http://gcn.gsfc.nasa.gov/gen/gcn3/3390.gcn3
———. 2005b, GCN Circ. 3700, http://gcn.gsfc.nasa.gov/gen/gcn3/3700.gcn3
Roming, P. W. A., et al. 2006, ApJ, 651, 985
Sako, M., Harrison, F. A., & Rutledge, R. E. 2005, ApJ, 623, 973
Schaefer, B. E., & Xiao, L. 2006, preprint (astro-ph/0608441)
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sokolov, V. V., et al. 2001, A&A, 372, 438
Thoene, C. C., Fynbo, J. P. U., & Jakobsson, P. 2006a, GCN Circ. 5747, http://gcn.gsfc.nasa.gov/gen/gcn3/5747.gcn3
Thoene, C. C., Perley, D. A., & Bloom, J. S. 2007, GCN Circ. 6663, http://gcn.gsfc.nasa.gov/gen/gcn3/6663.gcn3
Thoene, C. C., et al. 2006b, GCN Circ. 5373, http://gcn.gsfc.nasa.gov/gen/gcn3/5373.gcn3
van Dokkum, P. G. 2001, PASP, 113, 1420
Wainwright, C., Berger, E., & Penprase, B. E. 2007, ApJ, 657, 367