CASTING LIGHT ON THE “ANOMALOUS” STATISTICS OF Mg II ABSORBERS TOWARD GAMMA-RAY BURST AFTERGLOWS: THE INCIDENCE OF WEAK SYSTEMS

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Received 2009 May 21; accepted 2009 October 15; published 2009 November 11

ABSTRACT

We revisit echelle spectra (spectral resolution $R \approx 40,000$) of eight gamma-ray burst (GRB) afterglows to obtain the incidence ($dN/dz$) of weak intervening Mg II systems at a mean redshift of $\langle z \rangle = 1.5$. We show that $dN/dz$ of systems having rest-frame equivalent widths $0.07 \, \text{Å} \leq W_{\text{Mg II}} \leq 1 \, \text{Å}$ toward GRBs is statistically consistent with the incidence toward quasi-stellar objects (QSOs). Our result is in contrast to the results for Mg II systems having $W_r \geq 1 \, \text{Å}$, where $dN/dz$ toward GRBs has been found to be larger than toward QSOs by a factor of $\approx 4$. We confirm the overdensity albeit at a factor of $\approx 3$ only. This suggests that any explanation for the GRB/QSO discrepancy, be it intrinsic to the absorbers or a selection effect, should be inherent only to the galaxies that host strong absorbers in the line of sight to GRBs. We argue that, of all scenarios that have been proposed, lensing amplification is the one that could explain the strong Mg II enhancement while allowing for no significant enhancement in the weak absorbers.

Key words: gamma rays: bursts – gamma rays: observations – gravitational lensing – intergalactic medium – quasars: absorption lines – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

The recent refinements in rapid-response spectroscopy of high-redshift gamma-ray burst (GRB) optical afterglows have opened a new era in the study of the intergalactic medium (IGM; Vreeswijk et al. 2004; Fiore et al. 2005; Chen et al. 2005). In fact, using GRB afterglows instead of quasi-stellar objects (QSOs) as background sources represents a superb complement to the absorption line technique in terms of redshift coverage (the highest redshift objects detected are GRBs; e.g., Olivares et al. 2009; Tanvir et al. 2009), ease of absorption system identification (no emission lines in afterglow spectra), and new insights into the interstellar medium of the host galaxies (Savaglio 2006; Prochaska et al. 2007), not to mention the novel access to the absorbers via deep imaging that the rapid fadeout of the afterglow permits (e.g., Chen et al. 2009; Pollack et al. 2009).

The first systematic, spectroscopic study of intervening systems toward GRB afterglows delivered the first surprise. Using spectra sensitive to rest-frame equivalent width (EW) $W_{\text{2796}} \geq 1 \, \text{Å}$ Mg II systems at a mean redshift of $\langle z \rangle = 1.1$, Prochter et al. (2006, hereafter P06) identified 14 such strong systems in a sample of 14 afterglow spectra at velocities $\beta c > 3000 \, \text{km} \, \text{s}^{-1}$ from the GRB redshift. The redshift path covered yielded almost one strong Mg II system per unit redshift, a roughly four times higher incidence than toward QSO lines of sight at greater than 99.9% confidence. Since the intervening absorption systems are thought to be physically independent of the background source, this result has called for a serious revision of our understanding of absorption line surveys.

Four main astrophysical effects have been proposed to explain the observed discrepancy (see P06; Porcianci et al. 2007; Cucchiara et al. 2009; Sudilovsky et al. 2009): strong Mg II gas might be intrinsic to the GRB environment or host galaxy system; dust within strong Mg II absorbers might obscure faint QSOs that never get detected; GRBs might be gravitationally lensed (and amplified) by the absorbers. A fourth scenario, namely that small absorber sizes might make the distinct beam sizes of GRBs and QSOs affect the statistics differentially (Frank et al. 2007), has proven to be inviable (Pontzen et al. 2007; Thöne et al. 2008; Aoki et al. 2009). However, as argued in P06 and Porcianci et al. (2007), none of these effects alone are likely to explain the QSO/GRB discrepant Mg II statistics. More recent studies have shown that the C IV statistics of QSOs and GRB afterglows are consistent with each other (Tejos et al. 2007; Sudilovsky et al. 2007), although those surveys probed a much higher redshift and also probably different galactic environments.

In this paper, we use echelle spectra of GRB afterglows, sensitive to $W_{\text{2803}} \geq 0.07 \, \text{Å}$, to explore the weak Mg II systems. The QSO Mg II EW distribution shows a clear turnover around $W_r \sim 0.3 \, \text{Å}$, hinting at different populations (e.g., Churchill et al. 1999; Nestor et al. 2005; Milutinović et al. 2006; Narayanan et al. 2007, hereafter N07). Here, we show for the first time that, contrary to the strong systems, the weak ($W_r < 0.3 \, \text{Å}$) and the moderately strong ($0.3 \, \text{Å} < W_r < 1 \, \text{Å}$) Mg II statistics conform to those derived from QSO surveys. In view of these new results, we discuss possible explanations for the P06 result.

2. DATA AND SEARCH ALGORITHM

The GRB afterglow sample comprises eight echelle optical spectra ($R \equiv \lambda/\delta\lambda \approx 40,000$ and signal-to-noise ratio
redshift path density, \( \gamma \) Ly doublet. For this limit, the total redshift path is the lines having how many doublets were recovered over the total. The result of imposing the criterion \( 1 \sigma \) in this list by imposing a 5\( \sigma \) confidence limit on the stronger \( 2796 \) line, but no constraint on the doublet ratio (DR) in order not to exclude blended lines.

To test the sensitivity of our search algorithm, we ran it over a sample of synthetic spectra of S/N = 5 and containing Mg \( ii \) systems having a variety of column densities and Doppler parameters. This S/N or better is representative of \( \gtrsim 90\% \) of the redshift path, \( \Delta z \). The efficiency was inferred by counting how many doublets were recovered over the total. The result of this analysis was that our detection method recovers 100\% of the lines having \( W^{2803} \gtrsim 0.07 \) Å at this S/N level. Thus, for our survey we take \( W^{\min} = 0.07 \) Å in both components of the doublet. For this limit, the total redshift path is \( \Delta z = 10.42 \). The redshift-path density, \( g(z) \), is shown in Figure 1.

3. SAMPLE DEFINITIONS

We define following statistical samples.

**Full sample (FS):** All Mg \( ii \) systems between the redshifted Ly\( \alpha \) and Mg \( ii \) associated with the GRB, with \( W^{2803} \gtrsim 0.07 \) Å, and detected at the 5\( \sigma \) and 2.5\( \sigma \) confidence level in \( \lambda 2796 \) and \( \lambda 2803 \), respectively. The FS is composed of 23 Mg \( ii \) systems (listed in Table 2). Note that we did not find any system with \((\text{S/N}) > 5 \text{ pixel}^{-1}\) taken with the Keck/HIRES (Vogt et al. 1994), Magellan/MIKE (Bernstein et al. 2003), and VLT/UVES (Dekker et al. 2000) spectrographs. This data set comprises all current GRB echelle spectra available to our group.

Table 1 lists the targets that we have used, along with references. Five of these spectra were used in the P06 survey (GRB021004, GRB050730, GRB050820, GRB051111, and GRB060418) and three are new (GRB050922C, GRB060607, and GRB080810). Note also that our survey extends beyond \( z < 2 \), while the P06 survey was restricted to \( z \gtrsim 2 \). Data reduction was conducted in the same fashion as described in Tejos et al. (2007).

To identify Mg \( ii \) systems in our sample we proceeded in two steps. We first performed a blind and automatic search for absorption lines using the “aperture method” (Wolfe et al. 1986; Churchill 2008). This yielded a list of lines detected at the 2.5\( \sigma \) confidence level. Mg \( ii \) doublet candidates were searched for in this list by imposing a 5\( \sigma \) confidence limit on the stronger doublet \( \lambda 2796 \) line, but no constraint on the doublet ratio (DR) in order not to exclude blended lines.

The second step was to calculate EW values. To this end, we used direct pixel integration and, to conform to analysis techniques in QSO surveys (e.g., N07), complex systems were considered as a single one if the velocity span \( \Delta v < 500 \text{ km s}^{-1} \). A careful inspection by eye allowed us to exclude spurious systems and obvious blends, and the final sample was built by imposing the criterion \( 1 < \text{DR} < 2 \). This last condition did not exclude any possible system.

To test the sensitivity of our search algorithm, we ran it over a sample of synthetic spectra of S/N = 5 and containing Mg \( ii \) systems having a variety of column densities and Doppler parameters. This S/N or better is representative of \( \gtrsim 90\% \) of the redshift path, \( \Delta z \). The efficiency was inferred by counting how many doublets were recovered over the total. The result of this analysis was that our detection method recovers 100\% of the lines having \( W^{2803} \gtrsim 0.07 \) Å at this S/N level. Thus, for our survey we take \( W^{\min} = 0.07 \) Å in both components of the doublet. For this limit, the total redshift path is \( \Delta z = 10.42 \). The redshift-path density, \( g(z) \), is shown in Figure 1.

Figure 1. Number of lines of sight in the Mg \( ii \) survey and cumulative redshift path as a function of redshift for \( W^{\min} = 0.07 \) Å.

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

\[ W^{2803} > 0.07 \text{ Å} \] in the GRB080810 spectrum and that Mg \( ii \)-free sight lines are expected from QSO surveys.

**Intervening sample (IS):** All systems in the FS but excluding those ones within 5000 km s\(^{-1}\) of \( z_{\text{GRB}} \) (labeled as “Local” in Table 2). This sample is composed of 19 systems, having a median redshift of \( \langle z \rangle = 1.4 \). Figure 2 shows the velocity profiles of those systems with \( W^{2796} < 1 \) Å.

**Strong intervening sample (SIS):** All systems in the IS having \( W^{2796} \gtrsim 0.3 \) Å. This is the same cutoff used in QSO absorption line surveys (e.g., Nestor et al. 2005, N07). This sample is composed of 14 systems (labeled as “S” in Table 2) and is complete at the 99\% level along a redshift path of \( \Delta z = 10.86 \). Systems with \( W^{2796} \gtrsim 1.0 \) Å are labeled with a “VS” (very strong) in the table. This latter limit is the same used by P06.

**Weak intervening sample (WIS):** All systems in the IS having \( W^{2796} < 0.3 \) Å. This sample is composed of five systems (labeled as “W” in Table 2) and is complete at the 96\% level over \( \Delta z = 10.42 \). The QSO absorption line survey we compare...
with was that one by N07. However, these authors were able to use the more sensitive limit $W_{2796}^{\text{min}} = 0.02$ Å. Consequently, for the sake of comparison between the GRB and QSO data, we recomputed $dN/dz|_{\text{GRB}}$ using a subsample drawn from their line list.

### 4. RESULTS

Table 3 shows $dN/dz|_{\text{GRB}}$ (calculated in the same fashion as in Tejos et al. 2007) for four EW bins, along with $dN/dz|_{\text{QSO}}$ in the same bins. These numbers are plotted in Figure 3. At this point it is important to emphasize that, as in Tejos et al. (2007), our error estimation for the Poisson statistics is based on the tables given by Gehrels (1986) for small numbers. These errors are larger than the usual approximation, $\sigma_N = \sqrt{N}$.

From Figure 3 it is clear that our results for GRB sight lines match those ones for QSOs for EWs $W_{2796} < 1$ Å, while for those with $W_{2796} \geq 1$ Å we recover a similar overabundance as found by P06 which included low-resolution data. In the WIS our result for GRB sight lines, $dN/dz|_{\text{GRB}}(\langle z \rangle = 1.5) = 0.48^{+0.32}_{-0.21}$, is consistent with $dN/dz|_{\text{QSO}}(\langle z \rangle = 1.2) = 0.71^{+0.11}_{-0.10}$ that we infer from the data presented by N07 (55 systems at $0.4 < z < 2.4$ having $W_{2796} \geq 0.07$ Å and
Figure 2. Velocity profiles of intervening Mg \( \text{ii} \) systems with \( W_r^{2796} < 1.0 \text{ Å} \). The labels to the right of the redshifts indicate Mg \( \text{i} \) ("a") or Fe \( \text{ii} \) ("b") detections.

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

On the other hand, in the SIS we recover the result obtained by P06 for Mg \( \text{ii} \) systems with \( W_r^{2796} \geq 1 \text{ Å} \), although we find an overabundance of a factor of 3 only, instead of 4, when comparing with the QSO results by Nestor et al. (2005). Because our redshift path is only two-thirds that of P06, the significance of the result is reduced from 99.9% to \( \approx 95.5\% \). Nonetheless, the fact that we have added new lines of sight argues that the GRB/QSO discrepancy is real, and possibly not due to statistical uncertainties nor a posteriori subtleties. However, note that both

\( W_r^{2796} < 0.3 \text{ Å} \) in a total redshift path \( \Delta z = 77.6 \). We find that our central value is actually \( \approx 70\% \) of the incidence estimated for QSO sight lines, but this difference is not significant. Therefore, we consider an overabundance of weak Mg \( \text{ii} \) systems in GRB sight lines compared with that from QSOs to be very unlikely.

The slightly different redshift coverage between the N07 data and ours makes no significant difference in this comparison.
surveys have five spectra in common and are therefore not completely independent.

Finally, let us emphasize that there seems to be a transition at \( W_r^{2796} \geq 1 \, \text{Å} \), as we see no significant GRB/QSO differences for intermediate EW values (0.3 \( \text{Å} \leq W_r^{2796} < 1 \, \text{Å} \)). This is more clearly seen in Figure 4, which shows the EW distribution in our GRB sample compared with previous parameterizations obtained from QSO samples (Nestor et al. 2005; Steidel & Sargent 1992).

5. DISCUSSION AND IMPLICATIONS

The fact that we do not find any discrepancy between the statistics of QSO and GRB weak Mg \( \text{II} \) systems opens the question as of why there is an overabundance of systems only for \( W_r^{2796} > 1 \, \text{Å} \) systems in front of GRBs. Although the extant sample of afterglow spectra is still small, our result suggests that any explanation for the GRB/QSO discrepancy, be it intrinsic to the absorbers or a selection effect, should be inherent only to the galaxies that host strong absorbers in the line of sight to GRBs. In the following, we discuss how the different models proposed to explain the P06 result may or may not be reinforced in light of our new results on weak systems.

Absorbers intrinsic to the GRBs. The present high-resolution spectra seem to rule out an intrinsic origin of the Mg \( \text{II} \) systems for two reasons. First, the line profiles, as seen at high-spectral resolution, show no indication of broad and shallow absorption troughs, characteristic of BAL QSOs.7 Second, if some of the Mg \( \text{II} \) systems were intrinsic to the GRB, we would expect an overabundance also for the \( W_r < 1 \, \text{Å} \) Mg \( \text{II} \) systems, which we do not observe (indeed, an overabundance of strong C \( \text{IV} \) would be expected too, and that is also not observed; Tejos et al. 2007).

GRB and QSO beam sizes. The geometrical model proposed by Frank et al. (2007; based on different GRB and QSO beam sizes, both comparable to the Mg \( \text{II} \) absorber characteristic sizes) has been tested and ruled out by subsequent observational analysis (Pontzen et al. 2007). Furthermore, initial claims of line-strength variability from Hao et al. (2007) in a single sight

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**Table 3**

| \( W_r \) (Å) | \( N_{abs} \) | \( \Delta z \) | \( \langle z \rangle \) | \( dN/dz_{GRB} \) | \( dN/dz_{QSO} \) |
|----------------|-------------|-------------|-----------------|-----------------|-----------------|
| 0.07 \( \leq W_r^{2803} \) and \( W_r^{2796} < 0.3 \, \text{Å} \) | 5 | 10.42 | 1.46 | 0.48^{+0.32}_{-0.21} | 0.71^{+0.14}_{-0.10} |
| 0.3 \( \leq W_r^{2796} < 0.6 \, \text{Å} \) | 3 | 10.80 | 1.41 | 0.28^{+0.27}_{-0.15} | 0.29 \( \pm 0.04 \) |
| 0.6 \( \leq W_r^{2796} < 1.0 \, \text{Å} \) | 2 | 10.86 | 1.22 | 0.18^{+0.24}_{-0.12} | 0.21 \( \pm 0.02 \) |
| 1.0 \( \leq W_r^{2796} \) | 9 | 10.86 | 1.34 | 0.83^{+0.38}_{-0.23} | 0.28 \( \pm 0.01 \) |

Note.

- \( a \) Values in this column were calculated from N07 (\( W_r < 0.3 \, \text{Å} \)) and Nestor et al. (2005) (\( W_r \geq 0.3 \, \text{Å} \)). Since no redshift list is available in Nestor et al. (2005), we calculated \( dN/dz \) assuming similar redshift coverage and \( \frac{dN}{dz} (W_r^a < W_r < W_r^b) = \frac{dN}{dz} (W_r^a < W_r) - \frac{dN}{dz} (W_r^b < W_r) \).

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**Figure 3.** Redshift number density of Mg \( \text{II} \) absorption systems toward GRB afterglows (filled squares; see the numbers in Table 3). Empty squares (slightly offset in \( x \) for the sake of clarity) depict the QSO results from N07 (\( W_r^{2796} < 0.3 \, \text{Å} \)) and Nestor et al. (2005; \( W_r^{2796} \geq 0.3 \, \text{Å} \)). The triangle indicates the P06 result for GRBs. Note that both surveys have five spectra in common and are therefore not completely independent. Also note that the high EW bin corresponds to \( W_r^{2796} \geq 1 \, \text{Å} \).

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

**Figure 4.** EW distribution of Mg \( \text{II} \) absorption systems toward GRB afterglows (filled squares). The solid line corresponds to the best-fit power law to the data points. The dotted and dashed lines correspond to the expected distributions from QSO sight lines: an exponential fit for systems at \( W_r^{2796} \geq 0.3 \, \text{Å} \) (dotted line; from Nestor et al. 2005) and a power-law fit for systems at \( W_r^{2796} < 0.3 \, \text{Å} \) (dashed line; from Steidel & Sargent 1992).

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

7 However, we note that very shallow systems would not, in most cases, be detected in our GRB spectral sample.
line (GRB060206) have been refuted (Thöne et al. 2008; Aoki et al. 2009). Nevertheless, we will consider this model in light of our new observations.

A consequence of the geometrical model (see Porciani et al. 2007) is that a fraction of weak systems in QSO spectra should have $DR \approx 1$. From the N07 sample we find this fraction to be $\approx 5\%$. Due to the smaller GRB beam sizes, the same fraction in GRB spectra is expected to be lower than this value. In contrast, we find that two out of five systems with $W_{2796} < 0.3$ Å show $DR \approx 1$ (note that taking larger EW values would include saturated lines). Thus, this number, though not significant, does not support the geometrical model.

In addition, the model also predicts an underabundance of weak systems. This is suggested by our data for $W_{r}^{2796} < 0.3$ Å systems, but the $dN/dz$ values are consistent at the 1σ confidence level.

**Dust.** As discussed in P06 and Porciani et al. (2007), the apparent high incidence of strong Mg $\text{II}$ absorbers toward GRBs might be explained by an underestimated incidence of strong Mg $\text{II}$ systems toward QSOs, as a consequence of sources that get lost due to dust obscuration. Although there is mounting counterevidence for a dust bias in QSO surveys (Ellison et al. 2001; Ellison & Lopez 2009; Ménard et al. 2008), from the point of view of the GRBs data alone our result on weak absorbers, a priori does not rule out the dust-obscuration scenario, at least qualitatively. This is so because dust is supposed not to have a considerable obscuring effect when $W_{r} < 1$ Å (Ménard et al. 2008).

On the other hand, a scenario where dust reduces the incidence of strong systems only in QSO sight lines is puzzling. In this scenario, the GRBs provide the unbiased (i.e., “real”) EW distribution but the observed EW distribution for GRBs is atypical (see Figure 4) when compared against any other line surveyed along QSO or GRB sight lines (e.g., C $\alpha$, Ly$\alpha$; Paschos et al. 2009). It seems that there is a transition at $W_{2796}^{r} \geq 1$ Å, where the EW distribution does not decrease as it would be expected. Therefore, in view of our new results, we conclude that dust is unlikely to explain the differences between Mg $\text{II}$ toward QSO and GRB sight lines.

**Gravitational lensing.** Source amplification due to strong gravitational lensing may bias the GRB spectral samples toward targets that contain more intervening absorbers, if these occur in the lensing galaxies (P06; Porciani et al. 2007). Our spectral sample does not offer a direct means to infer what kind of Mg $\text{II}$ systems may be associated with galaxy configurations being more or less lensing efficient. Obviously, further deep late-time imaging observations of GRB fields (e.g., Chen et al. 2009) must be carried out in order to identify the absorbing galaxies and possibly look for impact-parameter/line-strength correlations.

Nevertheless, if we speculate that the strong absorber overdensity is purely explained by a selection effect due to lensing magnification, our results can help us estimate the fraction $f_{l}$ of magnified GRBs that otherwise would not have been spectroscopically observed. To estimate $f_{l}$, let us consider a Mg $\text{II}$ survey composed by $M$ QSO sight lines. Then, the expected number of absorption systems will be

$$N_{QSO} = \left. \frac{dN}{dz} \right|_{QSO} \langle \Delta z \rangle M,$$

where $\langle \Delta z \rangle$ is the average redshift path per sight line and $dN/dz|_{QSO}$ is the expected incidence of systems (assumed unbiased; a quantitative detail of a possible lensing bias in QSO surveys is beyond the scope of this paper).

Let us now consider an equivalent GRB survey with $M$ sight lines. If the observed number of absorption systems, $N_{GRB}$, is a factor of $e$ greater than $N_{QSO}$, then the excess of systems will be $N_{e} = N_{QSO}(e - 1)$. Let $L$ be the total number of lensed sight lines in that GRB survey. The fraction of magnified GRBs is then

$$f_{l} = \frac{L}{M}.$$ 

If we assume that the excess of systems is just due to lensing (either macro or microlensing$^8$), then any extra system corresponds to a lensed sight line:

$$L = N_{e},$$

and therefore

$$f_{l} = (e - 1) \left. \frac{dN}{dz} \right|_{QSO} \langle \Delta z \rangle.$$ 

Thus, in order to reproduce the factor of $\approx 3$ enhancement that is observed at this EW level, we estimate that $f_{l}$ must be of the order of $\approx 60\%$ ($e \approx 3$, $N_{GRB}/dN/dz|_{QSO} \approx 0.3$, and $\langle \Delta z \rangle \approx 1$). Such a fraction would add twice as many strong systems as encountered if there were no lensing. $^9$ Similarly, an enhancement factor of $\approx 2$ (still consistent with our result at the 1σ c.l.) would require $f_{l} \approx 30\%$. Since more realistically $L \leq N_{e}$, this estimate of $f_{l}$ should be taken as an upper limit. Note that we do not provide here a quantitative assessment of the lensing magnification but instead we assume that it is large enough to provide $f_{l} > 0$. In fact, in the above situation our results would imply that the lensing agents contribute only systems with $W_{r} \geq 1$ Å (where $e > 1$; note that this could be easily explained if weak absorbers were indeed more external to galaxies, as proposed by N07 among others). In summary, we believe that lensing by the galaxies hosting strong absorbers provides a viable explanation to the QSO/GRB discrepancy (see also Vergani et al. 2009).

A test of the lensing hypothesis could be made with very rapid and deep spectroscopy of “dark” bursts (e.g., Perley et al. 2009), for which $dN/dz|_{GRB}$ should show no enhancement. In addition, as mentioned above, another test of this bias is that there should be more massive (and more luminous) intervening galaxies at low impact parameters in sight lines where the Mg $\text{II}$ EW is larger.

### 6. SUMMARY

We have used echelle spectra of eight GRB afterglows, three of them new, to show that the incidence of weak Mg $\text{II}$ systems ($0.07 \lesssim W_{r}^{Mg\text{II}} < 1$ Å) is the same as toward QSO lines of sight. There seems to be a transition at $W_{r} \approx 1$ Å, above which $dN/dz|_{GRB}$ rises significantly to a factor of a few with respect to $dN/dz|_{QSO}$, as found by P06. In view of the present results on weak absorbers, we suggest that the GRB/QSO discrepancy should arise in the galaxies that host the strong absorbers. Effects associated with the GRB phenomenon like ejected absorbers or

$^8$ The optical depth for microlensing increases at low impact parameters from $\sigma_{c.l.}$.

$^9$ Note that this argument becomes unrealistic for a factor of $\approx 4$ enhancement, for which $f_{l}$ would approach $\approx 100\%$. 
different beam sizes are not supported by the data presented here nor a selection effect due to dusty absorbers. Instead, of all effects proposed in the literature, a bias toward sources amplified by lensing seems to be in best agreement with our findings.

We thank the anonymous referee. This paper includes data obtained through the Gamma-ray Bursts Afterglows as Probes (GRAASP) Collaboration (http://www.graasp.org) from the following observatories: the W. M. Keck Observatory, which is a joint facility of the University of California, CIT, and NASA, and the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. This paper also includes data based on observations made with ESO Telescopes at the Paranal Observatories under programs 070.A-0599(B), 075.A-0603(B), and 077.D-0661(A). S.L. and N.T. are partly supported by the Chilean Centro de Astrofísica FONDAP no. 15010003, and by FONDECYT grant no. 1060823. J.X.P. is partially supported by NASA/Swift grant NNG05GF55G and an NSF CAREER grant (AST-0548180).

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