The Astrophysical Journal, 659:218–224, 2007 April 10

STRONG Mg II SYSTEMS IN QUASAR AND GAMMA-RAY BURST SPECTRA

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Received 2006 September 8; accepted 2007 January 4

ABSTRACT

The incidence of strong Mg II systems in gamma-ray burst (GRB) spectra is a few times higher than in quasar (QSO) spectra. We investigate several possible explanations for this effect, including dust obscuration bias, clustering of the absorbers, different beam sizes of the sources, multiband magnification bias of GRBs, and association of the absorbers with the GRB event or the circumburst environment. We find that (1) the incidence rate of Mg II systems in QSO spectra could be underestimated by a factor of 1.3–2 due to dust obscuration; (2) the equivalent width distribution of the Mg II absorbers along GRBs is consistent with that observed along QSOs, thus suggesting that the absorbers are more extended than the beam sizes of the sources; (3) on average, GRB afterglows showing more than one Mg II system are a factor of 1.7 brighter than the others, suggesting a lensing origin of the observed discrepancy; (4) gravitational lensing (in different forms, from galaxy lensing to microlensing) can bias high the counts of Mg II systems along GRBs if the luminosity functions of the prompt gamma-ray emission and of the optical afterglows have a mean faint-end slope approaching $-5/3$ to -2; and (5) some of the absorbers can be associated with the circumburst environment or produced by supernova remnants unrelated to the GRB event itself but lying in the same star-forming region. With the possible exception of magnification bias, it is unlikely that one of these effects on its own can fully account for the observed counts. However, the combined action of some of them can substantially reduce the statistical significance of the discrepancy.

Subject headings: gamma rays: bursts — quasars: absorption lines

Online material: color figures

1. INTRODUCTION

Magnesium is an α-process element produced by red giant stars and dispersed in the interstellar medium by supernova explosions and stellar winds. In the redshift interval $0.3 \lesssim z \lesssim 2.2$, the Mg II doublet (2796, 2804 Å) produces absorption lines in the optical spectrum of background sources. The strong absorption systems (with equivalent width $W > 0.3$ Å) are thus believed to be good tracers of metal-enriched gas associated with galaxies (e.g., Bergeron & Boisse 1991; Steidel et al. 1994). Typically these systems have multiple velocity components (Churchill & Vogt 2001).

Recent high-resolution imaging studies of quasar fields provided evidence that strong Mg II absorption is produced in patchy gaseous envelopes, up to impact parameters of 80 h^{-1} kpc, surrounding galaxies of different morphological types (Churchill et al. 2005 and references therein). The completion of large and homogeneous quasar (QSO) samples as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two Degree Field Quasar Survey (2QZ; Boyle et al. 2000; Croom et al. 2004) allowed accurate statistical studies. The amplitude of the cross-correlation function between Mg II systems and luminous red galaxies suggests that absorbers with $W > 1$ Å are hosted within dark matter halos with characteristic masses of 10^{11}–10^{12} $M_\odot$ and could be associated to galactic superwinds (Bouché et al. 2006). Using the SDSS Early Data Release, Nestor et al. (2005) identified over 1300 Mg II doublets with $W > 0.3$ Å and measured their equivalent width distribution over the redshift range $0.366 \le z \le 2.269$. Similarly, Prochter et al. (2006a) found nearly 7000 Mg II systems with $W > 1$ Å in the spectra of 50,000 QSOs from the SDSS DR4. This corresponds to a redshift path density $dN/dz \simeq 0.24$ at $z = 1$. These results have been extended to lower redshift (and weaker column densities) by Nestor et al. (2006). This study suggests that the gas clouds associated with weak Mg II systems are a physically distinct population from those producing strong Mg II absorbers (see also Nestor et al. 2005).

Gamma-ray bursts (GRBs) with bright optical afterglows can also be used as background sources. Somewhat surprisingly, Prochter et al. (2006b, hereafter P06b) identified 14 Mg II systems with $W > 1$ Å along 14 GRB lines of sight (for a total redshift path of 15.5 at a mean redshift $\bar{z} = 1.1$). This corresponds to $dN/dz = 0.90^{+0.83}_{-0.50}$ (symmetrical 99% Poisson[4] confidence interval), an incidence rate that is a few times larger than that inferred from the QSOs of the SDSS data set. A similar (but much less statistically significant) discrepancy, $dN/dz = 0.62^{+1.13}_{-0.49}$ (with an additional ~30% uncertainty due to the redshift path), has been reported by Stocke & Rector (1997) in the optical spectra of 21 radio-selected BL Lacertae objects. However, recent redshift determinations (see, e.g., Sbarufatti et al. 2005) showed that one out of the five strong systems found by Stocke & Rector (1997) is associated with the host galaxy. This reduces the cosmological incidence rate to $dN/dz = 0.49^{+1.06}_{-0.41}$.

In this work, we critically review some possible explanations of the discrepancy between the counts of Mg II systems along GRBs and QSOs. The paper is organized as follows. In § 2 we estimate the importance of dust obscuration bias along lines of sight toward QSOs. The effect of different beam sizes between GRBs and QSOs and the solution proposed by Frank et al. (2007, where QSO beams are assumed to be larger than GRB ones by a factor of 2) are discussed in § 3. The roles of gravitational lensing and magnification bias of GRB afterglows are presented in § 4.

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[4] Clustering of the absorbers produces super-Poisson fluctuations; this effect is discussed in § 2.

Finally, in § 5 we discuss the possibility that some of the Mg II systems along GRBs are produced in the circumburst environment. Our results are summarized in § 6.

2. DUST OBSCURATION BIAS

The presence of dusty absorbers along the line of sight could obscure the optical light from background QSOs and produce a selection bias in magnitude-limited samples (Ostriker & Heisler 1984; Heisler & Ostriker 1988; Fall & Pei 1993). If the obscuration bias is important, radio-selected QSOs (which are unaffected by dust) should present a larger number of absorbers on average. Recent studies did not find strong evidence for dust reddening and extinction (Ellison et al. 2001; Akerman et al. 2005; Jorgenson et al. 2006). However, radio samples are very small and cannot lead to definitive conclusions. Even though the number counts of absorbers in radio and optically selected QSOs are in agreement, 1 σ statistical uncertainties are consistent with 60% of damped Lyα systems being missed in optical magnitude-limited surveys (Ellison et al. 2004).

Could dust obscuration bias of the QSO samples explain the discrepancy with the incidence of Mg II systems in GRB spectra? A few dusty systems with color excess $E(B-V) \sim 0.1$ have indeed been found (Junkkarinen et al. 2004; Ellison et al. 2006). On the other hand, statistical studies give contrasting evidence for dust obscuration. Characteristic values of $E(B-V) = 0.06-0.1$ have been reported for Zn II and Ca II systems with large W (Vladilo & Péroux 2005; Wild et al. 2006). However, Murphy & Liske (2004) found no evidence for dust reddening of QSOs by foreground damped Lyα systems. Similarly, York et al. (2006) could measure some appreciable reddening only in QSOs with very strong Mg II absorbers ($W > 1.53$ Å). Moreover, radio and X-ray-selected SDSS quasars do not appear to be more reddened than optically selected ones. In both cases the typical color excess is $E(B-V) \simeq 0.01$.

All these results are puzzling and contradictory. In order to estimate the importance of dust obscuration in the SDSS sample of Mg II absorbers we have developed the following simplified model. We consider a population of QSOs at $z = 2.3$ with luminosities distributed according to the luminosity function determined by the SDSS (Richards et al. 2006). These QSOs will be obscured by foreground galaxies. To model the galaxy distribution, we use 24 mock light cones extracted from the largest N-body simulation of the concordance cosmology performed so far, the Millennium Run (Springel et al. 2005), in which galaxies are associated with dark matter halos via semianalytic modeling (Kitzbichler & White 2007). The past light cone of an observer (i.e., an event with coordinates x, y, z, t_0) consists of all the paths of light that reach the observer at t_0. Basically, it contains all the galaxies that the observer could detect with an ideal experiment, since they are connected by null geodesics with the observer himself. We shoot 10^3 random lines of sight for each light cone and count how many galaxies we find within a given impact parameter $b = 80\ h^{-1}$ kpc (Churchill et al. 2005). We then associate a Mg II absorber to an intervening galaxy probabilistically with a covering factor $f = 0.5$ (Churchill et al. 2005). We only consider galaxies with (unextincted) absolute magnitude $M_B < M_{\rm thr}$ and choose $M_{\rm thr}$ to match a given dN/dz. As a first case, we also assume that Mg II systems contain some dust with a bimodal distribution: a fraction f_d of them have $E(B-V) = 0.1$ (with a Small Magellanic Cloud [SMC] extinction curve), while all the rest have $E(B-V) = 0.01$. Dust obscuration cannot be discussed separately from gravitational lensing that boosts the luminosity of background sources. For this reason, we also compute the magnification due to all intervening mass concentrations along a given line of sight assuming that they are singular isothermal spheres (the resulting magnifications have a mean of 1.03 and an rms value of 0.04, but the distribution is very positively skewed; nearly 0.8% of the sources are amplified by more than 20%).

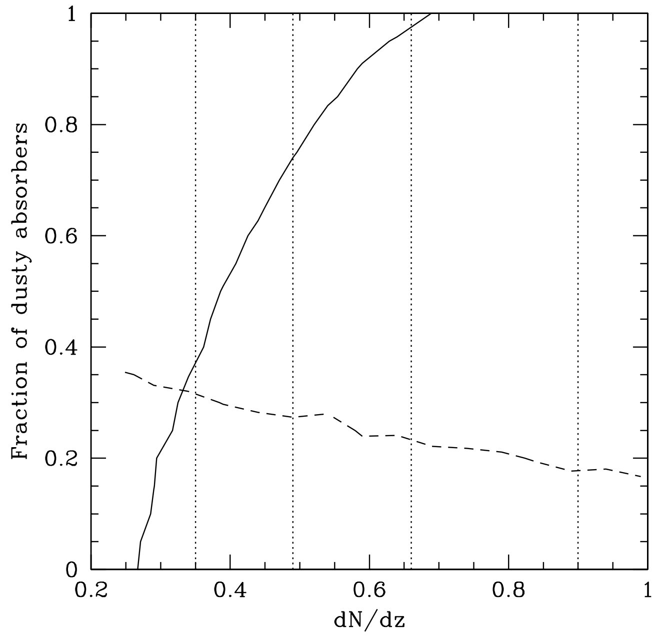

FIG. 1.—Underlying number density of strong Mg II systems and the fraction of dusty absorbers that match the observed abundance of Mg II systems (*solid line*) and the observed fraction of absorbers along very reddened lines of sight (*dashed line*) in the SDSS. The dotted lines mark the 0, 1, 2, and 3 σ Poisson fluctuations for the observed density along GRBs. [*See the electronic edition of the Journal for a color version of this figure.*]

Our results are summarized in Figure 1. The abscissa shows the true number density of the underlying Mg II systems (those revealed along GRB lines of sight), while the ordinate gives f_d: the fraction of dusty absorbers. The solid line indicates the parameter pairs for which SDSS would observe $dN/dz = 0.24$. Obscuration bias can decrease the observed density of absorbers by a maximum factor of $\sim$3. In order to match the observed density of strong Mg II systems in SDSS, the number density of underlying absorbers cannot be higher than $dN/dz \simeq 0.7$, but in this case, all Mg II systems should be very dusty. This would be in contrast with observations. York et al. (2006) found that only 14% of the Mg II systems with $W > 0.3$ Å in the SDSS catalog (and 36% of those with $W > 2.4$ Å) lie along very reddened lines of sight [$\Delta(g-i) \geq 0.2$]. If this fraction amounts to $\sim$20% for $W > 1$ Å, the only way to reconcile our results with the observational data is the case where $dN/dz \simeq 0.33$ (corresponding to $M_{\rm thr} \simeq -21.65$)[5] and $f_d \simeq 0.33$. In this case, SDSS would miss 16% of the QSOs, which are intrinsically brighter than its magnitude limit (the effect of color selection is less important) and include 1% of the total number due to magnification bias (plus dust obscuration). Note that the median and mean halo masses of the Mg II absorbers are 3.0×10^{11} and $7.5 \times 10^{11}\ M_\odot$, in good agreement with Bouché et al. (2006). We explicitly checked that our results do not change substantially by using a Milky Way (MW) extinction curve for the dusty absorbers.

In order to test if our results depend on the assumed distribution of reddening, we repeated our Monte Carlo simulations assuming a two-parameter Weibull distribution for $E(B-V)$ (for an SMC

[5] Note that reducing either the maximum impact parameter b or the covering factor f would make the absorbers' host galaxies fainter for a given dN/dz.

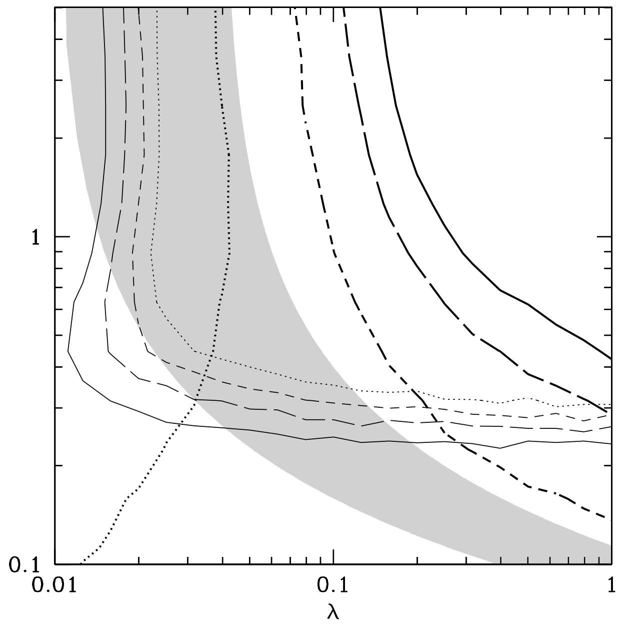

FIG. 2.—Parameters of the reddening distribution of strong Mg II systems. Thick and thin curves respectively mark the set of parameters for which the observed abundance of absorbers and the fraction of very reddened lines of sight match the SDSS values. Solid, long-dashed, short-dashed, and dotted lines refer to $dN/dz = 0.90$, 0.66, 0.49, and 0.35 (i.e., to 0, 1, 2, and 3 σ Poissonian fluctuations in the counts of GRB absorbers), respectively. The shaded area is bounded by the loci where the median observed color excess $\lambda[\ln(2)]^{1/\gamma}$ is 0.01 (*lower boundary*) and 0.04 (*upper boundary*). Models for which thin and thick curves of the same type cross within the shaded area are consistent with all the observational constraints. [*See the electronic edition of the Journal for a color version of this figure.*]

extinction curve). The cumulative Weibull distribution for a variable $x \geq 0$ is $C(x) = 1 - \exp[-(x/\lambda)^\gamma]$, and it is fully determined by the shape parameter $\gamma > 0$ and the scale parameter $\lambda > 0$. This distribution is interesting because it can attain many different shapes based on the value of γ. In particular, for $\gamma < 1$ the corresponding probability density function decreases monotonically and is convex; for $\gamma = 1$ it becomes the exponential distribution; for $\gamma > 1$ it vanishes at $x = 0$ and admits a mode at $x = \lambda(1 - 1/\gamma)^{1/\gamma}$; for $\gamma = 2$ it gives the Rayleigh distribution; for $\gamma < 2.6$ it is positively skewed; for $2.6 < \gamma < 3.7$ it closely approximates a normal distribution; and for $\gamma > 3.7$ it is negatively skewed. We find that only monotonically decreasing distributions for $E(B-V)$ with $\gamma \sim 0.3$–0.5 are compatible with the data.

In this case, there are many solutions that match both the density of Mg II absorbers and the fraction of absorbers along very reddened QSOs observed by SDSS (see Fig. 2). However, if we also require that the median observed color excess is of order 0.01 (as found in the SDSS by York et al. 2006) we have to assume that the underlying incidence rate is $dN/dz \simeq 0.30$ (corresponding to $M_{\rm thr} \simeq -21.7$). This increases up to $dN/dz \simeq 0.45$ ($M_{\rm thr} \simeq -21.4$) if the 2QZ $E(B-V)$ value (0.04; Outram et al. 2001) is adopted.

In summary, we found that estimates of dN/dz based on QSO spectra are likely to be underestimated by a factor $\sim$1.3–2 if dust obscuration bias is important. If $dN/dz \sim 0.35$ (0.45), we find that there is a 0.15% (1.3%) chance to find 14 absorbers or more in a redshift path of 15.5 because of random fluctuations. This shows that it is unlikely that dust obscuration bias fully explains the difference in the number of Mg II absorbers along GRBs and QSOs. Note that in our simulations, the scatter of the number of absorbers per line of sight is generally larger than expected for a Poisson distribution because the host galaxies of the absorbers are clustered. If, on average, there are $\bar{N}$ absorbers per line of sight, the variance of the counts is $\sigma^2 = \bar{N}(1 + \bar{N}\bar{\xi})$, where $\bar{\xi}$ is the mean two-point correlation function computed by averaging over pairs of points both lying within a narrow cylinder with radius b parallel to the line of sight. For $b = 80\ h^{-1}$ kpc and a redshift interval $0.3 < z < 2.2$, the galaxies hosting the absorbers have typically mean correlations of some percent (slightly depending on the mean galaxy luminosity). Whenever $\bar{N} \gtrsim 1$, super-Poisson fluctuations are then appreciable. A number, X, of independent lines of sight have to be combined together to obtain a redshift path of 15.5. This increases both the mean counts and the scatter by a factor of X so that the total excess of the scatter with respect to Poisson remains $1 + \bar{N}\bar{\xi}$ as for single lines of sight. In consequence, the scatter in the number of Mg II systems is nearly Poissonian along QSOs and super-Poissonian along GRBs. Future data with increased statistics might then be used to estimate the clustering amplitude of GRB absorbers.

3. STATISTICS OF ABSORPTION LINES AND BEAM SIZE

Frank et al. (2007, hereafter F07) propose a geometric explanation for the different incidence rate of strong Mg II systems in QSO and GRB lines of sight. They argue that the difference in the statistics can be readily explained if the size of the QSO beam is approximately 2 times larger than the GRB beam, provided the size of the Mg II absorbers is comparable to the GRB beam and of order $\lesssim 10^{16}$ cm^2. This is in contrast with a number of theoretical and observational estimates suggesting that the typical QSO beam is a few times smaller than the GRB beam (see § 4 in F07 and references therein). We show here that the solution worked out by F07 do not include an additional effect that changes the outcome of their model.

In what follows, r is the comoving radial distance and D_a is the angular diameter distance. For simplicity, let us consider a population of gas clouds with comoving number density $n(z)$, proper cross section σ, and equivalent width distribution $f(W_0)$ (normalized to unity). The clouds can be detected as absorption lines in the spectrum of background continuum sources with angular beam size Ω_b. If the beam size is much smaller than the solid angle subtended by the gas clouds, i.e., $\Omega_b \ll \sigma/D_a^2(z)$, the number density of absorption lines per unit redshift and equivalent width is

$$\frac{d^2N}{dW_0\,dz} = \sigma n(1+z)^2 \frac{dr}{dz} f(W_0). \tag{1}$$

On the other hand, if the clouds are much smaller than the beam of the background source, i.e., $\Omega_b \gg \sigma/D_a^2(z)$, two new effects need to be accounted for. First, the observed equivalent width is proportional to the covering factor of the cloud (i.e., to the fraction of the beam area covered by a single absorber), $W_{\rm obs} = \sigma/[\Omega_b D_a^2(z)]W_0 = [\sigma/\sigma_b(z)]W_0$. Second, the mean number of absorbers scales proportionally to the area of the beam (note that this effect was apparently neglected by F07), so that

$$\frac{d^2N}{dW_{\rm obs}\,dz} = \sigma_b n(1+z)^2 \frac{dr}{dz} \frac{\sigma_b}{\sigma} f\left(\frac{\sigma_b}{\sigma} W_{\rm obs}\right). \tag{2}$$

The last possibility is obtained when $\sigma_b \simeq \sigma$. In this case, the number of absorption lines is

$$\frac{dN}{dz} \simeq \left(\sqrt{\sigma} + \sqrt{\sigma_b}\right)^2 n(1+z)^2 \frac{dr}{dz}, \tag{3}$$

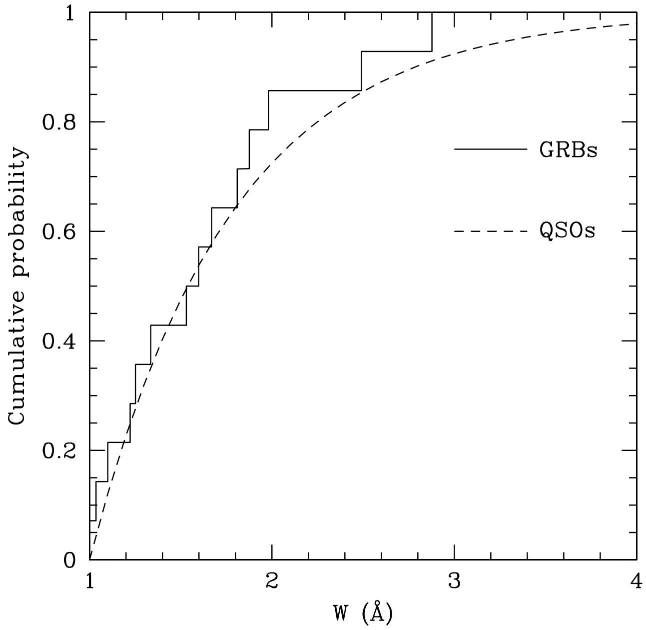

Fig. 3.—Cumulative probability distribution of the Mg II equivalent widths along GRBs listed in P06b (*solid histogram*) compared with the fit for QSO absorbers given by Prochter et al. (2006a). The two distributions are compatible at the 95.7% confidence level in the Kolmogorov-Smirnov sense. [*See the electronic edition of the Journal for a color version of this figure.*]

and Monte Carlo simulations must be used to derive the corresponding distribution of $W_{\rm obs}$ that depends on the relative positions and shape of beam and absorbers.

Let us now consider two different classes of sources (for instance, GRBs and QSOs) and denote their relative beam size by $x = \Omega_G/\Omega_Q$. At every redshift, from equation (2) we derive

$$\frac{d^2N_G}{dW_G\,dz}(W_G, z) = x^2\,\frac{d^2N_Q}{dW_Q\,dz}\left(W_Q = xW_G, z\right). \tag{4}$$

Therefore, to find 4 times more absorbers with $W > 1$ Å along GRBs than along QSOs, the relative beam size must satisfy the equation

$$4\int_{1\,\text{Å}}^{\infty}\frac{d^2N_Q}{dW_Q\,dz}\,dW_Q = \int_{1\,\text{Å}}^{\infty}\frac{d^2N_G}{dW_G\,dz}\,dW_G = x\int_{x\,\text{Å}}^{\infty}\frac{d^2N_Q}{dW_Q\,dz}\,dW_Q.$$

Adopting the fit for the equivalent width distribution derived either by Nestor et al. (2005) or by Prochter et al. (2006a) it is easy to show that this equation does not admit solutions.

This applies to small absorbers and only approximates the case in which absorbers and beams have similar sizes. We performed a number of Monte Carlo simulations varying the beam and absorber sizes. For GRB afterglows we both considered disk and ring geometries (with varying thickness), while we only considered disklike QSO beams. In no case could we reproduce the observational results. If the F07 solution holds, the distribution of Mg II equivalent widths along GRBs should be flatter than in QSOs (this is also evident in our Monte Carlo simulations). However, we found that the equivalent widths listed in P06b are perfectly consistent with the distribution derived from SDSS QSOs (Fig. 3). The Kolmogorov-Smirnov test suggests that the observed equivalent widths for GRB absorbers are compatible (at the 95.7% confidence level) with being a random sampling of the probability distribution derived from SDSS QSOs.

There are some other observational results that the solution proposed by F07 cannot explain: (1) along QSOs there are no apparently unsaturated Mg II absorption lines with a doublet ratio (1:1), as would be expected if small saturated systems were being diluted by a larger QSO beam; (2) an apparently unsaturated Mg II absorption system with a doublet ratio (1:1) has been detected along GRB 030226 (Shin et al. 2006) in the spectrum of GRB 030226, thus suggesting partial covering of the GRB beam; and (3) if the strong Mg II systems resemble intercloud medium of the MW, their sizes are likely to be in the range 1–1000 pc (e.g., Kobayashi et al. 2002; Rauch et al. 2002; Churchill et al. 2003; Ding et al. 2003), which are difficult to reconcile with the sizes proposed by F07.

4. STATISTICS OF ABSORPTION LINES AND LENSING

Only a few spectra of optical GRB afterglows have been taken. Is it possible that the sample is heavily biased toward lines of sight intersecting a large number of absorbers? Gravitational lensing due to intervening material could in principle boost the afterglow luminosity by amplifying its beam size. This would make optical spectra easier to take.

Combining the data by P06b with those by Nardini et al. (2006), we find that afterglows with more than one Mg II absorber are, on average, a factor of 1.7 brighter[6] than the others. According to a Student's *t*-test, there is a 10% chance that this difference is due to random fluctuations. If this result is strengthened by increased statistics (currently only four afterglows showing more than one strong Mg II absorber are known), it is then likely that some form of lensing caused by mass concentrations associated with the absorbers themselves is the cause of their increased detection probability.

The galaxies hosting the absorbers represent obvious lens candidates. However, since Mg II absorbers are seen at large distances from galaxy cores, it is unlikely that they can produce large magnifications. Our Monte Carlo simulations presented in § 2 show that lines of sight with more than two Mg II absorbers have a mean magnification of 1.04, and only 2% of them are magnified by more than a factor of 1.2 (see also Ménard 2005). Strong lensing is a very rare phenomenon. Only a few GRBs in every thousand detections are expected to be strongly lensed by galaxy-sized halos (Porciani & Madau 2001). Millilensing by $10^7\,M_\odot$ halos has an optical depth that is about 1000 times smaller than the strong lensing one (Porciani & Madau 2000).

Afterglow spectra are generally taken within the first few hours after the gamma-ray triggering event when most of the optical emission is expected to come from a narrow ring of radius $r_s \simeq 4\times10^{15}(t/1\ \text{hr})^{5/8}(1+z_{\rm GRB})^{-5/8}$ cm, which is expanding at superluminal speed on the sky (Waxman 1997). The beam size is thus comparable with the Einstein radius of compact solar mass objects at cosmological distances $r_{\rm E} \simeq 5\times10^{16}(M/M_\odot)^{1/2}$, and GRB afterglows can be efficiently microlensed by intervening stars and massive compact objects (MACHOs). When the source can be regarded as pointlike with respect to the lens, microlensing produces a constant amplification depending on the impact parameter of the lens b (Loeb & Perna 1998). On timescales of days (observer frame), the magnification then increases and reaches a maximum value when the source size crosses the lens ($r_s = b$). This rather sharp brightening is a characteristic signature of

[6] In terms of their optical luminosity measured 12 hr (in the GRB rest frame) after the trigger.

microlensing events. For large impact parameters, when the mean magnification is <2, and for broader source rings, this feature is less pronounced (see Fig. 1 in Loeb & Perna 1998) and could then be not easily detected observationally. For sources at $z \sim 2$, the microlensing optical depth is $\tau \simeq 0.65\Omega_{\mu 1}$, where $\Omega_{\mu 1}$ denotes the present-day density of microlenses in units of the critical density of the universe (Baltz & Hui 2005). Even in the most optimistic assumption that 20% of the dark matter is in MACHOs, only a few percent of the GRB afterglows should be affected by microlensing. In summary, unless the intrinsic luminosity function of GRBs (and of their afterglows) is extremely steep and magnification bias plays an important role (see below), a lensing explanation of the increased Mg II absorption along GRB lines of sight should be regarded as very unlikely in the standard cosmological scenario.

The lensing solution works better in the presence of a cosmological population of small dark matter clumps. Mini clusters of dark matter (axion-like or Higgs-like) particles naturally form when a scalar field undergoes a second-order phase transition below the QCD scale (Hogan & Rees 1988). Their existence does not violate any observational constraint, provided that their mass is smaller than $10^4\ M_{\odot}$, and they would behave as efficient lenses if their physical size is smaller than their Einstein ring, which corresponds to a lower mass limit of a few times $10^{-6}\ M_{\odot}$ (Zurek et al. 2007). Assuming that all the dark matter is in miniclusters, we expect that nearly 30% of the *Swift* afterglows could be strongly microlensed. To explain the observed abundance of Mg II absorbers, however, QSOs need not suffer from these microlensing events. In other words, QSO beams have to be larger than the Einstein ring of the miniclusters (and, thus, of the GRB beams). Current estimates of the QSO size ($<10^{15}$–10^{16} cm) then favor minicluster masses, which are smaller than 1 $M_{\odot}$. Patchy obscuration of the GRB optical beam by dust in the circumburst environment could make GRB beams smaller than expected. Albeit very speculative, this scenario would certainly favor the detection of afterglow spectra with an increased number of absorbers, even though it is difficult to estimate the net effect on the observed dN/dz. Note that this result is not in contradiction with § 4. If the absorber size is much larger than both the beam sizes, then the equivalent width distribution function is expected to be the same for QSOs and GRBs.

An appealing possibility is that GRB afterglows are strongly affected by magnification bias. Light sources that are particularly bright in more than one wave band are especially likely to be lensed (Borgeest et al. 1991; Wyithe et al. 2003). This "multiband magnification bias" could be very important for GRBs whose optical and gamma-ray luminosities are found to be statistically independent (Nardini et al. 2006). It is easy to show that, independently of the lensing optical depth (and thus of the kind of lens), the fraction of lensed objects at a given redshift approaches unity when the mean faint-end slope of the luminosity functions in the two bands approaches −2 (Wyithe et al. 2003).[7] For the faint end of the gamma-ray luminosity function, the universal structured jet model predicts a slope of $\gamma = -2$ (Rossi et al. 2002; Zhang & Mészáros 2002), while observational estimates based on number counts give $\gamma = -1.57 \pm 0.03$ (Firmani et al. 2005) and $\gamma = -1.7 \pm 0.1$ (Schaefer et al. 2001). The luminosity function of optical afterglows is not known. Nardini et al. (2006) find that most of the observed afterglows have a similar luminosity, but they do not discuss selection effects. The fact that many afterglows are not detected in the optical band might suggest that the slope of the luminosity function is rather steep indeed. Magnification bias could then be responsible of the different counts of Mg II absorbers between GRBs and QSOs. Note that optically selected QSOs have a faint-end slope of $\gamma \simeq -1.6$ (Boyle et al. 2000; Croom et al. 2004), while (single band) magnification bias becomes important for $\gamma \simeq -3$; thereby, under this scenario we do not expect QSOs to be affected by microlensing events.

5. ASSOCIATION OF Mg II SYSTEMS TO GRBs

We now consider the possibility that the strong Mg II systems are associated with the GRB event. This solution is particularly attractive, since it gives an "additive" correction instead of a "multiplicative" one. In other words, at variance with the solutions explored so far that multiply the incidence rate of Mg II lines by a constant factor, it is sufficient that a few of the 14 P06b absorbers are associated to the GRB events to fully solve the discrepancy in dN/dz. Both the hint for a partial covering of Mg II systems along some GRB lines of sight and the failed optical detection of the galaxies responsible for Mg II absorptions (Ellison et al. 2006) support this hypothesis. The major limitation, however, is the need for cold, metal-enriched gas moving at semirelativistic speeds. Even assuming that the five P06b systems with the largest inferred velocities are produced by intervening galaxies (as expected from § 2), while the rest are associated with GRB events, we still find that the mean peculiar velocity of the intrinsic systems is 6×10^4 km s^{-1} (with a dispersion of 3×10^4 km s^{-1}).

In the fireball model, afterglow emission is produced when the fastest ejecta from the central engine sweep up and shock the circumstellar medium. This happens at typical distances of 10^{16}–10^{17} cm from the central engine. Gas responsible of Mg II absorption must thus lie farther away than this. In order to produce absorption with column densities of 10^{15} cm^{-2}, which fully cover a QSO beam, one needs as little as $10^{-7}\ M_{\odot}$ of material with solar metallicity. Wolf-Rayet winds, binary interactions, and a supernova explosion could have easily transported such an amount of metal-enriched gas at these distances. The GRB shock has enough energy to accelerate this gas to semirelativistic velocities only within $\sim 10^{18}$ cm from the central engine. However, most likely, the swept-up material will also be heated to temperatures well above the ionization threshold of Mg II.[8] Therefore, no Mg II absorption will be possible until the gas temperature cools down below ∼a few times 10^4 K. Even though the action of Rayleigh-Taylor instabilities will help reshaping the structure of the clouds and produce a multiphase medium, it seems unlikely that this sequence of phenomena could produce the observed absorption. It is also difficult to conceive how Mg II systems could appear in the intense photoionization field of the GRB afterglow. The characteristic isotropic equivalent luminosity of the optical afterglow in the Cousins R band after 12 hr (in the rest frame) is 4.47×10^{30} ergs s^{-1} Hz^{-1} (Nardini et al. 2006). Assuming a power-law spectral energy distribution with index β and a time decay with index α, the number of ionizing photons

[7] The detection of an X-ray signal is often required to accurately locate GRB afterglows for optical follow-up. Three-band magnification bias is even more efficient than the case discussed in the main text. For independent luminosities in the different bands, the critical mean faint-end slope is −5/3 (close to the observed value for the prompt gamma-ray emission). Note, however, that gamma- and X-ray luminosities of GRB afterglows seem to correlate rather tightly (e.g., Nardini et al. 2006), and this would again imply a critical slope closer to −2.

[8] Unless the relativistic shock does not penetrate the dense, metal-rich cloudlet, which is also possible (M. Vietri 2006, private communication) and would make Mg II absorption easier.

(with energy above the second photoionization threshold for Mg, $E > E_{\rm thr} = 15.04$ eV) emitted per unit solid angle from $t_{\rm min}$ to $t = t_{\rm max}$ (both in seconds) is

$$\frac{dN_{\rm phot}}{d\Omega} = \frac{5.37\times 10^{55} t_{\rm max}}{\beta(1-\alpha)}\left(\frac{1.82 \text{ eV}}{E_{\rm thr}}\right)^{\beta} \times \left(\frac{43{,}200}{t_{\rm max}}\right)^{\alpha}\left[1-\left(\frac{t_{\rm min}}{t_{\rm max}}\right)^{1-\alpha}\right]. \quad (5)$$

For typical values $\alpha = \beta = 1.3$, $t_{\rm min} = 3$ days, $t_{\rm max} = 1$ month, this gives 10^{58} photons sr^{-1} that can potentially produce a second ionization of Mg atoms. Most of these photons will actually be absorbed by atoms of H, C, N, and O, which (assuming solar abundance ratios) are more abundant than Mg and have lower photoionization thresholds. An optically thin shell, $n < 20$ nuclei cm^{-3}, exposed to such a photoionizing flux gets fully ionized on extremely short timescales. Detailed calculations for higher density clouds require an accurate treatment of radiative transfer and are beyond the scope of this paper. The presence of structured jets (with fast and slow components), already invoked to explain C IV, Si IV, and H I absorption associated with GRB 021004 (Starling et al. 2005), is probably needed.

In the less favored supranova model (Vietri & Stella 1998), a supernova event precedes the GRB with a time lag ranging from weeks to a year. Radio observations suggest that the fastest ejecta of "normal" supernovae Ibc (i.e., fast electrons) have typical velocities of $\sim 0.3c$ (Berger et al. 2003), which are in agreement with the velocities of the absorbers in P06b. If the ejecta travel at a constant velocity of $\sim 10^5$ km s^{-1}, they will need $\sim$10–100 days to cover a distance of 10^{16}–10^{17} cm. Longer delays are needed to transport the metals produced by the supernova at these distances. The observed narrowness of Mg II lines ($\Delta v \sim$a few hundred kilometers per second) poses some strong constraints on the physical size of the absorbers. To first approximation, in an explosive event, $\Delta v/v = \Delta R/R$ (with v as velocity of the ejecta and R as their distance from the supernova), which implies a linear size for the absorbers of $\sim 10^{12}$–10^{13} cm. Thereby, these systems could either be associated with narrow and dense shell-like structures or to small condensations. However, it is difficult to imagine how the gas could keep cold and to reconcile the required delays between the supernova and the GRB phases with observations (e.g., Mészáros 2006).

An alternative mechanism for producing the observed Mg II system requires that the material emitting the afterglow is lumpy. Mészáros & Rees (1998) investigated spectral features arising from ultrarelativistic ions in the pre-afterglow fireball outflow. In this model, metal-rich inhomogeneities (blobs or filaments) are typically very small (10^5 cm) and dense ($\sim 10^{18}$ cm^{-3}), although their surface covering factor can be quite high. If these structures survive up to the afterglow emission, they could be responsible of the observed Mg II absorption, since they are entrained in the flow that produces the burst. Some kind of magnetic mechanism should be, however, invoked to keep these blobs collimated in the afterglow phase.

A promising scenario is to assume that the observed Mg II systems are associated with supernova remnants (SNRs) in the vicinity of the GRB. Mg II absorption lines from local SNRs and superbubbles look similar to those detected along high-z QSOs and appear to be made of several components with small velocity dispersion (Danks 2000; Bond et al. 2001; Welsh et al. 2001). Imagine that a GRB line of sight crosses the shell of a young SNR that is expanding at a velocity of $v \sim 3\times 10^4$ km s^{-1}. Also assume that the shell is spherical and that it produces two absorption features (we postulate the presence of cold pockets of gas in the shell) in the GRB spectrum: one blueshifted and one redshifted by the amount $(1+z_{\rm GRB})(1 \pm v/c)$. Since GRBs are normally associated with the highest redshift absorbers in their spectra, one would erroneously assign a redshift $(1+z_{\rm GRB})(1+v/c)$ to the GRB and say that the second absorber moves with a relative velocity of $2v$ with respect to it. How likely is it that a GRB line of sight intersects a SNR? A typical star-forming region such as 30 Doradus has a characteristic size of $\sim$100 pc, while a young SNR has a radius of $\sim$10 pc. The optical depth for crossing a shell along a random line of sight toward the GRB is thus of order unity if the number density of SNRs is $\sim 3\times 10^{-5}$ pc^{-3}, which corresponds to nearly 15 objects within a single star-forming region. X-ray studies of 30 Doradus have detected several SNR candidates and five superbubbles (Townsley et al. 2006 and references therein), thus showing that the probability for a line of sight to cross a SNR is not negligible. Note that not in all GRB spectra will the expanding shell of a SNR produce two absorption lines. Sometimes features of the host galaxy will be present together with one line from the SNR. In this case the velocity difference between the lines will be smaller.

6. SUMMARY

We addressed possible explanations for the different incidence rate of strong Mg II systems along GRBs, which is about $\sim$4 times higher than along QSOs. There are a number of phenomena that potentially contribute: dust obscuration bias, different beam sizes between GRBs and QSOs, gravitational lensing, and association of GRB absorbers with the circumburst environment. Our results can be summarized as follows.

1. Considering a simplified model for Mg II absorption based on a set of realistic numerical simulations of galaxy formation and able to reproduce all the observational constraints, we showed that the incidence rate of Mg II systems in QSO spectra can be underestimated by a factor of 1.3–2 due to dust obscuration bias. This is not enough to fully explain the discrepancy with the number of absorbers along GRBs.

2. We critically discussed the solution proposed by F07, where QSOs are assumed to be a factor of 2 larger than GRBs. Accounting for the dependence of both the equivalent width and the number density of absorbers with the beam size, we showed that it is not possible to fully explain the difference in the observed counts by assuming that the two classes of background sources have different characteristic sizes. We also found that the equivalent width distribution of Mg II systems detected along GRB lines of sight is compatible with being a random sampling of the QSO one at the 95.7% confidence level. This suggests that the absorbers are larger than the sources and provides evidence against the solution proposed by F07.

3. We showed that GRB afterglows with more than one absorber are brighter than the others by a factor of 1.7. If confirmed by increased statistics, this finding would suggest a lensing origin of the Mg II discrepancy. However, in the standard cosmological scenario, lensing optical depths are small and difficult to reconcile with the observed counts of Mg II absorbers. This may hint toward the existence of an exotic population of lenses. For instance, microlensing due to mini dark matter clumps could explain the difference, but this also requires QSO beams to be larger than GRB afterglows, which is in disagreement with current observational estimates.

4. Due to their multiband selection and their emission properties, GRB afterglows are particularly sensitive to magnification bias. Independently of the nature of the underlying lenses, a large fraction of the observed GRBs would be lensed if the average faint-end slope of their gamma-ray and optical luminosity functions approaches $-5/3$ to -2. According to current models for prompt and afterglow emission this is not unlikely. Present observations suggest a slope of $\gamma \sim -1.6$ for the prompt gamma-ray emission, while the luminosity functions of optical afterglows is totally unconstrained. Magnification bias then provides a viable solution to the observed discrepancy.

5. The production of Mg II absorbers in the circumburst environment (either by cold and dense cloudlets of metal-rich material accelerated to semirelativistic speeds or, most likely, by SNRs unrelated to the GRB event itself but lying in the same star-forming region) could further reduce the statistical significance of the observed discrepancy to a level compatible with statistical fluctuations due to small-number statistics.

We conclude that, with the possible exception of magnification bias, it is unlikely that one of these effects on its own can fully account for the observed counts. However, the combined action of some of them can substantially reduce the statistical significance of the discrepancy between the incidence of strong Mg II systems in QSO and GRB spectra.

We thank B. Carswell, M. Haehnelt, F. Miniati, M. Pettini, E. Pian, M. Rees, and M. Vietri for useful discussions. P. Madau is warmly thanked for comments on an early version of this paper. M. V. acknowledges the hospitality of ETH, where this project was started.

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