DUST EXTINCTION BIAS IN THE COLUMN DENSITY DISTRIBUTION OF GAMMA-RAY BURSTS: HIGH COLUMN DENSITY, LOW-REDSHIFT GRBs ARE MORE HEAVILY OBSCURED

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ABSTRACT

The afterglows of gamma-ray bursts (GRBs) have more soft-X-ray absorption than expected from the foreground gas column in the Galaxy. While the redshift of the absorption can in general not be constrained from current X-ray observations, it has been assumed that the absorption is due to metals in the host galaxy of the GRB. The large sample of X-ray afterglows and redshifts now available allows the construction of statistically meaningful distributions of the metal column densities. We construct such a sample and show, as found in previous studies, that the typical absorbing column density \(N_{\text{H}\alpha}\) increases substantially with redshift, with few high column density objects found at low-to-moderate redshifts. We show, however, that when highly extinguished bursts are included in the sample, using redshifts from their host galaxies, high column density sources are also found at low-to-moderate redshift. We infer from individual objects in the sample and from observations of blazars that the increase in column density with redshift is unlikely to be related to metals in the intergalactic medium or intervening absorbers. Instead we show that the origin of the apparent increase with redshift is primarily due to dust extinction bias: GRBs with high X-ray absorption column densities found at \(z \lesssim 4\) typically have very high dust extinction column densities, while those found at the highest redshifts do not. It is unclear how such a strongly evolving \(N_{\text{H}\alpha}/A_V\) ratio would arise, and based on current data, remains a puzzle.

Key words: dark ages, reionization, first stars – early universe – galaxies: ISM – gamma-ray burst: general

Online-only material: color figures

1. INTRODUCTION

While it is now generally accepted that long-duration gamma-ray bursts (GRBs) primarily originate in the explosions of massive stars due to their association with Type Ic supernovae, the precise nature of the progenitors and the environment in which the burst occurs are not known. Most progress to date has been made through afterglow observations, providing redshifts, emission mechanisms, and information on the host galaxies. However the X-ray afterglows are still poorly understood. Indeed, one of the outstanding puzzles in understanding long GRBs is the nature and origin of the soft-X-ray absorption observed in the majority of afterglows. Most GRB afterglows show evidence of absorption in the soft end of the X-ray spectrum significantly in excess of what is expected from the Galactic gas column. This has been known statistically from samples since the BeppoSAX era (Galama & Wijers 2001), though first observed at high confidence in a single spectrum with XMM-Newton (Watson et al. 2002). It has generally been assumed from the beginning that the soft-X-ray opacity is due to photoelectric absorption by the inner shells of the atoms in a column of metals—primarily O, Si, S, Fe, He—in the host galaxy of the GRB, in a fashion directly comparable to the X-ray absorption observed due to gas in the Galaxy. However, the absorption was quickly realized not to be directly analogous to Galactic soft-X-ray absorption. The X-ray absorption in the Galaxy is strongly correlated with the dust and H\(\alpha\) column densities (see Watson 2011, and references therein). However, for GRBs, the correlation with dust extinction was not clear and, if it existed, was certainly at least an order of magnitude lower in dust-to-metals ratio compared to the Local Group (Zafar et al. 2011a; Schady et al. 2010). There was also no obvious correlation with the H\(\alpha\) column densities (Watson et al. 2007; Campana et al. 2010; Schady et al. 2011). More recently a further puzzle was added. Campana et al. (2010) showed that the observed X-ray absorptions rose with redshift, with the highest column density objects (log \(N_{\text{H}\alpha} \sim 23\)) appearing at the highest redshifts, and no comparably high column densities occurring at low redshifts (log \(N_{\text{H}\alpha} \lesssim 22\) at \(z < 1.5\)). This result was particularly puzzling since the X-ray absorption measures the total metal column density, and the gas metallicity is expected to decrease rather than increase to high redshift.

It was noted by Behar et al. (2011) that the observed opacity at low energies, while high at low redshift, tended toward an asymptotic value at \(z \gtrsim 2\). This was interpreted as possible evidence for the detection of absorption by a diffuse, highly ionized intergalactic medium (Behar et al. 2011). Such an interpretation has the virtue that it would solve the problems of the lack of correlation observed between the Ly\(\alpha\)-determined H\(\alpha\) column densities and the X-ray column densities in GRB afterglows, and the very low apparent dust-to-metals ratios.

Finally, a recent investigation of a largely redshift-complete sample of bright GRBs (Campana et al. 2012) found a statistically insignificant mild increase of X-ray absorption with redshift and interpreted it as due to increasing absorption by intervening systems in higher redshift GRBs.

In this paper we address the nature of the X-ray absorption in GRB afterglows; we investigate the apparently increasing absorption with redshift, the claim of a possible detection of the warm-hot intergalactic medium (WHIM), and the role of dust extinction. In Section 2, we detail the data used and our data analysis method. In Section 3, we provide the results of our analysis. Section 4 contains a discussion of the interpretation of these results.
2. OBSERVATIONAL DATA AND METHODS

We analyzed the X-ray telescope (XRT) data from every long-duration burst observed by Swift up to 2010 November. For each GRB in this set with a known redshift, we used the spectra produced by the auto-analysis of Evans et al. (2009) with the corresponding response files and fitted a model consisting of a power law absorbed by Galactic gas and gas at the redshift of the GRB to each data set. We obtained redshifts for all bursts from the literature, primarily from Fynbo et al. (2009), Jakobsson et al. (2012), Krühler et al. (2012), and GCNs. This resulted in 175 GRBs. The data from windowed timing (WT) and photon counting (PC) modes were fitted separately. The Galactic gas was modeled with an absorber fixed at a level set by the dust extinction in the direction of the GRB (Schlegel et al. 1998) with $N_{\text{HI}} = 2.2 \times 10^{21} A_V$, as suggested by Watson (2011). The method used to determine the Galactic column density of metals (whether using the neutral hydrogen or the dust as a tracer) does not appear to significantly affect the results as we obtain similar values for the excess absorption as previous authors where the GRBs analyzed are in common (Campana et al. 2010). The absorption at the redshift of the GRB was allowed to be free to vary. The model used was $\text{tbabs}(\text{tbabs}(\text{pow}))$ in Xspec with metallicities from Anders & Grevesse (1989). We used the absorption model of Wilms et al. (2000) to fit the data as the atomic cross-sections are more accurate. We use the metallicity of Anders & Grevesse (1989) for ease of comparison with previous results, which generally use these abundances. It should be noted that while these abundances are significantly higher than the best estimates of the solar photosphere abundances (Asplund et al. 2009), they are likely a better estimate of the typical Galactic ISM abundance (Watson 2011). In any event, as noted above, we sidestep this metallicity conversion problem for the Galactic absorption simply by using the measured relationship between dust and X-ray absorption. However, it should be borne in mind that the excess equivalent hydrogen column densities we report here are determined assuming an abundance approximately 50% higher than solar. Thus, for almost any GRB host these numbers are lower limits to the actual gas column density and, if the real gas column is sought, should be corrected for the probable metallicity of the GRB host galaxy. In this paper, we simply use the equivalent hydrogen column density as a proxy for the total metal column density. We do this for comparison with previous work, since this is what has been done by many authors before; also, because we cannot determine individual metal column densities, the hydrogen proxy is the easiest one to deal with in a simple way.

The absorption in the X-ray afterglows of some GRBs appears to decrease as a function of time (e.g., Starling et al. 2005; Gendre et al. 2007; Campana et al. 2007). For this reason, where the WT and PC data gave statistically different values of the absorption, the later PC data give us a conservative (low) value of the absorption. However, the WT data often have considerably higher signal. Therefore, where the PC and WT mode data gave results consistent within 1σ (68% confidence), the value with the smallest uncertainty was used. Where the results were discrepant at > 1σ, the PC value was used. This procedure will be conservative in the sense that it will tend to lower values of $N_{\text{HI}}$.

We determined extinction estimates for the GRB afterglows from the works of Zafar et al. (2011a), Greiner et al. (2011), Schady et al. (2010), and Kann et al. (2010) primarily. In cases where no explicit estimate of extinction could be found, we used the deepest limits from optical/NIR observations from the literature and the corresponding X-ray data to determine values or limits on $\beta_{\text{XOX}}$ (van der Horst et al. 2009; Jakobsson et al. 2004), where $\beta_{\text{XOX}} = \beta_X - \beta_{\text{OX}}$. From these data, we could then also derive limits on the rest-frame extinction: we use the theoretical and empirical determination that $\Delta \beta = 0.5$ (Zafar et al. 2011a; Sari et al. 1998) and that, hence, $\beta_{\text{XOX}} \leq 0.5$. We then assumed an SMC extinction curve, found by all works to date to be most typical of the extinction for most GRB afterglows (Zafar et al. 2011a; Greiner et al. 2011; Schady et al. 2010; Kann et al. 2010), to determine a limit on the minimum extinction required to make the optical/NIR photometry consistent with $\beta_{\text{XOX}} \leq 0.5$.

3. RESULTS

As with previous work, we find very significant absorbing column densities in excess of the Galactic value for most bursts. Similarly, we also find that the mean absorption increases with redshift (Figure 1). And while we know that the lower bound for detection of absorption increases strongly as a function of redshift, we do not reproduce the most interesting previous finding that the upper envelope of the absorbing column density increases with redshift (Campana et al. 2010). In the distribution shown in Figures 1 and 2, the vast majority of objects have $\log N_{\text{HI}} < 22.6$, with only two outliers above this value: one at $z \sim 2.2$ and the other at $z \sim 8.2$. We do not have the total absence of GRBs with $\log N_{\text{HI}} \gtrsim 22$ at $z \lesssim 2$ found previously (Campana et al. 2010; Behar et al. 2011). The more complete, bright sample analyzed in Campana et al. (2012) showed this effect as well, with a few high column density objects appearing.

Figure 1. X-ray absorption of GRB afterglows as a function of redshift. Overplotted in larger symbols is the mean absorption in a given redshift window taking into account upper limits. GRBs with redshifts obtained from absorption lines in the optical afterglow are plotted in blue. Those with redshifts obtained from host galaxy emission are plotted in red. The bias introduced due to dust extinction is clear in the systematically higher column densities in the emission redshift GRBs ($\Delta \log N_{\text{HI}} = 0.31 \pm 0.08$). The host emission redshift sample still has lower absorption at low redshifts, possibly due to significant remaining incompleteness in the sample, and there is no evidence for a more constant distribution of column densities than in the afterglow-selected sample. The dotted line marks a 10$^{20}$ cm$^{-2}$ absorber at $z = 0$ evolved as $(1 + z)^{5.5}$, showing the approximate detectability threshold for absorption as a function of redshift for a typical Swift-XRT GRB afterglow.

(A color version of this figure is available in the online journal.)
at low redshift, allowing these authors to infer that the previous absence of such bursts was a selection bias.

So, why were these low-redshift, high-absorption GRBs missing from previous analyses? Coding the distribution by dust extinction, the answer is immediately apparent (Figure 2): almost all of the low-redshift, high-absorption GRBs have high extinction ($A_V > 1.5$). These GRBs are: 051022, 060202, 060719, 060814, 061222A, 070306, 070521, 080207, 080607, and 090417B. The high rest-frame extinction of these objects makes it very difficult to obtain a redshift from the optical afterglows. As an aside, intrinsic curvature has never been invoked for the soft-X-ray downturn in the general case because the shape of the downturn does not fit typical GRB models, requiring low-energy slopes different from those observed in the prompt phase (Kaneko et al. 2008) because the measured absorption is occasionally found to be constant in spite of large spectral changes, for example in GRB 100901A where we find the spectral slope changes from $\Gamma = 1.7 \pm 0.03$ to $2.2 \pm 0.05$ between the WT and PC data, but the excess absorptions are $4.1^{+0.4}_{-0.3} \times 10^{21}$ cm$^{-2}$ and $4.1 \pm 0.6 \times 10^{21}$ cm$^{-2}$. As an aside, intrinsic spectral curvature is observed in many blazars, but their spectra are considerably more complex than GRB afterglows and the difference in their low-energy slopes is typically small, with $\Delta \beta \lesssim 0.5$ (Donato et al. 2005; Perlman et al. 2005). Indeed, it should be noted that intrinsic curvature has never been invoked as a general explanation, though it may play a role in the few objects at the highest redshifts (Butler & Kocevski 2007).

4. WHAT IS THE ORIGIN OF THE X-RAY ABSORPTION IN GRB AFTERGLOWS?

The results outlined in the previous section raise more questions than they answer. The peculiarity now is no longer why there are no high-absorption GRBs at low redshift, but why do high-absorption, low-extinction objects show up at high redshift, but not at lower redshifts? While we might expect a strong bias against getting redshifts for dust-obscured GRBs at high redshift, we would not expect any bias against low-extinction GRBs at low redshift.

4.1. Intrinsic Curvature

We can readily exclude intrinsic curvature as an explanation for the soft-X-ray downturn in the general case because the shape of the downturn does not fit typical GRB models, requiring low-energy slopes different from those observed in the prompt phase (Kaneko et al. 2008) because the measured absorption is occasionally found to be constant in spite of large spectral changes, for example in GRB 100901A where we find the spectral slope changes from $\Gamma = 1.7 \pm 0.03$ to $2.2 \pm 0.05$ between the WT and PC data, but the excess absorptions are $4.1^{+0.4}_{-0.3} \times 10^{21}$ cm$^{-2}$ and $4.1 \pm 0.6 \times 10^{21}$ cm$^{-2}$. As an aside, intrinsic spectral curvature is observed in many blazars, but their spectra are considerably more complex than GRB afterglows and the difference in their low-energy slopes is typically small, with $\Delta \beta \lesssim 0.5$ (Donato et al. 2005; Perlman et al. 2005). Indeed, it should be noted that intrinsic curvature has never been invoked as a general explanation, though it may play a role in the few objects at the highest redshifts (Butler & Kocevski 2007).

4.2. The Warm-hot Intergalactic Medium

We can also exclude a smooth, highly ionized intergalactic medium, the so-called WHIM, as the explanation for the absorption, as proposed by Behar et al. (2011). We can see very quickly that there are many GRB afterglows at $z \gtrsim 3$ with absorptions well below the apparent proposed level of the smooth WHIM (Figure 2).

A more general argument is a structured WHIM, where it is only the average opacity above $z \sim 2$ that would tend to a detectable value while individual sight lines could have
disparate values. As opposed to the smooth WHIM, individual GRB afterglows with low absorption values could be reconciled to this model. A potentially useful sample to compare to are type 1 active galactic nuclei (AGNs). Their spectra are known in most cases to be free of gas or dust absorption, and to show no evolution in absorbing column density as a function of redshift up to $z \lesssim 3$ (Mateos et al. 2010).

However, an analysis of the X-ray spectra of small samples of high-redshift AGNs observed with XMM-Newton appears to show substantial absorbing column densities in the radio-loud, but not the radio-quiet AGNs (Page et al. 2005; Yuan et al. 2006; Saez et al. 2011). Among the high-redshift, radio-loud AGNs approximately 50% show a downturn at low energies, and about 25% show a noticeable upturn, suggesting that the spectra are not simple power laws and may be considerably more complex (Page et al. 2005). None of the seven radio-quiet objects in the Page et al. (2005) sample shows a significant up- or downturn. Tavecchio et al. (2007) have suggested that the downturn observed in at least some, and possibly all (Sambunara et al. 2007), radio-loud AGNs is intrinsic curvature of the low-energy side of the inverse Compton emission component, and successfully modeled this in the object RBS 315. Indeed, intrinsic curvature is known in the spectra of blazars at low redshift. It mimics absorption and is present up to fairly hard energies (Perlman et al. 2005; Fossati et al. 2000). Furthermore, the apparent “absorption” observed in low-redshift blazars is peculiar in that no atomic absorption edges or lines are ever observed (e.g., Watson et al. 2004; Blustin et al. 2004), further strengthening the conclusion that the observed downturns are in fact due to intrinsic curvature. Therefore, finding evidence of such curvature in some higher redshift radio-loud AGNs should not be a surprise. In the analysis of RBS 315, Tavecchio et al. (2007) examined two epochs of XMM-Newton spectroscopy taken three years apart. Fitting both data sets with an absorbed power law, they found that the measured absorption had increased by more than 50%. This apparent variability of the downturn argues forcibly against a WHIM origin, since the WHIM is unlikely to vary on a three-year timescale.

4.3. High-density, Low-ionization Foreground Absorbers

It might also be argued that the apparent increase of the X-ray absorption with redshift is related to high-density (neutral or low-ionization) intervening absorbers along the line of sight to the GRBs. And, indeed, the paucity of low column density systems at high redshift is curious, though currently not highly significant statistically given that the detectability threshold at high redshift is so high. Campana et al. (2012) calculate the distribution of Lyα absorbers with redshift based on observational data and show that it is too low to explain the high absorptions observed at high redshift. They contend that the number of absorbers foreground to GRBs may be double that observed foreground to QSOs based on the numbers of high equivalent width Mg ii absorbers discovered (Vergani et al. 2009). Using this larger number, they find that the neutral absorbers could plausibly explain the high X-ray absorption systems found at the highest redshifts. However, they do not take into account the metallicity evolution of damped Lyα absorbers with redshift, but assume that the mean metallicity of the absorbers is solar. This is important since the X-ray absorption measures metals not hydrogen. Prochaska et al. (2003) demonstrate that the metallicity of intervening absorbers evolves strongly with redshift, such that the contribution from $z = 2$–4 absorbers will be 0.5–1.0 dex lower than plotted in Figure 2 of Campana et al. (2012). This demonstrates that even by doubling the number of intervening systems, neutral absorbers along the line of sight are simply insufficient to induce the observed X-ray absorption in GRBs. Furthermore, such absorbers should be detected in the optical unless they are at very low redshift ($z \lesssim 0.3$) or have very low column density. This seems unlikely on either count, since one would have to pack a large number of absorbing systems into the redshift space $z < 0.3$ and have far fewer at $z > 0.3$. In addition, we would expect to detect such absorbing systems $z < 0.3$ relatively easily in emission, as galaxies are close to the lines of sight. In addition, the excess of Mg ii absorbers is only found at very large equivalent widths; at lower equivalent widths the numbers for GRBs and QSOs are the same (Vergani et al. 2009). Thus doubling the population of low column density sources is unjustified. Another way of looking at this is to examine the relationship found by Ménard & Chelouche (2009) between $N_{\text{HI}}$ and Mg ii equivalent width for QSO intervening Lyα systems. The mean number of high equivalent width ($W_{\lambda,0} > 1$ Å) Mg ii absorbers found by Vergani et al. (2009) is 0.7 per redshift interval for GRBs. The typical equivalent width of these systems is a few Å. This corresponds to an $N_{\text{HI}} \sim 1 \times 10^{20}$ for $W_{\lambda,0} = 2$ Å. Regardless of the redshift, this is vastly insufficient to explain the X-ray absorption. Even assuming that the Mg ii absorber is at $z = 0.5$, the apparent contribution to a $z = 4$ GRB is only $2 \times 10^{21}$ cm$^{-2}$. We would then require at least five such $z < 1$ systems for every $z = 4$ GRB or a single system with $W_{\lambda,0} > 6$ Å at $z = 0.5$ in most $z > 4$ GRBs, which is the largest equivalent width ever observed for any GRB to date. In other words, most GRBs would need to have absorption systems similar to, or larger than, GRB 991216 (Vreeswijk et al. 2006), and this is not observed (Vergani et al. 2009). In addition, we would have not to observe the corresponding galaxy at relatively low impact factor at such low redshifts. Finally, this solution does not really answer the fundamental problem of the peculiarly low dust-to-metals ratio; we would expect to observe substantial extinction if the absorbers were predominantly at moderate redshift, since damped Lyα absorbers appear to have a dust-to-metals ratio similar to the Local Group (Vladilo 1998; Ménard & Chelouche 2009).

5. THE ORIGIN OF THE APPARENT INCREASE IN X-RAY ABSORBING COLUMN DENSITY WITH REDSHIFT

We have shown that the apparent increase in X-ray absorbing column densities with redshift is mitigated when dust-extinguished bursts are included in the sample, i.e., we fill in the high-absorption, low-redshift bursts that are missing from Figure 2 of Campana et al. (2010). We have also shown that the bursts with the highest absorbing column densities are also typically the most dust extinguished at low-to-moderate redshift ($z \lesssim 4$). This is similar to the conclusion that there is a tight correlation between “dark” GRBs and high X-ray absorption GRBs found recently (Campana et al. 2012). Furthermore, we still lack redshifts for many bursts—many of these are dark bursts and are almost certainly heavily extinguished. If most of the most highly absorbed bursts are at low redshift, i.e., are similar to the other obscured bursts we have found, they may provide the population needed to correct the apparent increase in X-ray absorption to high redshift. We therefore conclude that the increasing X-ray absorption observed so far as we go to high redshift is principally due to a dust-extinction bias. However, a complete, unbiased sample of sufficient size is required to
answer this question. Campana et al. (2012) argue for a moderate remaining increase with redshift in their 90% complete sample of bright GRBs, but have insufficient statistical power to make the claim with confidence.

An increasing X-ray absorption due to a dust extinction bias is contrary to what we would naively expect; extinction at high redshift has a dramatic effect on the observed optical/NIR flux since we are observing the rest-frame far-UV where dust extinction is at its most severe. At low redshift we see that the most X-ray absorbed bursts have higher extinction. One would expect that bursts at high redshifts with large X-ray column densities would very rarely be detected. The opposite seems to be the case. This is apparent in Figure 3, where there is a clear redshift gradient in the metals-to-dust ratio plane; in particular, no high metals-to-dust ratio objects are detected at low redshift. Such objects should be easily detected.

The simplest interpretation of this unexpected behavior is that the fraction of metals in the dust phase is dramatically lower at \( z \gtrsim 4 \) than at lower redshifts. But, as indicated above, we do not find this a likely explanation. There must be other explanations for this apparent change, and we note that the mean metallicity decreases strongly with redshift (Prochaska et al. 2003) and this change may reflect the more pristine environments found earlier in the age of the universe. It will be difficult to solve this mystery for certain until we have a clear idea of what causes the X-ray absorption and precisely where it occurs.

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