AN EXPLANATION FOR THE DIFFERENT X-RAY TO OPTICAL COLUMN DENSITIES IN THE ENVIRONMENTS OF GAMMA RAY BURSTS: A PROGENITOR EMBEDDED IN A DENSE MEDIUM

YAIR Krongold1 and J. Xavier Prochaska2

1 Instituto de Astronomía, Universidad Nacional Autónoma de Mexico, Apartado Postal 70-264, 04510 Mexico DF, Mexico
2 Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA; xavier@ucolick.org

Received 2012 December 19; accepted 2013 July 1; published 2013 August 22

Abstract

We study the \( \gtrsim 10 \) ratios in the X-ray to optical column densities inferred from afterglow spectra of gamma ray bursts (GRBs) due to gas surrounding their progenitors. We present time-evolving photoionization calculations for these afterglows and explore different conditions of their environment. We find that homogenous models of the environment (constant density) predict X-ray columns similar to those found in the optical spectra, with the bulk of the opacity being produced by neutral material at large distances from the burst. This result is independent of gas density or metallicity. Only models assuming a progenitor immersed in a dense (\( \sim 10^{-22} \text{ cm}^{-3} \) cloud of gas (with radius \( \sim 10 \text{ pc} \)), with a strong, declining gradient of density for the surrounding interstellar medium (ISM) are able to account for the large X-ray to optical column density ratios. However, to avoid an unphysical correlation between the size of this cloud and the size of the ionization front produced by the GRB, the models also require that the circumburst medium is already ionized prior to the burst. The inferred cloud masses are \( \lesssim 10^6 M_\odot \), even if low metallicities in the medium are assumed (\( Z \sim 0.1 Z_\odot \)). These cloud properties are consistent with those found in giant molecular clouds and our results support a scenario in which the progenitors reside within intense star formation regions of galaxies. Finally, we show that modeling over large samples of GRB afterglows may offer strong constraints on the range of properties in these clouds, and the host galaxy ISM.

Key words: galaxies: ISM -- gamma-ray burst: general

Online-only material: color figures

1. INTRODUCTION

Gamma ray bursts (GRBs) are the most powerful sources of radiation in the universe. Although they shine for brief periods of time, their afterglows are capable of ionizing their surrounding material to large distances—tens to hundreds of parsecs (Perna & Loeb 1998; Perna & Lazzati 2002; Prochaska et al. 2008; Piranomonte et al. 2008; D’Elia et al. 2009a). Therefore, GRB afterglows can ionize the medium close to the progenitor, the region of star formation containing the progenitor, and even part of the interstellar medium (ISM) of the host galaxy. Furthermore, as the light travels along our line of sight, GRB afterglows “illuminate” the host galaxy in absorption, giving us a detailed view of the surrounding gas. As a result, GRBs have been used over the last decade as probes of the physical conditions of the ISM in distant galaxies (e.g., Savaglio 2006; Prochaska et al. 2007b). In addition, it has been established that GRBs probe different regions than quasars (likely because GRBs originate in star-forming regions), making studies of the environments of both objects complementary to one another (Vreeswijk et al. 2004; Prochaska et al. 2007b).

The material around GRBs has been observed spectroscopically both at X-ray and optical/UV frequencies. There is clear evidence for intrinsic absorption due to high columns of material in the X-ray spectra for the majority of GRB afterglows (Butler et al. 2006; Watson et al. 2007; Campana et al. 2012). The measured opacities imply metal column densities gauged by oxygen of \( N_\text{O} \approx 10^{10} \text{ cm}^{-2} \). For a solar metallicity, which is likely rare (Prochaska et al. 2007b; Savaglio et al. 2012), this implies an effective hydrogen column density \( N_\text{H} \approx 10^{22} \text{ cm}^{-2} \). Optical/UV spectroscopy also reveals strong intrinsic absorption in a large fraction (\( \approx 90\% \)) of sightlines to GRBs (Savaglio et al. 2003; Prochaska et al. 2007a; Fynbo et al. 2009). From these data, one may estimate the column densities for oxygen from the measurements of unsaturated transitions of Si, S, and Zn assuming solar relative abundances. Typical values are \( N_\text{Si}^\text{UV} \approx 10^{18} \text{ cm}^{-2} \) with a large dispersion. One also measures, from damped H I Ly α absorption, neutral hydrogen column densities of \( N_\text{H} \approx 10^{21–22} \text{ cm}^{-2} \) (Jakobsson et al. 2006). These X-ray and optical/UV spectroscopic observations each require a large reservoir of gas along the sightline, presumably tracing the circumburst medium and the larger-scale, ambient ISM of the galaxy.

However, when a direct comparison between the X-ray and optical inferred column densities toward individual GRBs has been possible, a discrepancy has been observed: the inferred column density of atoms and ions from X-ray studies are systematically larger (by factors of a few to several orders of magnitude) than the column densities measured in the optical/UV (Watson et al. 2007; Schady et al. 2011; Campana et al. 2012). Since the absorption observed in the X-rays is sensitive to the total column density of material in the line of sight (produced from neutral atoms up to highly ionized, but not fully stripped species), while that in the optical/UV region depends on the ionization state of the gas (probing better absorption by cooler gas), it has been proposed that the discrepancies are the result of photoionization of the gas close to the GRB by its own radiation field (Watson et al. 2007; Schady et al. 2011). The large X-ray column densities also suggest a dense environment near the burst location (Campana et al. 2012) while analysis of fine-structure transitions in the optical/UV indicates that the neutral gas lies at distances of

5 Standard treatment in the literature is to recast these metal column densities as equivalent H column densities, but that is not necessary nor preferred for the following analysis.
GRB afterglows have roughly a power-law spectrum (due to synchrotron processes), with emission extending from X-ray to radio frequencies. Therefore, the emission of GRB afterglows contains a large fraction of ionizing photons that will ionize and heat the surrounding material. These photons will produce an ionization front that will expand over time as additional radiation impinges on the gas. An ionization structure is expected around the burst, with highly ionized material near the burst and progressively less ionized gas farther out, owing to the geometrical dilution of the radiation field, the finite propagation time of the ionization front, and the opacity of the circumburst medium. The ionization structure is also time-dependent, as both the GRB flux and the integrated opacity of the gas evolve.

To model the behavior of the ionization front and structure with time, we have performed a series of time-evolving photoionization calculations using a code developed originally to measure the evolution of ionized gas near active galactic nuclei. The code solves a set of linear differential equations that describe the evolution of the abundance of the different ions \( n_i \) as a function of the variation of the incident flux with time, and as a function of the ionization and recombination processes (that also are time-dependent). For a detailed discussion on time-evolving photoionization processes we refer the reader to Nicastro et al. (1999) and Krongold et al. (2007).

The code calculates the ionic abundances as a function of time for H and He, as well as for heavier elements, namely, C, N, O, Ne, Mg, Al, Si, S, and Fe. It includes first order radiation transfer, as the impinging radiation is attenuated by a series of optically thin layers of material (with thickness \( \sim 10^{16} \) cm for \( n_H = 1 \) cm\(^{-3}\)), and is diluted by geometry. The code does not include diffuse radiation (due to recombinations) in the radiative transfer calculations (although they are included in the time evolution of the ionized species). This is a good approximation in the case of the material around GRB afterglows because the expected densities in these regions (\(<10^5 \) cm\(^{-3}\)) imply recombination times much longer than the duration of the burst. For the conditions in this gas, the recombination time ranges from tens to thousands of years (to first order, the recombination time is inversely proportional to the number density of atoms in the gas).

The code solves the time evolution in the first parcel of gas for the whole light curve, then it uses the attenuated (time-dependent) flux exiting this shell as the impinging flux for the next one. This procedure is repeated until the ionization fraction is calculated at all times up to a given distance. In our calculations we have produced models up to 100 pc from the ionizing source. We only consider distances larger than 1 pc from the burst location. This has the advantage of reducing considerably the computing time of the models. At closer distances, the medium is completely stripped by the GRB radiation only a few seconds after the onset. A full description of the code will be given in a forthcoming paper. Calculations using this code have been previously presented for intrinsic absorption observed in the line of sight to GRB 080330 (D’Elia et al. 2009a, GRB080319B (D’Elia et al. 2009b), and GRB050922C (Piranomonte et al. 2008).

As a simple test case, we present models for GRB 050730 and compare against an analogous calculation by Prochaska et al. (2008). The calculations were performed using the same parameters reported by these authors, namely, the luminosity of ionizing photons, the light curve, and the SED of the GRB afterglow, as well as the gas density (which is assumed to be homogeneous with \( n_H = 10 \) cm\(^{-3}\)). Figure 1 (left panel) presents our results. The similarities between the ionization structure predicted by our model (left panel in the figure) and the one calculated by Prochaska et al. (Figure 3 in their
The Astrophysical Journal, 774:115 (11pp), 2013 September 10

Krongold & Prochaska

Figure 1. Time-dependent photoionization model of the ISM surrounding GRB050730. The model was produced assuming the same conditions used by Prochaska et al. (2008), including a homogeneous medium with number density $n(H) = 10 \, \text{cm}^{-3}$. This comparison provides a test of the two codes and we find excellent agreement in the results. Left: ionization structure at observed time $t = 1 \, \text{ks}$. Right: ionization fractions for high ionization charge states as a function of distance at three different times, showing the time evolution of the ionization structure. (A color version of this figure is available in the online journal.)

paper) at 1000 s after the burst are reassuring. This figure also reveals the stratification of ionization states within the surrounding medium. In particular, it can be observed that the higher ionization charge states are formed closer to the source, up to a distance $\sim 15 \, \text{pc}$ away from the burst, where the ionization front is located.

In Figure 1 (right panel), we illustrate the time evolution for several ions. In particular those high ionization ions that can be more easily observed in the UV/optical spectra of GRBs, as well as $\text{O}^{7+}$, which is a natural tracer of the highly ionized gas that may provide a significant X-ray opacity. During the first few thousand seconds (observer frame time), gas up to 5–10 pc away from the burst can reach a high level of ionization (showing states such as $\text{N}^{5+}, \text{O}^{6+}$). At tens of kiloseconds, similar ionization conditions would be driven to even larger distances (tens of parsecs). At these times, the gas closer to the GRB will no longer be observed in these ions because the gas will be driven to even higher ionization states (e.g., $\text{N}^{5+}, \text{O}^{7+}, \text{O}^{8+}$) that are not observed in UV/optical spectra but instead in X-rays. This plot exemplifies, in a simple way, the expected time evolution of the ionization structure near the GRB.

We note in passing that observations of GRB afterglows are typically carried out several hours (kiloseconds to tens of kiloseconds) after the burst. Thus, if the hot gas is indeed photoionized by the afterglow, observations of highly ionized gas do trace the close environment of the GRB, which may include the circumstellar medium of the progenitor star and/or the star-forming region where it was embedded.

3. A FIDUCIAL GRB MODEL

Long-duration GRBs show a significant diversity in their spectral properties and in the characteristics of intrinsic absorption imprinted on their afterglows. In a future work, we intend to explore this diversity to infer variations in properties of the circumburst medium. In this paper, we focus on the specific challenge of the set of GRBs that exhibit strong X-ray absorption with more modest absorption in the optical/UV. It is illustrative, of course, to consider the problem quantitatively. To that end, we consider a fiducial model for a GRB event that is representative of many GRBs. Our fiducial model (described below) is based on the average properties of the sample of Swift GRBs presented by Margutti et al. (2013) for which data of the prompt and afterglow emission have been analyzed.

3.1. GRB Emission

The GRB emission is characterized by a light curve that tracks the time evolution of the luminosity and an SED that may also vary with time. The X-ray light curve can be described in general by two different phases (e.g., Willingale et al. 2007). Each phase is frequently modeled and observed to follow a broken power law $L \propto t^\alpha$. The first phase (hereafter referred to as the prompt phase) is strongly related to the prompt $\gamma$-ray emission, and consists of a nearly constant emission followed by a steep decay (Tagliaferri et al. 2005; Goad et al. 2006). In the second phase (hereafter the afterglow phase) the light curve flattens and then follows a “normal decay” (the break in this phase is generally interpreted as the shock break-out, i.e., the time when the size of the relativistic beam matches the physical extent of the jet).

In the following, we model the prompt phase considering a constant emission up to $t_p = 85 \, \text{s}$ after the burst followed by a steep decay described by $\alpha_1 = -2.0$. We consider the transition between the prompt and afterglow phases to occur at $t_p = 100 \, \text{s}$. From this time on, we model the afterglow light curve by a power law with $\alpha_2 = -1.0$. We do not model the break in the second phase from flat to “normal” decay. This break usually involves a small change in slope and takes place at later times, when the bulk of the photons has already been emitted. Thus it has little effect on our results. Our choice of $\alpha_2$ and $t_p$ is based on the average values found by Margutti et al. (2013). The rest of the
parameters were constrained to match the average luminosities found for GRBs by these same authors (see below).

Although the GRB emission is believed to be dominated by synchrotron emission, its SED is both predicted and observed to be relatively complex (Sari et al. 1998). One often models it as a series of power laws $L_\nu \propto \nu^{-\beta}$ across the electromagnetic spectrum. Our photoionization modeling, however, is only sensitive to the SED at rest-frame energies from 1 Ryd to 100 keV, i.e., the UV to X-ray passbands. Therefore we model the SED as a single power law. We note however, that there can be strong spectral evolution between the prompt and afterglow phases of the light curve and that the early SED has not been studied systematically. However, studies of individual cases show a much harder slope than that in the afterglow (e.g., Butler et al. 2006; Stratta et al. 2009). In the following we assume $\beta = 0.0$ in the prompt phase (before $t_b = 100$ s) and $\beta = 1.0$ for the afterglow.

Lastly, we have set the afterglow luminosity. We consider a total X-ray energy $E_{X,\text{iso}} = 4.1 \times 10^{55}$ erg integrated between 0.3−10.0 keV and from $t = 0$ s to $t = 10^4$ s. The amount of X-ray energy released in the prompt phase is $E_{X,\text{pri}} = 1.4 \times 10^{51}$ erg and that in the afterglow is $E_{X,\text{ag}} = 2.7 \times 10^{51}$ erg. These values are representative of the Swift GRB sample by Margutti et al. (2013). With these considerations, the total amount of ionizing photons emitted by this fiducial GRB is $\phi_0 = 2.1 \times 10^{51}$ photons up to $t = 10^4$ s.

### 3.2. Absorption of the GRB Afterglow

We compare the circumburst models ionized by the above afterglow to a characteristic set of measurements for gas column densities from analysis of X-ray and optical/UV afterglow spectroscopy. Given that the equivalent H column density obtained from the X-rays and the column density of neutral material obtained from the optical spectrum were derived assuming solar abundances (the neutral column density assumes solar abundances as it was measured from metals, not H), we compare the results of our models not to H, but rather to O. Analysis of those GRBs exhibiting significant X-ray opacity typically yields estimates for the effective hydrogen column densities of $N_{\text{H}} \approx 10^{22}$ cm$^{-2}$ (Watson et al. 2007; Schady et al. 2011; Campana et al. 2012). These values were derived by assuming solar abundances and a fully neutral medium. The implied column densities of oxygen therefore scale as $7 \times 10^{-4}$, giving $N_O^X \approx 10^{19}$ cm$^{-2}$. We adopt this as our fiducial value for the X-ray absorption.

Regarding the optical/UV spectroscopy, the commonly observed O i transitions are always saturated and one can only estimate $N_O^{\text{UV}}$ by scaling measurements of non-refractory elements (e.g., S, Si, Zn) assuming solar relative abundances. Values from the literature range from $N_O^{\text{UV}} = 10^{16}−18.5$ cm$^{-2}$. As emphasized in the Introduction, a significant fraction of GRBs with X-ray absorption show $N_O^X \approx 10N_O^{\text{UV}}$ (Schady et al. 2011). In the following, we adopt $N_O^{\text{UV}} = 10^{18}$ cm$^{-2}$ as our fiducial value.

Given that we will explore the conditions required to measure (much) larger columns in the X-rays than in the optical, and these conditions are likely due to ionization, we will evaluate our models considering that the observed X-ray column density is produced mainly by the ionized gas, while the optical column is produced by the neutral one. As will be clear from the models, this is indeed the case, and any contribution from the neutral material to the X-ray absorption is negligible if larger columns in this spectral region are required. Although we run models with many different conditions, we report here only the most relevant to explain the observations.

### 4. RESULTS AND DISCUSSION

#### 4.1. Uniform Models of the Circumburst Medium

We begin by examining the time-dependent results from a series of idealized models with constant gas density extending to a circumburst radius $r_{\text{CBM}} = 150$ pc. Calculations at larger locations are not required given that the ionization front for all models takes place inside this distance. Within this model framework, we explore a range of gas density ($n = 10$ and $n = 10^2$ cm$^{-3}$) and metallicity ($Z = Z_\odot$ and $Z = 0.01Z_\odot$).

Figure 2 shows the radius, as a function of time, to two transition regions driven by the afterglow for a series of models. These two transition regions are: (1) $r_{H_1}$, the radius at which the gas has a 50% hydrogen neutral fraction; and (2) $r_{O_{1X}}$, the radius at which the gas has 90% of its oxygen completely stripped of electrons. These define the neutral region ($r > r_{H_1}$) within the ambient medium which dominates the UV opacity, and the start of the ionized region ($r = r_{O_{1X}}$) where the X-ray bound–free and bound–bound opacity begins. Both radii have a power-law dependence during the prompt phase emission ($t < t_b = 100$ s). At $t_b$ the afterglow emission begins and the radiation impinging on the gas becomes much softer ($\beta = 1.0$). This produces a rapid rise in $r_{H_1}$ right after $t_b$, due to the larger number of UV

#### 4.2. Non-uniform Models of the Circumburst Medium

4. The authors do not report the O abundance assumed in their models. However, their models were carried out using Xspec. The standard abundances on Xspec can be varied according to different measurements, but all are consistent with the O abundance assumed here within a factor $\sim 1.5$. 

![Figure 2. Time-dependent evolution of the ionization fronts of two transition regions: (1) solid curves trace the radius $r_{H_1}$ at which the gas has a 50% hydrogen neutral fraction; and (2) dotted curves trace $r_{O_{1X}}$, the radius at which the gas has 90% of its oxygen completely stripped of electrons. The four models presented include two densities with two different metallicities each. We note very weak metallicity dependence in the results and find strong density variations only for $r_{H_1}$. In general $r_{H_1}$ exceeds $r_{O_{1X}}$ as expected, but the prompt emission radiation field is sufficiently hard that does predict $r_{O_{1X}} > r_{H_1}$ for short times in some models. (A color version of this figure is available in the online journal.)](image-url)
photons. At later times (t > 500 s) both \( r_{\text{OIX}} \) and \( r_{\text{HI}} \) follow a power law again, but with a different slope.

It is evident from the plot that there is relatively weak dependence of the radii with metallicity as these are set by either the density of the gas or the \( r^{-2} \) dilution of the flux. One also notes that the evolution of \( r_{\text{OIX}} \) is weakly dependent on the density. This is because the gas is never optically thick to photons that ionize O\(^{+}\) and \( r_{\text{OIX}} \) is mainly set by \( r^{-2} \) geometrical dilution of the afterglow. Each \( r_{\text{OIX}} \) curve reaches \( \approx 3 \) pc at \( t = 10^3 \) s, indicating the gas in the inner few parsecs cannot contribute to the observed X-ray opacity. In contrast, \( r_{\text{HI}} \) has a different evolution for the models considered. For models with higher density, the ionization front lies closer to the source owing to the greater opacity of the medium. Due to this larger opacity, in these models \( r_{\text{OIX}} \) can even be larger than \( r_{\text{HI}} \) for the few tens of seconds after the burst. This unusual ionization structure, where O\(^{+}\) can exist in the neutral H region, is due to the very hard SED of the prompt emission phase.

In Figure 3, we present the cumulative column densities of ionized (solid) and neutral (dotted) oxygen at \( t = 1000 \) s for a series of models. It is important to note that the ionized columns include only the contribution from charge states with at least one bound electron, e.g., O\(^{+}\) is not included. Under the assumption that the ionized gas must dominate the X-ray opacity, we require values of \( N_{\text{O}^{+}} \approx 10^{19} \) cm\(^{-2}\). It is evident from Figure 3 that this requires a very high density (\( n_{\text{HI}} > 10^6 \) cm\(^{-3}\)), even when one adopts a solar metallicity. If the large column densities observed in the X-ray spectra of GRB afterglows are indeed due to ionized material by the burst, then the densities and/or metallicities of the circumburst gas must be very large. Alternatively, one could reproduce the observed \( N_{\text{O}^{+}} \) values with neutral gas with much lower density extending to circumburst distances \( r_{\text{CBM}} \gg 100 \) pc. This would imply \( N_{\text{O}^{+}} \approx N_{\text{O}} \), which is inconsistent with the observations.

An additional interesting point is obvious when comparing the model with \( Z = 0.01 Z_{\odot} \) and \( n = 10^3 \) cm\(^{-3}\) with that having \( Z = Z_{\odot} \) and \( n = 10 \) cm\(^{-3}\). Although the ionization front takes place at different distances (Figure 2), the column densities inferred for ionized O have similar values within a factor of a few. This is expected, as the total column density of O depends almost linearly on both metallicity and density. However, without an a priori knowledge of where the ionization front takes place (as is the case with spectroscopic observations of GRBs), there is a degeneracy between the metallicity and the density of the material. Because of this, we will discuss models for solar metallicity in the rest of the paper, and will present those with different metallicities when appropriate.

A uniform prediction of these constant density models is that the column density of neutral material matches or even exceeds the ionized phase within the first 100 pc from the burst. This follows from the fact that \( r_{\text{HI}} < 20 \) pc (Figure 2) such that the medium is dominated by neutral gas along any given sightline.

Integrating to \( r = 100 \) pc, all the models predict larger columns of neutral than ionized O (by at least a factor of a few). As such, one predicts column densities probed by X-rays that exceed the optical/UV by only as much as 50% (\( N_{\text{O}^{+}} < 1.5 N_{\text{O}} \)). We note that it is likely that the ISM of the host galaxy extends further beyond the first 100 pc from the burst, making the X-ray and optical/UV columns even more similar. This violates the constraints of our fiducial afterglow model where \( N_{\text{O}^{+}} < 10 N_{\text{O}} \). Thus, unless the circumburst medium has size \( r_{\text{CBM}} \ll 100 \) pc, this model contradicts what is frequently observed. In this case, the bulk of the opacity (in both wavelength ranges) would be dominated by neutral material. We conclude that if the large columns found in the X-rays are indeed due to material ionized by the GRB afterglow, then the density and metallicity should be large, and the distribution of material cannot be homogeneous.

Given that the progenitors of long GRBs might be massive stars with stellar winds (Woosley 1993), possibly embedded in intense star-forming regions, we must consider the possibility that the material within a few tens of parsecs from the progenitor was ionized prior to the onset of the burst. Indeed, simple treatments of likely progenitors for GRBs predict such "pre-ionization" (Perna & Lazzati 2002; Whalen et al. 2008). Then, it is important to test how these conditions may affect the results presented above. We have produced a series of models varying \( r_{\text{preion}} \), the radius to which the gas has been pre-ionized prior to the GRB event. We assume an initial ionization distribution consistent with gas ionized by radiation following the SED of a massive star (\( M \sim 30 M_{\odot} \)) giving a H neutral fraction of \( f(H) = 10^{-3} \). For \( r_{\text{CBM}} \approx 100 \) pc, values of \( r_{\text{preion}} < 50 \) pc yield very similar results to those models without pre-ionization, as can be seen in Figure 3 (magenta line). This is because, although the ionization front and the ionized columns of material are larger due to the effects of the pre-ionization, at distances \( r \sim 2 r_{\text{preion}} \) from the burst the neutral column becomes comparable to that of ionized material. We note that \( r_{\text{preion}} \) might actually be much larger, satisfying the condition \( r_{\text{preion}} \approx r_{\text{CBM}} = 100 \) pc. In this case, the contribution to the total column density from the neutral material up to \( r_{\text{CBM}} \) would be negligible (given that this gas was already ionized by the progenitor). However, as before, at a distance \( \sim 2 r_{\text{preion}} \)
the neutral medium from the ISM of the host galaxy would contribute as much as the ionized material to the total column density, so that again $N_O^{X} \sim N_O^{UV}$. Then, in order to have $N_O^{X} \sim 10 N_O^{UV}$, the total optical path length from the burst location to the ending radius of the galaxy would have to be $\sim r_{CBM}$. While this might be indeed the case for a few GRBs, we consider this possibility unlikely, because it requires that most GRBs are located near the edge of their host galaxies contrary to observations (Bloom et al. 2002; Fruchter et al. 2006).

4.2. Circumburst Medium Models

Including Gradients of Density

Homogeneous models predict similar column densities in the X-ray and the optical/UV domains, with the bulk of the opacity due to neutral material at distances larger than a few tens of parsecs from the GRB. Furthermore, high column densities of ionized material require a circumburst medium with large density (or metallicity). Motivated by these results, we have explored simple models with gradients of density as a possible explanation for the larger X-ray column densities. The models presented here assume larger densities close to the burst, decreasing outward. We explore models with a step in the density: $n = n_1$ at $r \leq r_{\text{step}}$ and $n = n_2$ at $r > r_{\text{step}}$, with $n_1 > n_2$. In all models we assume $n_2 = 1 \text{ cm}^{-3}$. Although this model is overly simplistic, models with radial gradients in density give similar results.

Figure 4 presents our results. The most important difference with the homogeneous cases is that, in general, in the step function model the neutral column density can be, by design, much lower than that for the constant density models. This is clearly observed when comparing the models with $n_1 = 10^3 \text{ cm}^{-3}$ (blue and cyan lines in Figure 4 and blue line in Figure 3).

Indeed, some step function models do predict $N_O^{X} \sim 10 N_O^{UV}$. For instance, a model with $n_1 = 10^3 \text{ cm}^{-3}$ and $r_{\text{step}} = 5 \text{ pc}$ produces X-ray and UV column densities similar to the fiducial afterglow values (blue line in Figure 4). However, if the same model is considered, but with $r_{\text{step}} = 10 \text{ pc}$ (cyan line), then $N_O^{X} \sim N_O^{UV}$ and this condition is no longer satisfied. This is because in the second model $r_{\text{step}} > r_{H1}$, and the dense region can contribute significantly to the neutral absorption. In general, these models are only capable of producing larger columns in the X-rays than in the UV if $r_{\text{step}} \sim r_{H1}$. Since there is no physical reason to assume a relation between the size of the ionization radius (which depends on the GRB properties) and the size of the dense region, we conclude that these models cannot naturally explain the ensemble of observations. This motivates a further addition to the model.

4.3. Models Including Gradients of Density and Pre-ionization in the Circumburst Medium

Finally, we explore models with gradients of density, considering that the medium surrounding the GRB was already ionized before the burst explosion. As discussed before, there are strong arguments to assume a pre-ionized medium (Perna & Lazzati 2002; Whalen et al. 2008). We explore the same density distribution as in Section 4.2 ($n = n_1$ at $r \leq r_{\text{step}}$ and $n = n_2$ at $r > r_{\text{step}}$, with $n_1 > n_2$ and $n_2 = 1 \text{ cm}^{-3}$). To avoid cases where $r_{\text{step}} > r_{H1}$, which produce $N_O^{X} \sim N_O^{UV}$ (Section 4.2), we consider only models where the region of pre-ionized gas contains the dense cloud of material (that is $r_{\text{preion}} > r_{\text{step}}$). As before, we assume a H neutral fraction $f(H I) \sim 10^{-5}$. Figure 5 presents our results. There are two notable benefits in these models.

1. Given the pre-ionization condition, the column density of the ionized material is dominated by gas at $r < r_{\text{step}}$. Therefore, the value of $N_O^{X}$ measured is determined by the density and size of the denser region.

2. The neutral column density is produced, by design, outside the denser region. Therefore, $N_O^{X}$ is systematically lower than the column of ionized gas, i.e., $N_O^{X} \gg N_O^{UV}$.

We find that a model with $n_1 = 10^3 \text{ cm}^{-3}$ and $r_{\text{step}} = 10 \text{ pc}$ presents X-ray and UV column densities similar to the fiducial afterglow values. The cyan line in Figure 5 presents this model. This is not a unique solution, of course; many solutions are possible, with lower $n_1$ requiring larger $r_{\text{step}}$. However, the solutions must satisfy two important conditions: (1) $r_{\text{step}} \lesssim r_{\text{preion}} < r_{H1}$, so that there is no contribution from the dense region to the neutral column density, and (2) we require $r_{\text{step}} > r_{O10}$ so that the GRB does not entirely ionize the dense medium that provides the X-ray opacity.

Within these restrictions, the values that can reproduce our observations are constrained to be in the ranges $30 \text{ pc} > r_{\text{step}} > 5 \text{ pc}$ and $10^4 \text{ cm}^{-3} > n_1 > 5 \times 10^2 \text{ cm}^{-3}$. Different solutions produce X-ray and optical/UV column densities much different than the ratio of 10 from our fiducial value. For instance, a model with $r_{\text{step}} = 20 \text{ pc}$ and $n_1 = 10^3 \text{ cm}^{-3}$ (blue line in Figure 5) would easily produce two orders of magnitude larger column in the X-rays than in the optical/UV, as found in several objects (Campana et al. 2010). These restrictions also impose a minimum pre-ionization radius around the GRB progenitor (condition (1) above); regions with $r_{\text{preion}} \sim 20–30 \text{ pc}$ are enough to explain the observations (see Figure 5). We consider...
these values to be very conservative, since detailed modeling shows that the progenitor can pre-ionize the surrounding material at distances $\gtrsim 100$ pc (Whalen et al. 2008). We note that our results do not place much restriction on the value of $n_2$ (the only condition being to keep the neutral column density small). Assuming again that the neutral gas in the ISM extends for at least $\sim 100$ pc beyond the circumburst region implies that $n_2 \lesssim 10$ cm$^{-3}$.

Given that step function models are very simplistic, we have also computed models assuming a constant density up to a distance $r_{\text{step}}$ from the burst, and a density law parameterized by a power law ($n \propto r/(r_{\text{step}})^{\alpha}$) at larger distances. We find qualitatively similar results to the step models provided $\alpha \gtrsim 2$. These models also yield $N_{\text{O}}^X > N_{\text{O}}^\text{UV}$ for $r_{\text{step}} < 30$ pc.

We conclude that the different column densities found in the X-ray and optical/UV regimes of GRB afterglow spectra can be well explained by the presence of ionized material within a few tens of parsecs of the burst location. This requires that the GRBs are produced in dense clouds of material within the host galaxy, with column densities characteristic of molecular clouds, and that this material is ionized prior to the explosion (Whalen et al. 2008). Our results even permit ionized versus neutral column density ratios up to 2–3 orders of magnitude or more, as reported by Campana et al. (2010). We note that some evidence of evolution with cosmic time in the X-ray absorbing column has been reported in previous works (Campana et al. 2010; Behar et al. 2011). We plan to test different scenarios to explain this evolution in a forthcoming paper.5

4.4. Additional Considerations on Mass and Metallicity

An independent constraint on the metallicity of the medium surrounding the GRB may come from stellar evolutionary theory. In this theory, late-type massive stars, such as Wolf–Rayet stars, are considered the most likely progenitor candidates for GRBs (Woosley & Heger 2006). Furthermore, low metallicities ($Z \lesssim 0.1–0.3 Z_\odot$) are preferred by the models to avoid the spin-down of the stellar core (Izzard et al. 2004; Yoon & Langer 2005; Woosley & Heger 2006). We note however, that it is possible that the circumburst medium of the GRB has been contaminated with metals by the progenitor (at least to some extent). Thus, an extremely low metallicity is not strictly required to reconcile stellar evolutionary results with those presented here. However, somewhat low metallicities may still be expected in the circumburst region, and thus they are definitely desirable in the models. We note that it is possible to get large columns of ionized material with arbitrarily low metallicities, provided that the density of the clouds where the progenitors are embedded is large enough.

Nevertheless, large densities may imply unphysically large masses for the progenitor’s cloud. For the more massive model presented in Figure 5 (blue line), the implied mass for $r_{\text{step}} = 20$ pc is $\approx 10^6 M_\odot$. This is mass characteristic of molecular clouds within the Galaxy (Murray 2011). Even a circumburst medium with $Z = 0.1 Z_\odot$ may match our fiducial value for $N_X^\text{f}$ (red line in Figure 3). Only if $Z \ll 0.1 Z_\odot$ (e.g., GRB 050730; Chen et al. 2005) would one require significantly larger density ($n_1 > 10^4$ cm$^{-3}$; magenta line) and a correspondingly larger mass of the circumburst medium. To the best of the authors’ knowledge, no GRB has been detected with such a low metallicity medium that also shows significant X-ray opacity.

We conclude that the cloud’s radius, density, and mass required to explain the differences between the X-ray and optical/UV column densities may be large (particularly if low metallicities are also required), but are fully comparable with those found in giant molecular clouds. Thus, our results support a scenario where GRBs explode in giant molecular clouds within their host galaxies (Campana et al. 2006; Prochaska et al. 2008; Campana et al. 2010). A statistical study with observations of a large number of GRBs, spanning a wide range of luminosities, as well as X-ray and optical column densities, is required to further explore the properties of these clouds.

4.5. Ionic Column Densities and Time Variability

Two key ingredients in testing any model of the circumburst medium around GRBs is to study (1) the column densities of individual charge states, and (2) the possible variability (or lack of it) in the overall absorption properties of the material. In the following, we only discuss step function models including a pre-ionized medium, as these are the only ones consistent with the different X-ray and optical/UV column densities. We note that models with gradients of density are more likely to produce variability than models with constant density, because a charge state that was produced within the dense medium surrounding the GRB at short times after the burst might be produced outside this region at later times. This would result in strong changes in column density for that particular ion.

5 While our paper was in revision, we became aware of a recent work by Watson et al. (2013) suggesting that absorption by He I may be producing most of the X-ray column density, and may be responsible for its evolution. This idea requires an SED with a very hard X-ray to UV photon index ($\Gamma \sim -1$), much harder than what is usually observed in GRB afterglows. A full time-evolving photoionization model testing this idea is warranted.
To exemplify this, in Figures 6–8 we present the time evolution of the fraction of Si\textsc{iv}, C\textsc{iv}, and N\textsc{v} for two different models with $n_1 = 10^3 \text{ cm}^{-3}$ and $Z = 0.1 Z_\odot$. In the left upper panel of the plots (where a model with $r_{\text{step}} = 15$ pc is presented) one observes that 100 s after the burst, the vast majority of these ions are produced in the dense medium. However, when the observed time is $\sim 1000$ s, they are fully produced at $>15$ pc in the low density regions. Between these two times, the column density of these charge states decreases rapidly, as the peak in their fractional distributions moves out from the dense region into the diffuse medium (see solid lines in the bottom panel of Figures 6–8).

An important additional constraint on the structure of the dense clouds of gas is set by the measured column densities of N\textsc{v}, which traces more highly ionized gas. The UV transitions from this ion have thus far been observed to be unsaturated, with column densities $N(\text{N}^{4+}) \sim 10^{14} \text{ cm}^{-2}$ (e.g., Prochaska et al. 2008; Fox et al. 2008). This implies that N\textsc{v} must be produced outside of the dense regions during these observations. In the case of our fiducial model, this means that the maximum allowed dense region size is $r_{\text{step}} = 15–20$ pc, because for larger sizes N\textsc{v} would be produced inside $r_{\text{step}}$ even thousands of seconds after the burst, and the predicted column densities would be $\sim 100–1000$ times larger (see Figure 8). However, we note that the GRBs where N\textsc{v} and other high ionization UV charge states can be observed are distant ($z \gtrsim 2$) and $>10$ times brighter than our fiducial GRB luminosity (which is based on the average luminosity distribution by Margutti et al. 2013 and includes objects at all redshifts). Indeed, a model with five times more ionizing photons than our fiducial GRB produces N\textsc{v} at distances larger than 40 pc only 1000 s after the burst (see the upper right panel and dotted line in the bottom panel of Figure 8). This makes possible much larger sizes for the dense region. In these bright GRBs, absorption from different charge states can be produced at large distances from the burst (hundreds of parsecs or more depending on the GRB luminosity), consistent with the observations (e.g., Fox et al. 2008). This is because of the much smaller opacity in a pre-ionized medium, with respect to a neutral one. Thus, pre-ionization is not only required to explain the large X-ray to optical/UV column density ratios, but also to explain absorption by photoionized elements at large distances from the GRB.

We remark that our models predict no variability in the total column densities of optical/UV observed charge states at times $>500$ s, when the earliest spectroscopic observations in these wavebands are possible (e.g., Fox et al. 2008; D’Elia et al. 2009a). Our models, however, are not in contradiction with possible variations in individual charge states, as these can be produced by additional inhomogeneities in the diffuse medium, beyond $r_{\text{step}}$. These models are also consistent with the observations of variability in excited lines (e.g., Vreeswijk et al. 2007; D’Elia et al. 2009a), as these lines arise from material at large distances from the GRB region in the ISM of the host galaxy. The spectral variations are produced by UV pumping...
Figure 7. Time evolution of the fractional abundance and column density of C\textsc{iv}. Models and labels as in Figure 6.

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

Figure 8. Time evolution of the fractional abundance and column density of N\textsc{v}. Models and labels as in Figure 6.

(A color version of this figure is available in the online journal.)
Our results support a scenario in which the bursts are produced in dense condensations of material within their hosts. The masses, radii, and densities of these clouds are consistent with those found in giant molecular clouds, further implying that GRB are indeed produced within regions of intense star formation in galaxies. A case study for a fiducial GRB is too limited to further provide insights on the overall properties of such clouds (size, density, mass, and metallicity distributions). However, here we show that time resolved spectroscopy of X-ray and optical/UV data have strong diagnostic capabilities when compared to simple models. Producing detailed photoionization models—with physical parameters able to match the measured X-ray and optical column densities for a large sample of bursts—is a promising way to shed light on the physical properties of the star formation regions where the GRB progenitors are born and evolve, and also on the ISM of their hosts.

We thank the anonymous referee for thoughtful comments that improved our paper and Enrico Ramirez-Ruiz for insightful discussions. J.X.P. acknowledges support from NASA/Swift grants NNX07AE94G and NNX12AD74G. Y.K. acknowledges support from CONACyT 168519 grant and UNAM-DGAPA PAPIIT IN103712 grant. Y.K. and J.X.P. acknowledge support from a UC Mexus grant, FA 10-61.

REFERENCES

Behar, E., Dado, S., Dar, A., & Lair, A. 2011, ApJ, 734, 26
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Butler, N. R., Li, W., Perley, D., et al. 2006, ApJ, 652, 1390
Campana, S., Romano, P., Covino, S., et al. 2006, A&A, 449, 61
Campana, S., Salvaterra, R., Melandri, A., et al. 2012, MNRAS, 421, 1697
Campana, S., Thöne, C. C., de Ugarte Postigo, A., et al. 2010, MNRAS, 402, 2429
Chen, H.-W., Prochaska, J. X., Bloom, J. S., & Thompson, I. B. 2005, ApJL, 634, L25
D’Elia, V., Fiore, F., Perna, R., et al. 2009a, ApJ, 694, 332
D’Elia, V., Fiore, F., Perna, R., et al. 2009b, A&A, 503, 437
Dessauges-Zavadsky, M., Chen, H.-W., Prochaska, J. X., Bloom, J. S., & Barth, A. J. 2006, ApJL, 648, L89
Fox, A. J., Ledoux, C., Vreeswijk, P. M., Smette, A., & Jaunsen, O. A. 2008, A&A, 491, 189
Fruchter, A. S., Levan, A. J., Strolger, L., et al. 2006, Natur, 441, 463
Fynbo, J. P. U., Jakobsson, P., Prochaska, J. X., et al. 2009, ApJS, 185, 526
Goad, M. R., Tagliaferri, G., Page, K. L., et al. 2006, A&A, 449, 89
Izzard, R. G., Ramirez-Ruiz, E., & Tout, C. A. 2004, MNRAS, 348, 1215
Jakobsson, P., Fynbo, J. P. U., Ledoux, C., et al. 2006, A&A, 460, L13
Krongold, Y., Nicoastro, F., Elvis, M., et al. 2007, ApJ, 659, 1022
Lazzati, D., & Perna, R. 2002, MNRAS, 330, 383
Lazzati, D., & Perna, R. 2003, MNRAS, 340, 694
Margutti, R., Zaninoni, E., Bernardini, M. G., et al. 2013, MNRAS, 428, 729
Murray, N. 2011, ApJ, 729, 133
Nicoastro, F., Fiore, F., Perola, G. C., & Elvis, M. 1999, ApJ, 512, 184
Perna, R., & Lazzati, D. 2002, ApJ, 580, 261
Perna, R., Lazzati, D., & Fiore, F. 2003, ApJ, 585, 775
Perna, R., & Loeb, A. 1998, ApJ, 501, 467
Piranomonte, S., Ward, P. A., Fiore, F., et al. 2008, A&A, 492, 775
Prochaska, J. X., Chen, H.-W., & Bloom, J. S. 2006, ApJL, 648, 95
Prochaska, J. X., Chen, H.-W., Bloom, J. S., et al. 2007a, ApJS, 168, 231
Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007b, ApJ, 666, 267
Prochaska, J. X., Dessauges-Zavadsky, M., Ramirez-Ruiz, E., & Chen, H.-W. 2008, ApJ, 685, 344
Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17
Savaglio, S. 2006, NJPh, 8, 195
Savaglio, S., Fall, S. M., & Fiore, F. 2003, ApJ, 585, 638
Savaglio, S., Rau, A., Greiner, J., et al. 2012, MNRAS, 420, 627
Schady, P., Savaglio, S., Kirshler, T., Greiner, J., & Rau, A. 2011, A&A, 525, A113
Sheffer, Y., Prochaska, J. X., Draine, B. T., Perley, D. A., & Bloom, J. S. 2009, ApJL, 701, L63
Stratta, G., Pozanenko, A., Atteia, J.-L., et al. 2009, A&A, 503, 783

5. SUMMARY AND FUTURE WORK

In this work we present time-evolving photoionization calculations of the environments of GRBs. Our models indicate that the discrepancies found in the column density measurements carried out in the X-ray and optical/UV domains can be easily explained in terms of strong density gradients between the burst region, where the ionized X-ray absorption arises, and the extended (neutral) ISM of the host galaxy (imprinting absorption features in the optical/UV band). However, this requires that the dense medium surrounding the GRB is pre-ionized, as suggested by previous works.
Tagliaferri, G., Goad, M., Chincarini, G., et al. 2005, Natur, 436, 985
Vreeswijk, P. M., Ellison, S. L., Ledoux, C., et al. 2004, A&A, 419, 927
Vreeswijk, P. M., Ledoux, C., Smette, A., et al. 2007, A&A, 468, 83
Watson, D., Hjorth, J., Fynbo, J. P. U., et al. 2007, ApJL, 660, L101
Watson, D., Zafar, T., Andersen, A. C., et al. 2013, ApJ, 768, 23

Whalen, D., Prochaska, J. X., Heger, A., & Tumlinson, J. 2008, ApJ, 682, 1114
Willingale, R., O’Brien, P. T., Osborne, J. P., et al. 2007, ApJ, 662, 1093
Woosley, S. E. 1993, ApJ, 405, 273
Woosley, S. E., & Heger, A. 2006, ApJ, 637, 914
Yoon, S.-C., & Langer, N. 2005, A&A, 443, 643