PROBING THE WARM INTER-GALACTIC MEDIUM THROUGH ABSORPTION AGAINST GAMMA RAY BURSTS X-RAY AFTERGLOWS

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ABSTRACT

Gamma Ray Burst (GRB) afterglows close to their peak intensity are among the brightest X-ray sources in the sky. Despite their fast power-law like decay, when fluxes are integrated from minutes up to hours after the GRB event, the corresponding number counts (logN-logF relation) far exceeds that of any other high redshift (z>0.5) source, the flux of which is integrated over the same time interval. We discuss how to use X-ray afterglows of GRBs as distant beacons to probe the warm (10^5 K < T < 10^7 K) intergalactic matter in filaments and outskirts of clusters of galaxies by means of absorption features, the “X-ray forest”. According to current cosmological scenarios this matter may comprise 30–40% of the baryons in the Universe at z<1. Present-generation X-ray spectrometers such as those on Chandra and XMM-Newton can detect it along most GRBs lines of sight, provided afterglows are observed fast enough (within hours) after the burst. A dedicated medium-sized X-ray telescope (effective area \( \gtrsim 0.1 \text{ m}^2 \)) with pointing capabilities similar to that of Swift (minutes) and high spectral resolution (\( E/\Delta E \gtrsim 300 \)) would be very well suited to exploit the new diagnostic and study the physical conditions in the Universe at the critical moment when structure is being formed.

Subject headings: gamma rays: bursts, cosmology: observations, large-scale structure of universe

1. INTRODUCTION

Gamma Ray Burst (GRB) afterglows carry a relatively large fraction of the total GRB flux, often exceeding the total energy budget of the main event itself. Minutes after the GRB events, they are by far the brightest sources in the sky at cosmological redshifts (the redshift of 9 GRBs has been measured so far, ranging between z=0.4 and z=3.4, with a median of about z=1.3). For this reason the optical and infrared GRB afterglows have been proposed as probes of the high redshift Universe through the detection of absorption line systems along the line of sight (Lamb & Reichart 2000, Ciardi & Loeb 2000). However, optical and infrared afterglows have been detected in less than half of the GRBs observed by BeppoSAX. Moreover, they only carry a small fraction of the total GRB afterglow flux, most of which is in the X-ray band. We propose here to exploit X-ray resonant scattering lines in the GRB afterglow X-ray spectra to probe the warm component of the inter-galactic medium (IGM).

Hydrodynamic simulations show that at z<1 a large fraction (30–40%) of the baryons in the Universe are in a warm phase, shock-heated to temperatures of 10^5 – 10^7 K during the collapse of density perturbations (warm phase hereafter, see Davé et al. 2000 and references therein). According to the same simulations 10–20% of the remaining baryons end up in clusters of galaxies (with T > 10^7 K, hot phase), and 30–40% are in stars and colder gas clouds (T < 10^5 K, cold phase). Both the hot and the cold phases of the IGM have been detected and studied in detail in the X-ray and O-UV bands respectively. The cold gas is revealed through UV rest frame absorption lines. At z>1.5 these lines are redshifted in the optical and so easily detected in the spectra of bright background sources like quasars. At z \( \approx 1.5 \) their study is complicated by the limited capabilities of UV instruments. Hot gas shines in the 0.1–10 keV band due to bremsstrahlung emission and line emission, both proportional to the square of the gas density, and so primarily tracing peak densities. On the other hand, observations of the warm IGM expected away from the high density regions have yielded so far only limited information. Gas with T \( \approx 10^5 \) K has been revealed through OVI absorption at 1032, 1038 Å at z=0.1–0.3 (Tripp et al. 2000, Tripp & Savage, 2000). OVI has been detected at z=2–4 too (Kirkman & Tytler 1997, 1999), but in these cases the OVI lines are probably associated with Lyman-limit systems (16 < logN(III) < 19) and therefore with colder gas clouds in galaxies. Warmer IGM (10^5 < T < 10^7 K) can be detected and studied by measuring both the photoelectric absorption edges and the resonant scattering lines of C, O, Ne, Si, S, Mg, Fe, etc. in the X-ray spectra of bright background objects (the X-ray Gunn-Peterson test, Sherman & Silk 1979, Shapiro & Bahcall 1980, Aldcroft et al. 1994, Markevitch 1999). X-ray spectroscopy of absorption edges and resonant scattering lines is the only tool to probe such a warm, low density gas. In fact the strength of these features is linearly proportional to the gas density and therefore below a critical value, absorption wins over emission. This can be done best by studying with adequate energy resolution (E/\( \Delta E \gtrsim 300 \)) a bright background source. Previous studies proposed quasars as background objects (Aldcroft et al. 1994, Hellsten et al. 1998, Perna & Loeb 1998). The problem is that X-ray bright z > 0.3 quasars are rare: only 9 of the 96 AGNs in the HEAO1 Grossan et al. (1992) sample (flux of S_{2–10keV} \gtrsim 1.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}) have...
z > 0.3 and only 3 have z > 1. Only these AGNs can provide a few \(10^4\) counts in deep (\(\approx 100\) ks) exposures with present-generation X-ray satellites (Chandra and XMM-Newton). The systematic study of the warm IGM using fainter AGNs must then await for missions of the size of Constellation-X\(^4\) and XEUS\(^5\) (collecting area of 1 \(\to 10\) m\(^2\)), foreseen for the next decade. We find instead that every GRB X-ray afterglow can provide enough counts to study the warm IGM by using medium-high resolution X-ray spectroscopy, if observed within a few minutes after the GRB event. In just one year of activity an instrument with the effective area of a XMM-Newton or Astro-E mirror unit and a high resolution focal plane detector (such as a grating or a calorimeter), may study accurately tens to hundreds of lines of sight. The study of the warm filaments and cluster outskirts, possibly complemented with UV absorption studies, will provide new crucial information on the phase at which galaxies, groups and clusters formed, the metal enrichment and heating histories of the IGM, and the feedback between hot and warm halos and star-formation in galaxies (see e.g. Cavaliere et al. 2000).

### 2. THE X-RAY LOGN-LOGF OF GRBS AND OTHER HIGH Z SOURCES

The study of afterglows starting immediately after the GRB event is the main goal of missions such as Swift\(^6\). Briefly, once a GRB is detected, the satellite is automatically manoeuvred to begin imaging within tens of seconds of the GRB region with optical and X-ray telescopes. We derive in this section the expected high Galactic latitude GRB region with optical and X-ray telescopes. We focus on the soft X-ray band since the main absorption features imprinted by the IGM on the GRB X-ray spectra are below \(\sim 1\) keV (see below).

Frontera et al. (2000a,b) studied the evolution of the gammaray and X-ray spectra of 8 GRBs seen by BeppoSAX. Using their spectra and light curves we computed the ratio between the 2-10 keV flux 30-40 seconds after the GRB peak and the 50-300 keV flux at the peak. All points but one are in the range 0.02-0.2. The outlier, GRB980329, has a ratio ten time smaller, and is the only GRB in the Frontera et al. (2000b) sample to show significant absorption in the 2-20 keV spectrum (see below). In the following estimates we conservatively assume a ratio of 0.01.

GRB X-ray afterglows decay with time as power laws with index \(\delta\) in the range \(-1 \div -1.5\) (Costa 1999). Substantial evidence supports the view that the X-ray afterglow starts well within the GRB duration, when the GRB spectrum softens markedly. Indeed, when the power law decay of the X-ray afterglow observed hours to days after several GRBs is extrapolated backward in time, a good matching is found with the BeppoSAX WFC flux a few tens of seconds after burst onset (Piro 1999, Frontera et al. 2000b) We are thus justified in estimating the fluence of the X-ray afterglow by integrating the X-ray emission starting 40 sec after the GRB peak. We adopt a total integration time of 40 ks, assuming that up to this time after the main event the high–frequency cut–off of the synchrotron spectrum has not yet moved into the X-ray band. This is consistent with the fact that \(\approx 90\%\) of the bursts do display an X–ray afterglow (the few non-detection may be due to an insufficient sensitivity and/or too long a delay in the BeppoSAX NFI follow–ups). The X-ray spectrum deduced from both the WFC data, acquired seconds to minutes after the burst, and the LECS and MECS spectra, acquired several hours after the burst, are consistent with a power law model with energy index \(\alpha_F \approx 1.0\). So far, there is evidence for intrinsic X-ray absorption in one GRB only: GRB980329, \(N_H \approx 10^{22}\) cm\(^{-2}\), assuming solar abundances (Frontera et al. 2000b, Owens et al. 1998). All other GRBs analyzed by Owens et al. (1998) have a measured column density at the GRB redshift, where available, consistent with 0 at the 2 \(\sigma\) level. Excluding the GRB980329 event, the average best fit \(N_H\) at the GRB redshifts is \(2.5 \times 10^{21}\) cm\(^{-2}\). Since the column density computed in the observer frame scales roughly as \((1+z)^{-8/3}\) the spectrum seen by a \(z=0.1-0.3\) IGM cloud has an effective cutoff corresponding to an \(N_H \approx 0.5\) times that obtained at the mean GRB redshift of 1. We conservatively assume in the following a GRB \(N_H\) in the range \(1 - 3 \times 10^{21}\) cm\(^{-2}\) as seen by a gas cloud at \(z < 0.3\).

The GRB peak flux log \(F - \log S\) relationship is well known from \(10^{-8}\) to \(10^{-4}\) erg cm\(^{-2}\) s\(^{-1}\) (50-300 keV, see e.g. Fishman & Meegan 1995). Using the relationship between the GRB peak flux and the 2-10 keV emission 30-40 seconds after the peak and assuming the X-ray spectral shape discussed above, we predict the logN-logS of the 0.5-2 keV X-ray emission as it will be first seen by satellites with reaction capabilities similar to those of Swift. Figure 1 shows the number of objects at high galactic latitude (i.e. in half of the sky) as a function of the 0.5-2 keV flux integrated in 40 ks (the fluence, upper scale) and of the total counts accumulated in 40 ks by an instrument with the effective area of the XMM-Newton RGS (one unit). The GRB logN-logF is compared to the ROSAT logN-logF (adapted from Hasinger et al. 1998). This is dominated at high fluxes by nearby Seyfert galaxies and BL Lacertae objects. Most of the IGM is beyond the brightest 0.5-2 keV sources in the sky. The dotted line and the dot-dashed line show the number of 0.5-2 keV sources with \(z > 0.5\) and \(z > 1\) respectively; as estimated using the soft X-ray logN-logS of bright blazars (e.g. Wolter et al. 1991), the fraction of identified AGN in the RASS and the results of synthetic AGN models for the X-ray background (Comastri et al 1995). Figure 1 shows that under our conservative assumption there should be a few lines of sight per month with \(\geq 10^5\) counts. A few lines of sight per year may be studied with more than \(10^6\) counts. These estimates have to be compared with \(\approx 10\) lines of sight in total which can be studied with \(\geq 10^5\) counts by using \(z > 0.5\) AGNs as background beacons. We remark that this result strongly depends on the speed with which the afterglow is observed, i.e. for \(\delta = -1.3\) twice as many photons are emitted between \(t_0\) and \(10t_0\) than are emitted between \(10t_0\) and \(100t_0\).

### 3. X-RAY ABSORPTION FEATURES FROM THE IGM

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\(^4\)see e.g. http://constellation.gsfc.nasa.gov/science/igm2.html


\(^6\)Swift will be launched in 2003, see http://swift.sonoma.edu/
In order to study the warm IGM with background beacons, metal abundances must be sufficiently high that relatively strong absorption features are produced. Using numerical simulations Cen & Ostriker (1999) estimate a metallicity of at least $0.1Z_\odot$ for $z<0.5$, depending on the gas density. This is supported by several pieces of evidence. First, the metallicity of the hot intracluster medium is found to be $\approx 0.3Z_\odot$ in many cases; Second, collisionally excited OVI lines have been detected at $z<0.3$ (Tripp et al. 2000, Tripp & Savage 2000). Third, CIV and SiIV associated with Lyα clouds have been detected at $z>1.5$ (e.g. Songaila & Cowie 1996, Ellison et al., 1999). Finally, the nine Damped Lyα systems with detected metals and $z<0.7$ have a metallicity in the range $0.4-0.6Z_\odot$ (Savaglio et al. 2000), indicating that galaxies at $z<0.7$ can provide metals to the IGM.

The IGM transmitted spectrum can be used as a diagnostic of temperature, metal abundances, column and volume densities and gas dynamics. We calculated the line strength and profiles expected from a cloud of gas at a given redshift, with given temperature, column density and metal abundance using the code of Nicastro et al. 1999b). Ionization equilibrium was calculated using CLOUDY (Ferland 1999). Table 1 gives the equivalent width (EW) of the strongest resonant lines in four simulations for a cloud at $z=0.1$ and of equivalent hydrogen column density of $N_H = 10^{20} \text{cm}^{-2}$, metal abundance of $0.3Z_\odot$, $b = 200 \text{km s}^{-1}$ (the Doppler term $b$ includes also gas turbulence), and temperatures $T = 10^{5.5}, 10^6, 10^{6.5}$ and $10^7 \text{K}$. Kα and Kβ resonant transitions from He- and H-line ions of C, O and Ne produces the strongest features in the 0.2-3 keV band, along with a series of L resonant lines from Mg, S, Si and Fe. At $T = 10^5 \text{K}$ CIV and OVII are the dominant ions (their relative abundance being $>80\%$). At $T = 10^6 \text{K}$ He-like ions of C, O and Ne are still dominant, but H-like C is visible. At $T = 10^6 \text{K}$ OVIII is the dominant oxygen ion. A relatively strong FeXVII line at 0.825 keV is also visible. For $T = 10^6 \text{K}$ oxygen is nearly completely ionized and only a weak L-“forest” from highly ionized iron is present in the spectrum around 1 keV (FeXX at 0.967 keV being the strongest line). Reducing $b$ by a factor of two will reduce the EW by $\approx 30\%$. Figure 2 shows how the spectra with $T = 10^6 \text{K}$ and $T = 10^6.5 \text{K}$ would be measured by a typical grating (resolution of $\sim 1000$ at 0.3 eV, 500 at 0.5 keV and $\sim 300$ at 0.8 keV, and with similar sensitivity in this band). We assumed $10^5$ counts (0.5-2 keV) in each spectrum. With this signal to noise ratio ($\sim 10$ per eV) and with a resolution of 1 eV at 0.5 keV OVII and OVIII lines of EW=0.5-1 eV can be easily detected. In fact, the minimum EW detectable with a signal to noise of 5 given the above constraints is of $\sim 0.5$ eV (using equation (12) of Perna & Loeb, 1998). Ne and Fe lines of similar EW are more difficult to detect, due to the reduced resolution at increasing energies. Interestigly, CV and CVI lines at 0.3-0.4 keV of EW of only 0.3-0.4 eV are also easily detectable, thanks to
the \( \sim 0.3 \) eV resolution of the gratings at those energies. Our simulation shows that oxygen of column densities as low as \( N_H = 2 - 4 \times 10^{16} \) cm\(^{-2}\) can be detected in such high quality spectra at \( z = 0.1 \). Columns smaller by a factor of \( \approx 2 \) may be detected at \( z \approx 1 \), where the OVII and OVIII lines are redshifted to \( \approx 0.3 \) keV, due again to the improved resolution of gratings at low energies.

Our calculations adopt a collisional ionisation equilibrium. Whereas, photoionization from cosmic X-ray and UV backgrounds and from possible nearby sources like AGN and starburst galaxies, is expected to alter the relative ionic abundances, making their distributions as a function of the temperature wider than in the collisional case (Nicastro et al. 1999a). The contribution of photoionization to the gas ionization state is increasingly important for decreasing gas densities. In this case, the measurement of the equivalent width at least three lines of the same element can be used as a temperature and density diagnostics. The contribution of the afterglow itself to the gas ionization is negligible for distances higher than a few Mpc. The maximum number of ionizations per event is in fact \( \sim 5 \times 10^{12} \) and assuming conservatively that all the gas in the IGM has \( T = 10^6 \) K, and that the mean density is \( 5 \times 10^{-7} \) cm\(^{-3}\), the radius of the ionized bubble is \( \approx 3 \) Mpc (also see Perna & Loeb 1998b).

Finally we note that in principle combination of multiple absorption systems along a line of sight could complicate the resulting emerging spectrum, making the identification of the single components more difficult. OVII and OVIII \( \alpha \) and \( \beta \) lines are by far the most intense lines expected in a broad temperature range. Several authors evaluated the distribution of the oxygen line EW per unit redshift (Hellsten et al. 1998) or the probability to observe a given line EW per unit redshift (Perna & Loeb 1998, Jahoda, et al. 2000). The results indicate that a random line of sight up to \( z = 0.3-0.5 \) should contain the order of one system, or a few systems at most, with OVII or OVIII of EW \( \gtrsim 0.5 \) eV, easing the line identification process.

4. DISCUSSION AND CONCLUSIONS

The X-ray band provides a unique opportunity to probe the warm IGM through the detection of the so called “X-ray forest”. On the contrary, UV OVI lines can probe relatively low temperature plasmas only. We have shown that afterglows of GRBs can provide the most effective X-ray beacons at high \( z \), to study absorption features due to the warm IGM. A few afterglows per year should be bright enough, two-four hours after the main event, to produce spectra with 10,000-100,000 counts in the Chandra and XMM gratings, thus allowing the detection of warm IGM with H equivalent column density of \( \gtrsim 10^{20} \) cm\(^{-2}\). This can then be used to constrain the baryon cosmological mass density, independent on nucleosynthesis calculations. Swift, currently the only planned satellite with a much faster pointing capability (minutes), will allow the detection of absorption edges and blended lines from higher density regions (\( N_H \approx 10^{20} \) cm\(^{-2}\)) with the resolution afforded by its CCDs. Maintaining the Swift default pointing position (i.e. when the satellite is not observing a GRB) close to the direction of large structures like the Aquarius cluster concentration (Markevitch 1999), the Shapley super-cluster, etc, would increase the probability to observe a GRB behind these high density structures. This in turn would increase the probability of detecting the warm IGM component, if it is associated with the filaments connecting high–density regions as predicted by current cosmological scenarios (Davè et al 2000). Detection of significant absorption in these lines of sight would provide at the same time a first, direct, \textit{a priori} test of the growth of large–scale structure in the Universe.

More ambitiously, the technology and most of the hardware to put together a mission with the Swift slew capability, \( \sim 0.1 \) m\(^2\) collecting area and high resolution capabilities (such those provided by gratings or calorimeters), is currently available. The Swift trigger might be used by such a mission to slew quickly on a GRB event. Gratings can provide enough resolution to detect oxygen lines of EW \( \gtrsim 0.5 \) eV at \( z = 0.1-0.3 \) and, most intriguingly, EW of a few tenth of eV at \( z > 1 \). This will allow to probe oxygen columns as small as \( 10^{16} \) cm\(^{-2}\) at such cosmologic redshifts. Moreover, it might be worth considering upgrading the slew capabilities of satellites such as Constellation-X and XEUS. These satellites will have the throughput to acquire high resolution spectra with the order of millions of counts from GRB X-ray afterglows, provided that they can be observed fast enough after the GRB event (i.e. within one hour). This may allow one to push the study of the warm IGM to redshifts \( > > 1 \), through the detection of Fe, Mg, Si and S lines, opening the way to a \textit{direct} test of hierarchical clustering models for the growth of structures.

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REFERENCES

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Grossan, 1992, MIT, PhD thesis
Table 1: Equivalent width in eV of the strongest resonant lines

<table>
<thead>
<tr>
<th>T (K)</th>
<th>CV</th>
<th>CVI</th>
<th>OVII</th>
<th>OVIII</th>
<th>NeIX</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^5.5</td>
<td>0.63-0.36</td>
<td>–</td>
<td>1.12-0.55</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10^6.0</td>
<td>0.42-0.16</td>
<td>0.23-0.37</td>
<td>1.16-0.72</td>
<td>–</td>
<td>0.65-0.17</td>
<td>FeIX=0.11</td>
</tr>
<tr>
<td>10^6.5</td>
<td>–</td>
<td>0.01-0.02</td>
<td>0.43-0.12</td>
<td>0.31-0.53</td>
<td>0.56-0.14</td>
<td>FeXVII=0.31</td>
</tr>
<tr>
<td>10^7.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.02-0.04</td>
<td>NeX=0.04</td>
<td>FeXX=0.10</td>
</tr>
</tbody>
</table>

Kα and Kβ lines equivalent width is reported for the C, O and Ne ions.