GAMMA-RAY BURSTS AS X-RAY DEPTH GAUGES OF THE UNIVERSE

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ABSTRACT

We discuss the X-ray flux of gamma-ray burst afterglows at redshifts in the range 3–30, including the effects of the intergalactic He ii absorption. We point out that strong X-ray lines may form locally in burst afterglows starting minutes after the trigger. This can provide distinctive X-ray distance indicators out to the redshifts at which the first generation of massive stars form.

Subject headings: cosmology: miscellaneous — gamma rays: bursts — line: identification — X-rays: stars

1. INTRODUCTION

The first generation of stars in hierarchical cosmological models are expected to be metal-free and very massive (e.g., Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002), evolving through core collapse to form black holes (Woosley, Zhang, & Heger 2003). These can lead to a first generation of “collapsar” gamma-ray bursts (GRBs), which would be about 1 order of magnitude more massive and luminous than their counterparts (Schneider, Guetta, & Ferrara 2002). Spergel et al. (2003) use WMAP polarization data to deduce a reionization redshift of z ∼ 17 ± 5, assuming that below this the ionization is complete.

Observations of the most distant quasars (e.g., Fan et al. 2001) indicate that at z ≤ 6.4 the continuous Gunn-Peterson trough is replaced by partial blanketing of the continuum by the Lyα forest. He ii may play a significant role in determining the intergalactic medium (IGM) opacity in the soft X-ray range at z ≤ 6 (Miralda-Escude 2001). The IR/optical spectra of the first stars (Loeb & Barkana 2001) and/or distant long GRB afterglows (Lamb & Reichart 2000; Ciardi & Loeb 2000) provide redshift markers through their H i Lyα cutoff. For short GRBs, however, optical afterglows may be weak or absent (Panaitescu, Kumar, & Narayan 2001). Hence, X-ray redshift markers would be most useful, especially at z ≥ 6, where Population III objects may dominate.

Here we discuss the role of the He ii absorption, which, over most of the volume of the high-redshift IGM, is the major determinant of the optical depth blueward of 54.4/(1 + z) eV. The He ii opacity becomes negligible at energies above ~0.2 keV, allowing the X-ray spectrum of high-redshift sources to become observable in principle. The Fe group Kα energy is in this range for objects at z ≤ 30. These metals, while absent through most of the IGM at such redshifts, should be abundant in patches immediately surrounding Population III objects, as well as in GRBs. Other lines may also be useful at lower redshifts. Here we discuss the role of the Fe-group Kα X-ray lines as redshift markers in the range z ∼ 3–30, including the first generation of GRBs.

2. IGM OPACITIES AND GAMMA-RAY BURST X-RAY FLUXES

At z ≳ 6.4 the IGM acquires an increasing fraction of neutral gas (Fan et al. 2001), with the first protogalaxies and quasars forming at z ∼ 6–9. The cosmological parameters from WMAP are $\Omega_m = 0.29$, $\Omega_\Lambda = 0.71$, $\Omega_b = 0.047$, and $h = 0.68$, with a lower limit on the reionization redshift $z_r\sim 17$ ± 5 (Spitzer et al. 2003), which may signal the first generation of stars. Blueward of the H i Lyman limit the opacity drops with photon energy as $E^{-2}$. Helium is likely to be in its hydrogenic form, He ii. At the He ii ionization edge of 54.4 eV the cross section is $Z^4 = 16$ times higher than the H i bound-free cross section, and for $\sim 10\%$ He/H relative abundance the He ii opacity will be $\sim 1.6$ times more important than that of H i and dominate at energies above that. Its influence should be even stronger, since He recombines at a rate 5.5 faster than H, provided the source spectra are not too hard. The dominant sources at z ∼ 3 are likely to satisfy this, so the far-UV opacity is dominated by He ii. Miralda-Escude (2001) estimates this optical depth as $\tau_{0.22} = 1.7 \times 10^8 (\Omega_0 h Y_{0.007}/0.007) [H_0 (1 + z)^{3/2} H(z)] [(1 + z)/4]^{3/2}$, where $H(z)$ is the Hubble expansion. Using the above parameters we obtain for the He ii edge optical depth at $z, \sim 3$

$$\tau_{0.22} = 4.3 \times 10^3 (\Omega_0 h Y_{0.007}/0.007) [H_0 (1 + z)^{3/2} H(z)] [(1 + z)/4]^{3/2}.$$  

Above the edge the cross section is $\propto E^{-3}$ and the opacity becomes less than unity above

$$E_{\gamma} \sim 0.22 (\Omega_0 h Y_{0.007}/0.007) [H_0 (1 + z)^{3/2} H(z)] [(1 + z)/4]^{3/2} \text{ keV},$$

which is the “thinning” photon energy observed at $z = 0$ for which the IGM becomes transparent at the redshift $z_r$. Absorption in our galaxy can be comparable to that of intergalactic He ii (Miralda-Escude 2001), the energy (eq. [2]) corresponding to a Galactic column density $\sim 2 \times 10^{20}$ cm$^{-2}$ typical of moderately high latitudes. Above this energy the intergalactic H opacity is also negligible, and X-ray sources at redshifts $z \gg z_r \sim 3$ become observable.

The initial GRB luminosity is $L_{X,0} = 10^{52}L_{40}$ erg s$^{-1}$, or $L_X \sim 10^{49}(t'/t)^{b_1}E_{\gamma^\text{peak}}^{b_2}$ erg s$^{-1}$ (0.2–10 keV), where $t'\sim 10^5$ s is the time after trigger when the power-law decay starts, $a \sim 0.7$ is the energy spectral index, $b_1 \sim 1.1$ and $b_2 \sim 2$ are the energy flux time decay indices before and after the light curve steepens at $t_{\text{rise}} \approx 0.5$ day, primed quantities being in the source frame and unprimed in the observer frame. The observer frame energy flux of a source at $z$ at photon energy $E$ and time $t$ for a simple power-law decay is
where is the step function, $s$ and $(3)$. Lower the earlier source times. Of the five Fe lines in GRBs reported $(e.g., Piro 2002)$. A decay $\sim t^{-1}$ is assumed after $t_0 = 10(1 + z)$ s, steepening to $t^{-2}$ after $t_0 = 0.5(1 + z)$ days, for an initial source frame $0.2–10$ keV luminosity normalized to $L_\gamma = 10^{50}$ ergs s$^{-1}$ at $t$. The latter is likely to be an underestimate at $z \sim 6.5$, for which the fluxes might be $10–30$ times higher than the values given in the table.

$$F_L(z, t) = \frac{L_{\gamma,0}/(4\pi D_L(z)^2)(1 + z)^{-1-\alpha}[t/\tau]^{\gamma}[(1 + z)^{\beta}]}{4\pi D_L(z)^{2}(1 + z)^{-1-\alpha} = \frac{H}{(t/\tau)^{\gamma}}},$$

where $H(x)$ is the step function, $t_\gamma = \min\{t, 10(1 + z)\}$ s and $t_\gamma = 5 \times 10^{4}(1 + z)$ s are nominal values of the observer-frame decay initiation time and the break time, and $D_L$ is the luminosity distance, $\Omega_{\text{int}} = 1$, $\Omega_{\text{Q}} = 0.3$, and $\Omega_{\text{Q}} = 0.7$.

The observed X-ray fluxes of a nominal GRB afterglow at different observer times $t$ and redshifts $z$ derived from equation (3) are shown in Table 1.

### Table 1

| $z$ (1) | $E_{\text{kin}}$ (2) | $E_{\text{in}}$ (keV) (3) | $F_L(10^4 \text{s})$ (4) | $F_L(10^5 \text{s})$ (5) | $F_L(10^6 \text{s})$ (6) | $F_L(10^7 \text{s})$ (7) | $F_L(10^8 \text{s})$ (8) | $F_L(10^9 \text{s})$ (9) | $F_L(10^{10} \text{s})$ (10) |
|---------|----------------|--------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 3.0     | 0.486          | 0.22                     | 1.675                  | 1.90                   | 6.810                  | 5.411                  | 4.312                  | 3.413                  | 2.214                  |
| 6.5     | 0.912          | 0.22                     | 0.893                  | 6.110                  | 4.10                   | 3.511                  | 2.812                  | 2.213                  | 1.814                  |
| 9.0     | 1.216          | 0.22                     | 0.670                  | 4.10                   | 3.312                  | 3.012                  | 2.512                  | 2.013                  | 1.614                  |
| 12.0    | 1.581          | 0.22                     | 0.515                  | 3.010                  | 2.912                  | 3.212                  | 2.512                  | 2.013                  | 1.614                  |
| 15.0    | 2.310          | 0.22                     | 0.353                  | 2.010                  | 2.010                  | 2.012                  | 2.012                  | 2.013                  | 2.014                  |
| 30.0    | 3.770          | 0.22                     | 0.216                  | 1.310                  | 1.310                  | 1.311                  | 1.311                  | 1.312                  | 1.314                  |

Notes.—Col. (1): the redshift; col. (2): the intergalactic H Ly$\alpha$ wavelength, blueward of which the Gunn-Peterson absorption sets in; col. (3): the He I $\text{"thinning}$ energy $E_{\text{in}}$, blueward of which intergalactic absorption becomes negligible and the continuum reemerges from the through; col. (4): the Fe K$\alpha$ line energy; and cols. (5)–(10): the GRB afterglow continuum X-ray flux from eq. (3) at six different observer times $t$ after the trigger (in ergs cm$^{-2}$ s$^{-1}$ keV$^{-1}$).

3. GAMMA-RAY BURST X-RAY LINES

The strongest lines expected are from Fe K$\alpha$ at $E \sim 6.7(1 + z)$ keV, or possibly the nearby Ni, Co lines. Their detection requires high fluxes, which at high redshifts favors the earlier source times. Of the five Fe lines in GRBs reported by BeppoSAX or Chandra, four were in emission at observer times $t \sim 0.5–1$ day, and one was in absorption at $t \sim 10–20$ s (e.g., Piro 2002). Lower Z metal lines were reported at $t \sim 8–12$ hr with XMM (Reeves et al. 2002; cf. Rutledge & Sako 2003; Watson et al. 2002) and Chandra (Butler et al. 2003). The absence so far of line detections at $20 \leq t \leq 8$ hr may in principle be due to current instrument slewing time limitations. Swift, due for launch in 2003 December, will have fast slewing capability ($\leq 1$ minute), a wide-field gamma-ray detector, and narrow-field X-ray as well as optical detectors capable of moderate resolution spectroscopy. Thus, if strong enough lines are produced at minutes to hours, up to $\sim 100$ yr$^{-1}$ might be detected. Line production is facilitated by a high gas density in the neighborhood of the GRB. In photoionized models, Fe line formation requires ionization parameters $\xi = L/n_T^2 \sim 10^5$. This is easiest to satisfy, even at early times ($\geq$minutes), in “local” models involving radii comparable to those of the progenitor stellar envelope.

**Stellar funnel models.**—In these local models the lines arise in an envelope at $r \sim 10^{10}$ cm (typical of giants, or of WR or He stars $\sim 10^8$ s after envelope expansion starts). The ionization could be due to a long-lasting jet (Rees & Mészáros 2000) or bubble (Mészáros & Rees 2001), producing an X-ray continuum. X-ray absorption lines arise while there is gas in front of the jet, and after it is swept away the continuum from the jet on the funnel produces an emission reflection spectrum. The funnel gas density in equilibrium with the jet is $n_{\epsilon,\gamma} \propto L_{\gamma,0}/(4\pi D_L(z)^2)^{-1}$, where $L_{\gamma,0}$ is the ionization parameter of the blob-frame jet density, $z$ is the break time, and $D_L$ is the luminosity distance, using $\Omega_{\text{int}} = 1$, $\Omega_{\text{Q}} = 0.3$, and $\Omega_{\text{Q}} = 0.7$.

### Notes

1. N. Gehrels et al. 2003, invited talk at AAS/HEAD Meeting 35, 31.05 (http://swift.gsfc.nasa.gov/).

2. $E_\gamma \propto t^{-\alpha}$, where $\alpha$ is a geometrical factor and $\beta$ is the ratio of ionizing to total luminosity. The recombination time of an ion with $Z = 26Z_{26}$ is $t_{\text{rec}, Z} \sim 2 \times 10^{10}(\epsilon_0/10)^{1/2}T_{1/2}^{1/2}Z_{26}^{-2}$ s. Balancing the ionizations $\beta L/E_{\gamma,0}$, with $\epsilon_0 \sim 10$ keV, with the recombinations $\delta n_{\epsilon,\gamma}dL_t/\tau_{\epsilon,\gamma}$, where $x_{\epsilon,\gamma}$ is ion abundance and $\delta$ allows for recombination to other ions, the depth from which recombination photons escape is $d \sim (\beta/\epsilon_0)^{1/2}T_{1/2}^{1/2}Z_{26}^{-2}X_{26}^{-1}$ cm, and its Thomson scattering depth is

$$\tau_{\gamma} \sim n_{\epsilon,\gamma}d \sim 6 \times 10^{-4}(\beta/\epsilon_0)T_{1/2}^{1/2}Z_{26}^{-2}X_{26}^{-1},$$

which is less than 1 for $x_{\epsilon,\gamma} > 6 \times 10^{-4}(\beta/\epsilon_0)T_{1/2}^{1/2}Z_{26}^{-2}$. The solar Fe abundance is $4 \times 10^{-3}$, so an enrichment of $\geq 10$ (e.g., from metals dragged in the jet and deposited in the walls) allows line photons to escape unscattered from $d$. Radiative transfer calculations (Kallman, Mészáros, & Rees 2003) for the shallow incidence angles of stellar funnels and Fe abundances $30–100$ times solar yield line equivalent widths $0.5–1.0$ keV. A difference in beaming of the line and continuum can be incorporated in the geometrical factor $\alpha$, which affects the equivalent width. However, reflections in the funnel (McLaughlin et al. 2002) would lead Ni or Co photons to mimic Fe line photons, as well as tend to equalize the beaming of line and continuum. Note that the ionization parameter $\xi$ and condition (eq. [4]) for line photon emergence are independent of the luminosity (hence of the time).

**Jets with blobs.**—X-ray lines can also be produced locally, inside the stellar funnel, by metal-rich blobs entrained in the jet. These will be initially subrelativistic, $\Gamma_1 \sim 1$, with an equilibrium density $n_0 \sim 10^{12}L_{50/3}^{1/3}T_{1/2}^{1/3}cm^{-3}$ and ionization parameter $\xi \sim L/n_T^{2/3}T_{1/2}^{1/3}$. For a smoothed-out blob particle density a fraction $\xi$ of the blob-frame jet density, $n_b = \xi n_T/G_n/\Gamma_n$, where $n_T^{10^{12}}L_{50/3}^{1/3}T_{1/2}^{1/3}cm^{-3}$ and $\Gamma_n = 300\Gamma_2.5$ is
the jet Lorentz factor, the blob volume filling factor is \( f_v = \frac{r_b}{h} \), and the smallest dimension of a blob is \( r_b \sim r' \), where \( f_v \) is the blob surface coverage factor (Mészáros & Rees 1998).

The Thomson depth of a blob is \( \tau_{tb} \sim 20 \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \), and a fraction \( 1/\tau_{tb} \) of the ion's undergo ionizations and recombinations to accelerate the blob. The recombination time is \( \tau_{rec} \sim 4 \times 10^{-10} L_{50} r_{13}^{-1} Z_{25}^2 T_b \), and the ratio between the time for accelerating a blob to \( v \sim 0.1c \) and the stellar crossing time is

\[
\tau_{st}/\tau_v = \tau_{rec}/(c/R_5) \left( \frac{6 A_{e6}}{m_1} \right)^{1/2} \xi c \tau_{tb} \\
\sim 5 \times T^{-1} g^{-1} T'^{-2} Z_{25}^2 A_{e6} \xi G_{12.5}.
\]

Another limit would apply after the blobs have accelerated and the density drops to the point where Thomson scattering becomes the main contributor to the acceleration, leading to

\[
\tau_{st}/\tau_v \sim L_{50} r_{13}^{-1} (c/L_{Ed})^{-1} \tau_{tb} \sim 10^{-4} \tau_{tb} \theta_{1.1}^{-1}
\]

where \( r_b \) is the Schwarzschild radius and \( L_{Ed} \) is the Eddington luminosity. After becoming relativistic the blobs no longer contribute to the reprocessing, due to their lower density and higher ionization parameter, and their smoothed-out Thomson depth is at most comparable to that of the jet. For example, a mist of blobs with \( \xi \sim 1 \), \( f_v \sim 1/3 \), and \( T \sim 3 \times 10^4 \) has \( \tau_{st}/\tau_v \sim 0.07 \) and reprocesses the photoionizing continuum into narrow lines (\( \xi \omega \leq 0.1 \)) with a line-to-continuum ratio \( \xi \omega \leq 0.1 \).

**Transparency of local X-ray line models.**—To see unbroadened lines the jet must be optically thin to electron scattering and pair production. A jet of isotropic equivalent luminosity \( L_{j} \sim 10^{50} \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \), and a fraction \( 1/\tau_{tb} \) of the ions undergo ionizations and recombinations to accelerate the blob. The recombination time is \( \tau_{rec} \sim 10^4 \xi L_{50} r_{13}^{-1} Z_{25}^2 T_b \), and the ratio between the time for accelerating a blob to \( v \sim 0.1c \) and the stellar crossing time is

\[
\tau_{st}/\tau_v = \tau_{rec}/(c/R_5) \left( \frac{6 A_{e6}}{m_1} \right)^{1/2} \xi c \tau_{tb} \\
\sim 5 \times T^{-1} g^{-1} T'^{-2} Z_{25}^2 A_{e6} \xi G_{12.5}.
\]

Another limit would apply after the blobs have accelerated and the density drops to the point where Thomson scattering becomes the main contributor to the acceleration, leading to

\[
\tau_{st}/\tau_v \sim L_{50} r_{13}^{-1} (c/L_{Ed})^{-1} \tau_{tb} \sim 10^{-4} \tau_{tb} \theta_{1.1}^{-1}
\]

where \( \theta_{1.1} \) is the opening angle. The internal shocks of Population III stellar funnels may be important in the X-ray range, which would drop in time. Hence, from the above scalings, such lines can escape unBroadened even at early times of minutes, when \( L_X \sim 10^{50} \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \), and extending to \( t \gg \tau_v \).

**Supernova model.**—In this nonlocal scenario a supernova is assumed to occur approximately months before the GRB (Vietri & Stella 1999; Lazzati, Campana, & Ghisellini 1999; Weth et al. 2000; Vietri et al. 2001), and X-ray line appearance at \( \sim 1 \) day is attributed to geometrical light-travel time to a SN shell at \( \sim 10^{16} \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \) cm. Recent data on GRB 030329 (Henden et al. 2003; Stanek et al. 2003) indicate that a supernova occurred within \( \sim 2 \) days of the GRB, not enough for a shell to reach \( \sim 10^{16} \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \) cm. The supernova geometry is not conducive to emission lines at minutes or hours, although absorption lines might in principle be expected early. However, for significant equivalent widths, the shell must be extremely clumpy to have sufficiently short recombination times.

Radiative transfer calculations (Kallman et al. 2003) indicate that large equivalent widths are favored by shallow incidence angles, which are not expected in supernova shells, while being natural in “local” stellar funnels. In any case, the large continuum X-ray fluxes of equation (3) and Table 1 are independent of the specific line mechanism, the requirement for detecting lines at high \( z \) being a mechanism that produces high equivalent widths, preferably at source times of minutes to hours.

**High-redshift X-ray fluxes and lines.**—Population III stellar masses are larger and core temperatures are higher than in lower redshift stars, but the external envelope radii may be comparable. The core collapse would lead to a more massive black hole and a higher luminosity GRB (Schneider et al. 2002). However, funnel metal enrichment and X-ray line reprocessing would occur in the same way as for low \( z \), with comparable equivalent widths. In Table 1, Population III GRBs might appear at \( z \sim 6.5 \), and it is likely that for these the scaling \( L_X \sim 10^{50} \xi L_{50} r_{13}^{-1} f_v^{-1} T_b^{-2} \) used for the initial X-ray flux is an underestimate, which may need to be increased by a factor \( \approx 10–30 \). Column (4) of Table 1 gives the Fe Kα line energies in the observer frame for each redshift. The Ni and Co line energies would be within \( \sim 10\% \) of these. At \( z = 30 \) the lines appear at the threshold where the He II optical thickness reaches unity, and for \( z \approx 20 \) they are well within the regime where the continuum is unabsorbed by the IGM.

In some bursts (Reeves et al. 2002; cf. Rutledge & Sako 2003; Watson et al. 2002; Butler et al. 2003) Si, S, Mg, etc., lines are reported, but not Fe. This may be due to a steeper photoionizing continuum (Lazzati, Ramirez-Ruiz, & Rees 2002).

**4. DISCUSSION**

Studies of the first structures and the intergalactic medium at \( z \geq 6 \) require very bright sources with good distance indicators. Above these redshifts quasars are extremely rare, and the most numerous luminous sources expected are protogalaxies, intermediate mass accreting black holes, and supernovae, as well as GRBs. The latter are an outcome of massive stellar evolution, which is likely to precede galaxy formation and could have started at redshifts as high as \( z \sim 10–30 \) (e.g., Bromm & Loeb 2002). Within the first hours in its rest frame (\( \sim 8 \) days in observer frame), the GRB afterglow brightness exceeds that of the most luminous AGNs or any other quasi-steady source. This is particularly interesting in the X-ray range, where the He II Gunn-Peterson absorption is unimportant at energies \( \sim 0.2 \) keV for sources at \( z \geq 4 \). With space missions such as Swift, pointed X-ray observations started with
minutes can achieve detections out to \( z \sim 10–30 \) in integration times of hours, if GRBs occur at those redshifts.

Here we have discussed the possibility of measuring GRB redshifts of \( z \geq 3–30 \) using Fe group Kα lines or edges. These lines may form at early (minutes to days) times, independently of whether a supernova shell is produced. The observed line energies in Table 1 are above the IGM He II cutoff for \( z \geq 20 \). Lines from lower Z metals can also be used, which fall below the He II cutoff at lower redshifts than Fe, e.g., S xvi Kα at \( \approx 2.6/(1+z) \) is useful only out to \( z \approx 11 \). X-ray redshift measurements are especially interesting, since for detecting H Lyα cutoﬀs in faint distant objects NIR spectroscopy is necessary, mostly relying on large area ground telescopes subject to observing conditions and scheduling.

For GRBs similar to those observed at \( z \approx 4 \), the nominal X-ray fluxes (Table 1) at \( z \approx 12 \) are bright enough for low-resolution spectroscopy with Swift for \( t \leq 10^4–10^5 \) s, and easily detectable at least for \( t \approx 10^5 \) s. Because of the increasing K-corrections the fluxes do not decrease much with redshift beyond \( z \sim 4–5 \) and saturate or turn up at \( z \approx 8–12 \). For such nominal GRBs, the fractional number expected at \( z \approx 5 \) is \( \approx 50\% \), but only \( \sim 15\% \) may be detectable in flux-limited surveys, e.g., with Swift (Bromm & Loeb 2002). However, at \( z \approx 6–10 \) the Population III stars are likely to lead to black holes with masses \( 10–30 M_\odot \), and to GRBs whose luminosities could be significantly higher than at low redshifts, with factors \( E_{x,0} \) in equation (3) that could be 10–30 times higher than assumed in Table 1. In this case, the fraction at \( z \geq 5 \) detectable in Swift’s flux-limited survey could be \( \geq 20\%–30\% \) of the total, or \( \approx 20 \) yr−1.

With Chandra or XMM, grating spectroscopic observations of X-ray lines with rest-frame equivalent widths \( \leq 0.5 \) keV (as reported in nearby bursts) appear possible out to at least \( z \geq 12 \). For instance, for the “nominal” GRB of Table 1 of initial \( L_{x,0} = 10^{50} \) ergs s−1, with a line at \( E_{\text{line}} \sim 0.5 \) keV of equivalent width \( EW_{\text{line}} = EW_{\text{FWHM}} / (1+z) \sim 0.04 \) keV, observed at \( t_{\text{obs}} = 10^5 \) s and \( z = 12 \), a simulation with the XMM epic and XSPEC software (N. Brandt 2003, private communication) with an integration time \( 10^5 \) s gives a fit for a power-law spectrum plus a Gaussian line of \( \chi^2 = 682 \) for 679 degrees of freedom, while a power-law fit without the line gives \( \chi^2 = 642 \) for 676 degrees of freedom, corresponding to a line detection probability \( \approx 99.9\% \). A K-edge might be expected at \( \approx (4/3)E_{\text{Kα}} \), which could further improve the detection probability. For an initial \( L_{x,0} = 10^{51} \) ergs s−1, the fits should improve and may extend to higher redshifts. If no O/IR redshifts are available, the presence of just one feature (or at most two, in the energy ratio \( 1 : 4/3 \)) in the range 0.2–1 keV would strongly suggest that these are due to Fe-group elements, constraining the redshift to \( \sim 10\% \). Confusion with Si, Mg, etc., can be avoided, since these would appear as multiple lines, possibly with Fe lines at energies a factor \( \sim 2.5 \) higher. An isolated line or edge from Fe or Fe-group elements (§ 3) can be expected in GRBs resulting from massive stellar collapses, where these spectral features arise in the dense outer envelope of the progenitor. If pre-GRB supernova shells exist and if they generate similar equivalent widths, the same detection probabilities would apply. With an expected GRB detection rate of 100–150 yr−1 by Swift and on-board X-ray follow-up capabilities starting minutes after the trigger, significant progress may be possible in the investigation of the first stars and the high-redshift universe.

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