EARLY X-RAY/ULTRAVIOLET LINE SIGNATURES OF GAMMA-RAY BURST PROGENITORS AND HYPERNOVAE

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ABSTRACT

We calculate the X-ray/UV spectral line signatures expected from the interaction of a gamma-ray burst afterglow and a dense preburst environment produced by the progenitor. We explore the conditions under which Fe line and edge equivalent widths of ~1 keV can arise, and discuss the possibility of gaining information about possible progenitor scenarios using X-ray metal-line spectra in the first few days of a burst. A wind or supernova shell around the burst produces an X-ray absorption line spectrum and later emission lines, while a hypernova funnel model produces mainly emission lines. The Fe K-edge can in some cases be more prominent than the Fe Kα line. Under simple assumptions for the input continuum luminosity, current reports of observed Fe line luminosities are compatible with an Fe-enriched funnel model, while lower values are expected in shell models.

Subject headings: cosmology: miscellaneous — gamma rays: bursts — stars: mass loss — supernovae: general — ultraviolet: general — X-rays: general

1. INTRODUCTION

The nature of the progenitors of gamma-ray bursts (GRBs) is an unsettled issue of extreme interest (e.g., Fryer, Woosley, & Hartmann 1999; Paczynski 1998; Mészáros 1998)). It is becoming increasingly apparent that whatever the progenitor, the result may be a black hole (BH) plus debris torus that powers the GRB; the burning question is what gives rise to this system. Both compact binary (neutron star–neutron star [NS–NS] or BH–NS) mergers, other mergers (white dwarf–BH, helium core–BH), or the collapse of a massive, fast-rotating star (referred to as hypernovae or collapsars) could lead to such a BH plus debris torus energy source, and much current work centers on discriminating between the various progenitors.

Evidence concerning the progenitor comes both from the accumulating statistics on the offsets between GRB afterglow optical transients and their host galaxies (van Paradijs, Kouveliotou, & Wijers 2000) and from light-curve fits and continuum spectral information, providing evidence for either low (Wijers & Galama 1999) or high (Owens et al. 1998) density in front of the afterglow. However, the most direct diagnostics for the environment are probably X-ray and UV spectral lines (Bisnovatyi-Kogan & Timokhin 1997; Perna & Loeb 1998; Mészáros & Rees 1998b; Böttcher et al. 1998), and an interesting possible diagnostic for hypernovae or collapsars is the presence of Fe Kα emission lines, produced by fluorescent scattering from the outer parts of the stellar progenitor of the continuum X-ray photons originating in the afterglow of the GRB (Mészáros & Rees 1998b; Ghisellini et al. 1999; Lazzati et al. 1999).

Quantitative calculations of spectral diagnostics of GRB progenitors are hindered by the lack of detailed calculations or data on the evolution and mass-loss history in the period of months to years before the outburst. However, it is possible to guess what some of the generic features of such preburst environments may be. The purpose of this paper is to consider some very simplified but physically plausible progenitor configurations, and to explore in quantitative detail the range of possible X-ray/UV spectral signatures that can be expected from them in the timescale of hours to days after the outburst.

2. PREBURST ENVIRONMENTS AND COMPUTATIONAL METHOD

The task of finding useful progenitor diagnostics is simplified if the preburst evolution of the latter leads to a significantly enhanced gas density in the immediate neighborhood of the burst. In scenarios with a massive progenitor, such as a hypernova or collapsar, it is known that red supergiants and supernova progenitors in general are prone to have strong winds. One would expect such a strong mass-loss phase to produce a preburst environment that could have the form of a shell, e.g., as inferred in SN 1987a. For instance, a star evolving from a red giant to a blue giant phase might first emit a slower wind, which is later swept up into a shell by a faster wind. In some collapse or compact binary merger scenarios, e.g., of a BH or NS with a white dwarf or He core left over from a massive companion star, a supernova producing a metal-enriched supernova remnant (SNR) shell might precede the burst. In general, the shell would be expected to have dispersed before the burst occurs, but there could be rare cases in which it does not. Another possible scenario that has been discussed is the delayed collapse of a rotationally stabilized neutron star, which could lead to a burst with a SNR shell around it (Vietri & Stella 1998).

Another geometry characterizing massive-progenitor or collapsar models could arise if the giant progenitor is fast-rotating, e.g., due to spin-up from merging with a compact companion. Then the stellar envelope and the wind would be expected to be least dense inside a funnel-like cavity extending along the orbital-spin axis, with the GRB at the
tip of the funnel. However, detailed models for either a funnel-like environment or a shell resulting from a GRB progenitor are lacking so far. Therefore, our choice of parameters for these scenarios is purely phenomenological, and guided more by reported observations than by theoretical considerations.

For the computations, we need to treat in detail the photoionization and recombination of the various ions in the environment material, and in order to obtain spectra that can be compared to observations, we need to consider the time dependence. This is because the recombination and ionization has a natural timescale depending on the ambient density, the chemical abundance, and the flux received; because the ionizing spectrum from the GRB afterglow varies in time; and because the spectrum observed at a given observer time is made up of light arriving from different regions of the remnant, for which the source time is different. The problem can be simplified if the first timescale is shorter than the latter two, since in that case one can use a steady state photoionization code. The recombination time is \( t_{\text{rec}} \approx 10^3 \Sigma^{-2/7} n_{\text{ion}}^{-1} \) s for ions of charge \( Z \) at the typical temperatures and densities in the reprocessing gas, which is short compared with the timescales of \( \sim 10^5 \) s \( \sim 1 \) day considered, so the ionization equilibrium approximation is justified in the examples calculated below. In this paper we exploit this approximation, and make use of the XSTAR code\(^7\) (Kallman & McCray 1982, ) to calculate the spectrum. This is a steady state code which, for a given input spectrum, calculates the photoionization of a plasma in a shell at a given distance from the source, as a function of the density and chemical abundances. These position-dependent spectra in the source frame, which arise in integrated over the observer time-dependent spectra that would be actually measured. A restriction on the use of this code is that the effects of Comptonization can be included only in a rough manner. This is not a problem if the remnant is Thomson thin (column density \( \Sigma \lesssim 2.5 \times 10^{24} \) cm\(^{-2}\)), or if the incident continuum is absorbed over a column density smaller than this. Very little if anything is known about the nature and geometry of the remnants, and in the following discussion we assume situations in which either the above restriction is satisfied, or the effects of its violation can be estimated by means of a different Monte Carlo code (Matt et al. 1996) that is not subject to this restriction.

The input spectrum that we assume is typical of simple afterglow models (Mészáros & Rees 1997a; Waxman 1997), with phenomenological parameters chosen to approximate those of the observed afterglow GRB 970508. We take these to be a break luminosity \( L_{\text{br}} \approx 3.2 \times 10^{46} \) erg s\(^{-1}\) keV\(^{-1}\) with a break energy \( E_{\text{br}} = 1.96 \) keV at \( t = 10^3 \) s, a Band et al. (1993) spectrum with energy indices \( \alpha = 0.33, \beta = -0.75 \), and a standard time-decay exponent for the peak frequency of \( \gamma = -(3/2)\beta \).

3. SHELL MODELS

One type of environment model considered is a shell of gas at some distance from the burst, considered to be essentially stationary over the period of interest for its response to the above time-dependent input spectrum. The shells could be metal-enriched, especially if they arise from a supernova explosion before the burst, and possibly also if they involve a preprojected wind from a massive stellar progenitor (although in the latter, solar abundances are probably likelier). These shells could have a large coverage fraction, and would have a mean density much larger than typical interstellar medium (ISM) values, especially when blobs and condensations form via instabilities. Guided by the report of an Fe line detection peaking after about 1 day in GRB 970508 and GRB 970828 (Piro et al. 1999; Yoshida et al. 1999), one is led to consider shell radii \( R \gtrsim 10^3 \) km. A physical requirement is that the distance \( c t / (\gamma t) \) reached after 1 day by the afterglow shock producing the continuum be less than \( R \), with \( \Gamma \gtrsim 1 \). As an example, we assume that the shock is observed to reach the shell at an inner radius distance \( R \sim 1.5 \times 10^{16} \) cm at \( t_s = 1 \) day along the line of sight. Within the context of simple (adiabatic, impulsive, homogeneous external density) standard afterglow models, this could occur for a deceleration radius \( \lesssim R \), requiring a density between the burst and the shell higher than usually considered. A preshell density of \( n \lesssim 10^6 \) cm\(^{-3}\) could do this, involving a total mass of \( \sim 10^{22} M_\odot \), much less than in the assumed shell, and a Thomson optical depth \( \tau_T \ll 1 \). However, in scenarios leading to a shell, the conditions might differ substantially from those implied in snapshot fits to simple standard models (e.g., Wijers & Galama 1999), and the error bars in such fits are difficult to estimate. A complete model of the physics for both the input continuum and the reprocessing gas would be uncertain, especially in view of the preliminary nature of current X-ray line observations. For this reason, we prefer to consider a phenomenological input spectrum as a quantity given by observations, and treat the environment simply as a test particle gas, choosing its physical parameters in such a manner as to reproduce the current observations.

For computational reasons, the calculations are carried out for thin homogeneous spherical shells of different densities, which can be used to represent thicker inhomogeneous shells with the same mass per unit area and the same density in the filaments or blobs as in a homogeneous thin shell. The shell was assumed to have an Fe abundance either 10 or 10\(^2\) times solar (and solar for the other elements), and a hydrogen column density of \( N_H = 5 \times 10^{13} \) cm\(^{-2}\), with a total mass of \( M_\odot \sim 10^2 M_\odot \). The X-ray/UV spectrum as a function of observer time is shown in Figure 1, for several values of the particle density in the shell. The line spectrum becomes more prominent as the gas cools and recombines. Because of the very high luminosities and hard initial gamma-ray spectrum, initially all the Fe is fully ionized, and as it cools the strongest features initially are the Fe K\(\alpha\) and K-edge, which appear initially in absorption and later as recombination emission features, the strength of the K-edge feature peaking at later times than the K\(\alpha\) for these luminosities, and the K-edge line being more prominent and easier to detect for this input continuum luminosity. (For a lower input continuum luminosity with a steeper spectrum, however, the time sequence can reverse and the K-edge can be more prominent than the K\(\alpha\) feature.) As the continuum continues to decrease, the Fe K\(\alpha\) line becomes more important, shifting its energy gradually from 6.7 to 6.4 keV as the lower ions become in turn more predominant. At later times, the Fe K-edge recombination emission feature begins to emerge in emission as well.

\(^7\) XSTAR manual (T. Kallman & J. Krolik, 1998) is available at ftp://legacy.gsfc.nasa.gov/software/plasmacodes/xstar.
whereas at early times it is largely an absorption feature. After the Fe features have become important, with some delay, depending on the density and abundance, other features in the 2–3 keV range due to Si and S also become prominent, as well as an O recombination and Kα features at 0.86 and 0.65 keV.

The corresponding X-ray light curves in the 2–10 keV range are shown in Figure 2, along with the equivalent widths of the Fe Kα feature. The Fe Kα luminosity reaches values of $\lesssim 10^{43}$ erg s$^{-1}$, and the equivalent width (EW) reaches values of 0.2–3.5 keV in emission. The Fe K-edge feature in emission reaches values of $\lesssim 0.1$ keV in Figure 2 (bottom right; not plotted in figure), but at early times the K-edge absorption is substantial, as seen in Figure 1. In this example of a full shell, the EW of the Fe Kα in the 6.4–6.7 keV range and the Fe K-edge at $\sim 9.28$ keV continues to grow as the bulk of the diffuse K-edge recombination and fluorescent Kα photons reach the observer from the rim and the back portions of the shell, in response to the GRB time-dependent continuum. This growth continues until a time $t \sim R/c \sim 5$ days, when the diffuse radiation from the rim of the shell becomes visible. However, by this time the total X-ray flux (continuum plus lines) has decreased significantly (Fig. 1), and the signal-to-noise ratio (S/N) is less favorable for detection. Note that in this calculation the continuum source (i.e., the shock) crosses the shell at 1 day. At this point, the observed continuum X-ray luminosity temporarily increases, since the radiation along the line of sight is no longer absorbed by the shell, but then it continues to decrease according to the standard afterglow decay law. This temporary brightening would be enhanced, and might be dominated, by the heating of the shell as the shock goes across it; a consistent analysis of the shock heating would require a number of additional assumptions and detailed gasdynamical calculations, which are beyond the scope of this paper (see, e.g., Vietri et al. 1999 for an analytical estimate). A temporary brightening of the continuum at 1 day is in fact seen in the observations of GRB 970508 (Piro...
et al. 1999). The unabsorbed continuum reaching the observer after 1 day from beyond the shell is also responsible for the gradual refilling of the absorption troughs seen in Figure 1 at late times.

The effects of a jetlike fireball illuminating a spherical shell are also of interest. An example of the spectral evolution is shown in Figure 3, for a fireball whose continuum radiation is collimated in a jet of opening half-angle $\theta_j = 37^\circ$ (with other properties the same as for the spherical fireball of Fig. 1). In this example, the shell was assumed to be spherical, with the same dimensions and properties as in Figure 1. The effect of a jet is that the ring-shaped area of illuminated shell that is visible to the observer increases only up to a time $t_j = (R/c)(1 - \cos \theta_j) \sim 1$ day. After that time, the shell regions at angles larger than $\theta_j$ that become visible do not contribute any diffuse radiation, since they are not (and never were) illuminated by the continuum source. This choice of $\theta_j$ results therefore in K-edge and Kz equivalent widths that grow until $t_j \sim 1$ day and decay thereafter (see Fig. 4).

4. SCATTERING FUNNEL HYPERNOVA MODELS

A different configuration that may characterize hypernovae involves a funnel geometry. Accurate hypernova line diagnostics will be uncertain due to the absence of quantitative models, extending from minutes to days after the burst, of the gaseous environment in the outer layers and/or winds in such objects. We can, however, get an estimate of what may be expected by using a physically plausible toy model. We take a parabolic funnel as an idealized representation of the centrifugally evacuated funnel along the rotation axis of the collapsing stellar configuration, with the GRB at its tip. In order to produce line features that peak at about 1 day from such a model, the X-ray continuum must be inside the outer rim of the funnel for at least this long. A simple configuration with these properties is, for example, a wind with a scattering optical depth of extending out to $R = 1.5 \times 10^{16}$, in which there are two empty (or at any rate much lower density) funnels, inside which the fireball expands. The fireball is assumed to have the same luminosity per solid angle and spectral characteristics as used in the previous two shell models, and the funnel opening half-angle was taken to be $15^\circ$. For the funnel walls, we take a uniform density $n = 10^{10}$ cm$^{-3}$ and an Fe abundance of $10^2$; we assume the column density within $x_{Fe} = 10$ or $10^2$; we assume the column density within which reprocessing is most effective to be $\Sigma = 10^{24}$ cm$^{-2}$, the amount of reprocessing mass involved being $\sim 0.2 M_\odot$. An accurate calculation of the spectrum escaping from a funnel is not straightforward, since a rigorous prescription for treating multiple scatterings and a nonspherical geometry is difficult to implement in a code such as XSTAR. However, it is possible to obtain useful lower and upper limits for the actual equivalent widths by calculating the widths expected in two limits. A low estimate for the EW is computed by counting only the once-reflected line photons that are directed inside the opening angle of the funnel, and comparing them to the continuum photons (either direct or reflected) that are similarly directed inside the opening angle. The high limit for the EW is calculated using all the

Fig. 5.—Top: Spectrum of scattering funnel model with $x_{Fe} = 10^2$ as a function of time (top to bottom: 50, 66, 83, 100, 200, and 300 ks). The spectral luminosity is shown in the upper/lower bound approximation (all/once; see text). Bottom: Total and Fe light curves and Fe K-edge and Kx equivalent widths for the scattering funnel model as a function of time. The values are calculated for the upper/lower bound approximations (all/once; see text).

Fig. 6.—Same as Fig. 5, but for $x_{Fe} = 10$
once-reflected line photons (whether directed at the opening or not) and comparing them to the directly escaping plus all the reflected continuum. A spectrum as a function of time for the second limit (all) and $x_{Fe} = 10^2$ is shown in Figure 5.

The funnel model was taken to have the same input luminosity per solid angle as the shell models, but the incidence angle is shallower in funnels, and hence the effective heating per unit area is smaller than in shells at the same distance, which favors Fe Kz recombination; hence, the Fe Kz luminosity is larger. The upper and lower limits for this hypernova example with $x_{Fe} = 10^2$ (Fig. 5, bottom) show that at 1 day the Fe Kz luminosity is bounded between $2 \times 10^{44}$ and $6 \times 10^{42}$ ergs s$^{-1}$, and the Fe Kz line EW is bounded between 1.2 and $\sim 0.1$ keV, while the Fe K-edge EW, which is more prominent, is bounded between 2.7 and 0.2 keV. For $x_{Fe} = 10$, these values are lower by a factor $\sim 3$ (Fig. 6).

5. DISCUSSION

We have considered a series of models in which the environment of the burst can be represented as a shell of enhanced density at some radial distance from the burst. These shells could be the result of a preburst wind phase of a massive progenitor, a hypernova, a collapsar, or a merger involving a massive companion or its core. Alternatively, they might be supernova remnant (SNR) shells of a rare kind, which originated sufficiently recently that they have not yet dispersed before the burst occurs. Such shells can produce significant Fe Kz and K-edge luminosities and equivalent widths of the order of $\sim$ keV, provided that the density (possibly in the form of blobs) in the shell is large ($10^{10}$–$10^{12}$ cm$^{-3}$), and the coverage fraction is a substantial fraction of $4\pi$. For a mass of Fe in the shell $2.5 \times 10^{-3} M_\odot$ or $2.5 \times 10^{-4} M_\odot$ (a total shell mass $1 M_\odot$), the Fe Kz equivalent widths after 1 day can be $\text{EW} \lesssim \text{keV}$, comparable to the values reported by Piro et al. (1999) and Yoshida et al. (1999). However, the Fe Kz luminosity is $\lesssim 10^{43}$ ergs s$^{-1}$, which is low by a factor of 5–10. The higher density or more Fe-rich shells also show a drop in the continuum after $t \sim 10^8$ s due to Fe absorption and reemission (e.g., top right and both bottom panels of Fig. 2), a feature that qualitatively resembles an observed dip in the light curve of GRB 970508 at $\sim 5 \times 10^4$ s (Piro et al. 1999). We note that winds of $M \sim 10^{-4} M_\odot$ yr$^{-1}$ with velocities $v_\infty \sim 100$ km s$^{-1}$ varying on timescales of $\lesssim 100$ yr (characteristic of massive stars) would yield shell enhancements starting at $R \sim 10^{16}$ cm, with mean density $n \gtrsim 10^3$ cm$^{-3}$, in which condensations of $n \sim 10^{10}$–$10^{11}$ cm$^{-3}$ could form via instabilities. Dense shells may also form as a result of a fast wind phase of massive stars) would yield shell enhancements starting at $R \sim 10^{16}$ cm, with mean density $n \gtrsim 10^3$ cm$^{-3}$, in which condensations of $n \sim 10^{10}$–$10^{11}$ cm$^{-3}$ could form via instabilities.

We have also explored a different shell scenario, in which the Fe features would cut off abruptly after reaching a peak. This occurs if the continuum is beamed, e.g., if it is produced by a collimated fireball jet. In this case (Figs. 3 and 4), the diffuse radiation, including the Fe and other spectral features, cuts off after a time $t \sim (R/c)(1 - \cos \theta_j) \sim 1$ day, and for a $\sim 1 M_\odot$ shell at $R \sim 10^{16}$ cm with Fe abundance $10^{-10}$ times solar, the models produce Fe Kz equivalent widths of $\lesssim 0.3$–$3$ keV (depending on the density) peaking at 1 day.

Another series of models that we consider address the consequences of a funnel geometry in a spinning massive progenitor (hypernova or collapsar). If the stellar envelope or its wind can be assumed to extend out to radii of light-days with an appreciable density of the order of $n \sim 10^{-10}$–$10^{-11}$ cm$^{-3}$ (particularly in winds where the density drops slower than $r^{-2}$, e.g., in hourglass-shaped winds, such as that of SN 1987a), a wider range of luminosities and equivalent widths is possible after $\sim 1$ day. In this case, for $x_{Fe} = 10^2$ we obtain an Fe Kz luminosity of $L_{Fez} \sim 2 \times 10^{44}$ ergs s$^{-1}$ at $t \sim 1$ day (or a factor of 3 lower, for $x_{Fe} = 10$), comparable to the observational results. The equivalent width grows until the continuum source (or afterglow shock) moves beyond the radius where there is a substantial amount of stellar wind material to reprocess it (see Fig. 5). After that time we detect only the decaying shock continuum, which is now beyond the wind region, and a fast-decaying component from the funnel wall as it cools.

The calculations presented here indicate that a qualitative difference between shell and funnel models is that, whereas shells produce Fe Kz, K-edge, and features from other metals predominantly in absorption, and later also partly in emission, the funnel models are dominated by emission features throughout. This is due to the presence of material along the line of sight in the shell models, which is absent in the funnel case.

It is worth noting that in GRB 970508 the energy of the X-ray spectral feature discussed by Piro et al. (1999) agrees with that of a $6.7$ keV Fe Kz line at the previously known redshift, $z = 0.835$ (Metzger et al. 1997), while in GRB 970828 the energy of the X-ray spectral feature reported by Yoshida et al. (1999) is compatible with an Fe K-edge feature at $9.28$ keV in the rest frame, at the recently reported redshift $z = 0.958$ (Djorgovski et al. 2000).

A general point is that in the case of low-mass binary mergers, such as NS–NS or BH–NS, it is more difficult to see how shells or funnels would have formed and still be present within distances of $\gtrsim 10^{15}$–$10^{16}$ cm at the time of the burst. Hence, the detection of Fe K-edge and Kz features peaking at $\sim 1$ day at the strengths discussed here (and as reported by Piro et al. 1999 and Yoshida et al. 1999) would appear to be a significant diagnostic for a massive progenitor. Shells and funnels with dimensions of about a light-day are rough examples of extreme geometries that might characterize massive-progenitor remnants. However, a clear distinction between various types of massive progenitors (or mergers involving a massive progenitor) would require extensive quantitative calculations in the spirit of, e.g., Fryer et al. (1999) and Ruffert & Janka (1999), but considering more specifically the different preburst evolution and near-burst environments. What our present calculations are able to indicate is that Fe Kz equivalent widths of $\sim$ keV can be produced in a variety of plausible progenitor scenarios, but the absolute value of the Fe Kz line flux...
provides constraints on the combined values of the density, chemical abundance, and distance from the burst, as well as the geometry. Our present calculations, which include a number of simplifying assumptions, indicate that Fe-enriched funnel models agree better than shell models with the currently reported Fe line values. More detailed modeling, as well as more sensitive X-ray spectral line detections, should be able to provide valuable constraints on specific progenitors.

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