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IRON LINES FROM GRBS: CLUES TOWARD THE PROGENITOR

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RESUMEN

Investigamos los modelos más estudiados para progenitores de destellos de rayos gamma (DRGs) en términos de propiedades espectrales en rayos X posiblemente observables. Nos restringimos a líneas en rayos X cuasi-térmicas de material eyectado por una supernova ligada al destello. En el marco del modelo de la hipernova/colapsar se esperan destellos retardados (por algunos días o hasta meses) en rayos X térmicos, dominados por líneas. En la coalescencia de dos estrellas de Helio se esperan destellos en rayos X unos cuantos días después del destello de rayos gama. Estas características deben ser observables con *Chandra* y *XMM* a corrimientos al rojo relativamente altos. Algunas líneas de emisión débiles, unos cuantos días después del destello de rayos gamma, pueden resultar de una "supranova". En cualquiera de estos casos, se espera observar rayos X en absorción, en particular para la fase inmediatamente después del destello en rayos gamma. No se esperan estas características en destellos provenientes de la coalescencia de objetos compactos.

ABSTRACT

We investigate the currently most popular models of gamma–ray burst (GRB) progenitors in terms of potentially observable prompt or delayed X–ray spectral features. We focus on quasi–thermal X–ray line features from ejecta of a supernova related to the GRB. In the framework of the Hypernova/Collapsar model, delayed (a few days – several months after the GRB) bursts of line–dominated, thermal X–ray emission may be expected. The He–merger scenario predicts similar X–ray emission line bursts in the days following the the GRB. These X–ray signatures should be observable with *Chandra* and *XMM* out to rather large redshifts. Weak emission line features a few days after the GRB may also result from the supranova GRB scenario. In all three cases, significant X–ray absorption features, in particular during the prompt GRB phase, are expected. No significant X–ray spectral features result from compact–object binary mergers.

Key Words: **GAMMA-RAYS: BURSTS — SUPERNOVAE: GENERAL — X-RAYS: BURSTS**

1. INTRODUCTION

With the advent of *Chandra* and *XMM–Newton*, the detection of X–ray spectral signatures from the environments of cosmological gamma–ray bursts (GRBs) has become a realistic prospect. The marginal detection of a redshifted Fe Kα emission line in the afterglow of GRB 970508 (Piro et al. 1999) with the *BeppoSAX* NFI has stimulated a vital discussion about the possible origin of this line feature (Ghisellini et al. 1999; Lazzati, Ghisellini & Celotti 1999; Böttcher et al. 1999a; Böttcher et al. 1999b; Vietri et al. 1999; Weth et al. 2000; Böttcher 2000). So far, however, this discussion has concentrated on determining the conditions in the vicinity of GRB 970508 necessary to explain the iron line feature in the afterglow assuming this feature is real. This resulted in rather extreme conditions which may not be realized in any of the currently popular GRB models.

In this paper, we will take the opposite approach: we compute the properties of the late X–ray afterglow signatures predicted by the currently most popular GRB engines, using reasonable assumptions about the environments produced by the progenitors of these GRBs. In §2, we give a short description of the GRB model scenarios which we consider in this paper and discuss the environments surrounding each of these models. In §3, we present the X–ray absorption and emission line features produced by the long–duration GRB models (to compare with GRB 970508).

2. OVERVIEW OF PROGENITOR MODELS

2.1. *Compact–Object Merger*

This class contains the NS binary mergers, BH–NS mergers, and BH–WD mergers (Eichler et al. 1989; Narayan, Paczyński & Piran 1992; Mészáros & Rees 1992; Ruffert et al. 1997; Janka et al. 1999; Fryer et al. 1999). These events are believed to produce short gamma–ray bursts of sub–second durations (none of which could be localized well enough yet to allow the detection of X–ray and optical counterparts). The merger timescale due to gravitational angular momentum loss for these binaries is much longer than stellar evolution time scales, and such events are expected to happen far outside star-forming regions, probably even outside of the disk of the host galaxy. Thus, they will most likely happen in environments of very low ISM (or IGM) density. Furthermore, any left–over debris from the merging process will be accreted onto the newly formed black hole on sub–second time scales, so that the coalescence event itself will not produce a significant amount of external material either. Thus, short bursts produced in compact-object binary mergers are unlikely to show any significant X–ray emission line or absorption features attributable to the immediate vicinity of the burst.

2.2. *Supranova*

Stella & Vietri (1998) have proposed a model in which a supernova results in the formation of a rapidly spinning NS whose mass exceeds the Chandrasekhar limit. The NS is stabilized by centrifugal forces. After the NS spins down on a time scale of typically several months, the rotational stabilization becomes insufficient, and the NS collapses to form a black hole, rapidly accreting the outer layers of the NS. This model is also producing short bursts ($\lesssim 1$ s). However, the supernova which has preceded the final collapse event may have produced a rather dense shell section $\sim 10^{15} - 10^{17}$ cm from the central compact object. This pre–ejected material could well have enhanced metal abundances due to convective mixing during the SN event.

Thus, the pre–ejected SN shell in a supranova scenario may fulfill the requirements found in (Vietri et al. 1999; Weth et al. 2000; Böttcher 2000) to produce an Fe Kα emission line of the strength marginally detected in GRB 970508, assuming that it is illuminated and later shock–heated by a relativistic blast wave (which may not have the same energy per solid angle and the same bulk Lorentz factor as the section of the blast wave producing the observed GRB afterglow). However, realistic calculations of collapsing neutron stars (Ruffert et al. 1996; Fryer & Woosley 1998a) find that these collapses eject too much baryonic material and have too little energy to produce GRBs, and, in any event, the supranova is not a viable model to explain the line feature seen in GRB 970508, since that burst was a long–duration burst with $t_\gamma \sim 25$ s. We predict, however, that short–duration bursts, if produced by the supranova mechanism, may exhibit moderately strong X–ray emission line features from the illuminated and shock–heated material which was ejected in the course of the supernova. Time–dependent X–ray absorption features investigated in (Böttcher et al. 1999a) may also result from the vicinity of the GRB, since the progenitor of the supranova is likely to be a massive, young star, still located in the star–forming region where it was born.

2.3. *Collapsar / Hypernova*

The collapsar / hypernova model (Woosley 1993; Paczyński 1998; McFadyen & Woosley 1999) produces long–duration bursts when the core of a young, massive star collapses to form a black hole, and the associated supernova explosion launches an unsuccessful shock wave in the outer layers of the progenitor star so that part of the ejected material falls back and is accreted onto the black hole. Fryer et al. (1999b) have shown

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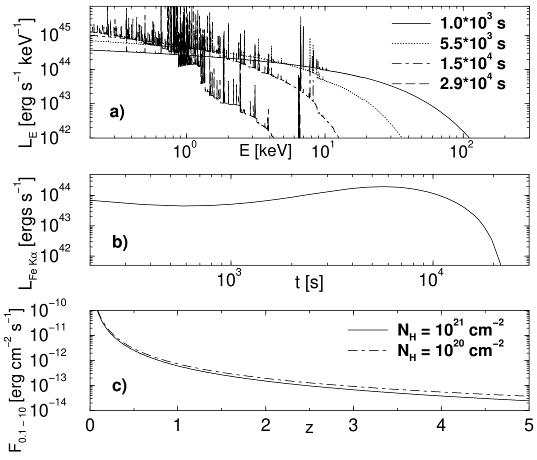

Fig. 1. X–ray spectra (a) and light curve of the Fe Kα emission line luminosity (b) for parameters appropriate to the He–merger scenario with a 15 $M_\odot$ progenitor. The lower panel (c) shows the resulting 0.1 – 10 keV flux (maintained over $\Delta t \sim 10^4$ s) as a function of the redshift of the burst, for two different values of the Galactic N_H. The spectra shown in panel (a) are not corrected for Galactic photoelectric absorption.

that the vast majority of collapsars are expected to occur as a result of binary star mergers. During the common–envelope phase of this merging process, part of the hydrogen envelope of the primary will be ejected to form a disk around the merging stars. With current stellar models, this common envelope phase occurs at least 10,000–100,000 yr before the collapse of the massive star, and the pre–ejected material will form a disk with an inner edge ($r_{\rm i}$) beyond 10^{15} cm from the central object. However, the radial evolution of stars is still uncertain, and the common envelope phase could occur just before collapse, producing a disk at $r_{\rm i} \sim 10^{13}$ cm. Since it originates mostly from the hydrogen envelope of the primary, the abundances of heavy elements might be depleted with respect to ISM abundances. The collapsar / hypernova model predicts highly beamed energy deposition responsible for the GRB along the symmetry axis (rotation axis), while outside the beaming cone the event will resemble a core–collapse (probably type Ib/c) supernova. A reasonable assumption is that in the course of this supernova, $\sim 1\,M_\odot$ of material is ejected to form a non–relativistic blastwave, which will ultimately energize the pre–ejected material via shock–heating. Potentially observable consequences of this interaction will be discussed in the next section.

2.4. *He-Merger*

In the He–merger scenario (Fryer & Woosley 1998b), long–duration GRBs are produced after a compact object (NS or BH) has spiraled into the helium core of a massive secondary and is rapidly accreting the remaining mass of the helium core. During the inspiraling (common–envelope) phase, which takes ~ 10 orbits, the hydrogen and part of the helium envelope of the secondary are ejected to form a disk of ~ 0.1–$1\ M_\odot$ at $r_{\rm i} \sim 10^{13}$ cm. Since the primary has undergone a supernova explosion prior to this evolutionary phase, the hydrogen envelope of the secondary might be enriched with heavy elements from the SN ejecta of the primary. Just as in the case of the collapsar model, the GRB itself is expected to be beamed, while along the equatorial plane of the binary system, the explosion will resemble a type Ib/c supernova, ejecting $\sim 1\,M_\odot$ of material at non–relativistic speed ($v_{\rm ej} \sim 10^9$ cm s^{-1}). The main difference between the collapsar/hypernova and the He–merger scenarios is thus that in the former case the disk of pre–ejected material is much further from the central explosion (by a factor of up to $\sim 100 - 10,000$) and is probably not metal–enriched.

3. X–RAY SPECTRAL FEATURES FROM COLLAPSARS AND HE–MERGERS

As the ejecta from the supernova, associated with the GRB explosion in the collapsar/hypernova and He–merger scenarios, expands, it encounters the disk of pre–ejected material and is rapidly decelerated, while

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shock–heating the disk material. This occurs with a delay of $t_X = (1+z)\, r_{\rm i}/v_{\rm ej}$ with respect to the GRB, where z is the redshift of the burst source. We calculate the hydrodynamical evolution of the shock wave and use XSTAR (Kallman & McCray 1982) to calculate the X–ray spectrum and cooling rate of the shocked material, which is assumed to be in thermal and ionization equilibrium at any given time.

Figure 1 shows our simulation results for a typical case expected in the He–merger scenario if the secondary is a $15\, M_\odot$ star. The times in the figure are measured in the rest–frame of the burst source and are relative to the onset of the blast–wave/disk interaction at $t_X = (1+z) \times 10^4$ s after the GRB, in the observer's cosmological reference frame. Panel (c) indicates that such X–ray signatures may actually be easily observable with *Chandra* or *XMM* out to substantial redshifts. In the simulation shown in Fig. 1 we assumed standard solar–system abundances for the disk material.

In the collapsar/hypernova scenario, the disk may be located significantly farther out so that the blast–wave/disk interaction takes place up to a factor $\sim 100 - 10{,}000$ later than in the He–merger scenario. At the same time, the disk located at such large distances is expected to have an accordingly lower matter density. We find that the flux level of delayed X–ray flashes from this scenario may be a factor ~ 100 lower than in the He–merger scenario. However, at the time these flashes are expected, the direct GRB afterglow will have faded to undetectable levels, so that no interference from this underlying continuum component will occur. Our results indicate that out to a redshift of $z \sim 1$, such X–ray flashes from the shock–heated pre–ejected disk may be detectable by *Chandra* or *XMM* within exposure times of $\lesssim 50$ ksec.

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