Iron line in the afterglow: a key to unveil Gamma–Ray Burst progenitors

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ABSTRACT

The discovery of a powerful and transient iron line feature in the X–ray afterglow spectra of gamma–ray bursts would be a major breakthrough for understanding the nature of their progenitors. Piro et al. (1999) and Yoshida et al. (1999) report such a detection in the afterglow of GRB 970508 and GRB 970828, respectively. We discuss how such a strong line could be produced in the various scenarios proposed for the event progenitor. We show that the observed line intensity requires a large iron mass, concentrated in the vicinity of the burst. The previous explosion of a supernova, predicted in the Supranova scenario, is the most straightforward way to account for such a large amount of matter. We discuss three different physical processes that could account for the line: recombination, reflection and thermal emission. Among these, reflection and thermal emission may explain the observed line features: reflection should be important if the remnant is optically thick, while thermal lines can be produced only in a thin plasma. The recombination process requires extremely high densities to efficiently reprocess the burst photons, whereas this process could work during the X–ray afterglow. Future key observations for discriminating the actual radiating process are discussed.

Key words: gamma rays: bursts — supernova remnants — X-rays: general — line: formation

1 INTRODUCTION

Piro et al. (1999) and Yoshida et al. (1999) report the detection of an iron emission line in the X–ray afterglow spectrum of GRB 970508 and GRB 970828, respectively. The line detected in GRB 970508 is consistent with an iron $K\alpha$ line redshifted to the rest–frame of the candidate host galaxy ($z = 0.835$, Metzger et al. 1997), while GRB 970828 has no measured redshift and the identification of the feature with the same line would imply a redshift $z \sim 0.33$. The line fluxes (equivalent widths) are $F_{Fe} = (2.8 \pm 1.1) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (EW $\sim 1$ keV) and $F_{Fe} = (1.5 \pm 0.8) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (EW $\sim 3$ keV) for GRB 970508 and GRB 970828, respectively. Although the significance of these features is admittedly not extremely compelling ($\sim 99\%$ in both cases), the implications that they bear are so important to justify a study on the mechanism that would produce them. A strong iron emission line unambiguously points towards the presence, in the vicinity of the burst, of a few per cent of iron solar masses concentrated in a compact region. Thus the presence of such a line in the X–ray afterglow spectrum would represent the “Rosetta Stone” for unveiling the burst progenitor.

Three main classes of models have been proposed for the origin of gamma–ray bursts (GRB): neutron star – neutron star (NS–NS) mergers (Paczynski 1986; Eichler et al. 1989), Hypernovae or failed type Ib supernovae (Woosley 1993; Paczyński 1998) and Supranovae (Vietri & Stella 1998). In the NS–NS model the burst is produced during the collapse of a binary system composed of two neutron stars or of a neutron star and a black hole. In this case the explosion should take place in a clean environment, due to the relatively large speed (up to $\sim 1000$ km s$^{-1}$) of such systems. Since the time required for the binary system to coalesce and merge is of the order of a billion year, the GRB should be outside the original star forming region and hence in a rarefied environment. On the contrary, in the Hypernova scenario, the burst is due to the evolution of a massive ($\sim 100 M_{\odot}$) star, which collapses forming a Kerr black hole, whose rotational energy is tapped in a few seconds, producing the burst. Hypernovae should be located in dense molecular clouds, probably iron rich, but there should be no Hypernova remnant.
The Supranova scenario (Vietri & Stella 1998) assumes that, following a supernova explosion, a fast spinning neutron star is formed with a mass that would be supercritical in the absence of rotation. As radiative energy losses spin it down in a time-scale of months to years, it inevitably collapses to a Kerr black hole, whose rotational energy can then power the GRB. A supernova remnant (SNR) is naturally left over around the burst location.

The detection of a strong iron line redshifted to the rest frame of the GRB progenitor poses severe problems to the NS–NS model, which could produce lines only inside the fireball. These hypothetical lines should be blueshifted by the bulk Lorentz factor $\Gamma$ of the fireball (Meszáros & Rees 1998a) and should then be detected at frequencies $\Gamma/(1+z)$ times larger.

X–ray line emission following GRB events has been recently discussed in the Hypernova scenario by Ghisellini et al. (1999) and Boettcher et al. (1998). None of these works predict, with reasonable assumptions on the burst surroundings, iron lines strong enough to be detectable during the X–ray afterglow. Moreover, line emission should last over a time–scale of years given the width of the emitting nebula. The production of a stronger line in the Hypernova scenario has been. mentioned by Meszáros & Rees (1998b), who consider recombination in a relatively dense torus, formed by the interaction of a compact companion with the pre–Hypernova envelope.

As we will show in this letter, the Supranova scenario can easily account for the large amount of iron rich material needed to explain the observed line features. This letter is organized as follows: in section 2 we derive model independent general constraints on the ambient material, in section 3 we discuss the line emission process and in section 4 we draw our conclusions.

## 2 General Constraints

We consider a line with a flux comparable to a typical afterglow X–ray flux: $F_{Fe} = 10^{-13} F_{Fe,-13}$ erg cm$^{-2}$ s$^{-1}$. This in itself constrains both the amount of line–emitting matter and the size of the emitting region.

Assume that the emitting region is a homogeneous spherical shell centered in the GRB progenitor, with radius $R$ and width $\Delta R \leq R$. The flux of the iron line cannot exceed the absorbed ionizing fluence $q F$ (where $F$ is the total GRB fluence and $q$ is the fraction of it which is absorbed and reprocessed into the line), divided by the light crossing time of the region, $R/c$. This, independently from the line flux variability, gives an upper limit to the size:

$$R < 3 \times 10^{18} \frac{q F_{Fe,-13}}{F_{Fe,-13}} \text{ cm}$$

(1)

Since $q$ is $\sim 0.1$ at most (Ghisellini et al. 1999), the emitting region is very compact, ruling out emission from interstellar material, even assuming the large densities appropriate for star forming regions.

The total line photons produced at 6.4–6.9 keV in $10^5 t_5$ seconds, for a GRB located at $z = \|$, are $\sim 3 \times 10^{52} F_{Fe,-13} t_5$. This means that, for a reasonable amount of iron, each atom has to produce a large number of photons. For this reason, we call $k$ the number of photons produced by a single iron atom and we use this parameter to constrain the required mass:

$$M_{Fe} \sim 150 F_{Fe,-13} t_5 \frac{t_5}{k} M_{\odot}$$

(2)

The parameter $k$ depends on the details of the assumed scenario, but general limits can be set. If we neglect thermal processes, which will be discussed in more detail below, any iron atom can emit photons only when illuminated by an ionizing flux, i.e. the burst itself or the afterglow high energy tail. Since burst light has enough power to photoionize all the matter in the vicinity of the progenitor (see e.g. Boettcher et al. 1998), line photons will be emitted only through the recombination process. Thus the value of the parameter $k$ will not be larger than the total number of photoionizations an iron atom can undergo during the burst and/or the afterglow. For iron $K$–shell electrons, with cross section $\sigma_K = 1.2 \times 10^{-20}$ cm$^2$ we have:

$$k \lesssim \frac{q E}{4\pi \epsilon_{ion} R^2} \frac{F_{Fe}}{F_{e,13}} \sim 6.5 \times 10^5 \frac{q E_{52}}{R_{16}^3}$$

(3)

where $E$ is the total energy emitted by the burst and/or afterglow and $\epsilon_{ion}$ the energy of a single ionizing photon.

Inserting equation 3 in equation 2 we obtain a lower limit on the iron mass $M_{Fe} \gtrsim 2.3 \times 10^{-5} F_{Fe,-13} t_5 R_{16}^2 / (q E_{52}) M_{\odot}$ which corresponds to a total mass:

$$M \gtrsim \frac{0.013 F_{Fe,-13} t_5 R_{16}^2}{q A_{\odot} E_{52}} M_{\odot}$$

(4)

i.e. a tenth of solar mass for $q \sim 0.1$ and $A_{\odot} = 1$, where $A_{\odot}$ is the iron abundance in solar units. These general requirements about the mass and its location exclude that the iron line can be emitted by interstellar material, even if made denser by a strong pre-Hypernova wind.

If such a large amount of mass were uniformly spread around the burst location, it would completely stop the fireball. In fact (see e.g. Wijers, Rees & Meszaros 1997) the fireball is slowed down to sub–relativistic speeds when the picked up mass equals the initial rest mass of the fireball. With a typical baryonic load of $\sim 10^{-4} M_{\odot}$, the mass predicted in equation 4 would stop the fireball after an observer time $t \sim \Gamma^{-2} R/c \sim 3 \times 10^4 \Gamma^{-2} s$, i.e. almost one day. Any surviving long wavelength emission should then decay exponentially in the absence of energy supply. The fireball synchrotron model have been applied to GRB 900508 by Wijers & Galama (1999) and Granot, Piran and Sari (1999).

Despite the differences of their results, both find an ambient density $n < 10$ cm$^{-3}$, nine orders of magnitude lower than the density required for the line production (see below). The only way to reconcile a monthly lasting power–law emission

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* Here and in the following we parametrize a quantity $Q$ as $Q = 10^{\varphi} Q_x$ and adopt cgs units.

† The cosmological parameters will be set throughout this letter to $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$ and $\Lambda = 0$.

‡ Assuming a wind of $m_{wind} = 10^{-4}$ solar masses per year and a wind velocity $v = 10^8$ cm s$^{-1}$, the total mass within a radius $R$ is $M = m_{wind} R/v = 3.2 \times 10^{-3} m_{wind,-4} R_{17}/v_{18} M_{\odot}$. 

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optical afterglow with iron line emission is through a particular geometry, in which the line of sight is devoid of the remnant matter. Therefore, the matter distribution must be anisotropic, with the bulk of the mass located outside the line of sight of the burst (see Fig. 1), even if the covering factor of this matter must be significant to reprocess a sufficient fraction of the primary burst photons in the line.

3 LINE EMISSION PROCESSES

We assume that the line emitting region is located at a distance R from the bursts, has a width ∆R, density \( n = (M/m_p)/(4\pi R^2 \Delta R) \) and scattering optical depth \( \tau_s = \sigma_T n \Delta R = (M/m_p)/(4\pi R^2) \). These values must satisfy the constraints derived in section 2 in addition to the nature of the first two processes discussed below to ensure that the optical depth is in the range 0.1–1, to let the matter absorb enough energy without smearing too much the iron line. Consistent values are solar mass located at \( R \sim 10^{16} \) cm, which gives \( \tau_s \sim 0.6 (M/M_\odot)/(R_{16}^2) \), and a particle density \( n = 9.5 \times 10^9 (M/M_\odot)/(R_{16}^2 \Delta R_{16}) \).

The third process discussed below requires instead \( \tau_s > 1 \), implying \( R < 8 \times 10^{15} (M/M_\odot)^{1/2} \) cm.

Since the line emitting material may well be a young supernova remnant, we allow for a high iron abundance of the plasma.

3.1 Multiple photoionizations and recombinations in an optically thin shell

If the plasma can remain cold and dense enough, burst photons can be reprocessed into line photons through recombination. When the plasma is illuminated by burst photons, iron atoms are rapidly ionized and a line photon is produced each time an electron recombines. Since burst photons rapidly re-ionize the hydrogenoid iron atom, the process can be very efficient and \( k \) can be large. Since the re-ionization time is very fast (\( \sim 10^{-5} \) s for a typical burst flux), it is the recombination time that measures the efficiency of the line emitting process. In this case \( k = t_{\text{ill}}/t_{\text{rec}} \), where \( t_{\text{ill}} \) is the illumination time and \( t_{\text{rec}} \) is the mean recombination time. Solving equation (2) for the k coefficient and substituting the iron mass \( M_{Fe} \), with the total mass of the shell \( M \) we obtain:

\[
t_{\text{max,rec}} \lesssim 1.3 \times 10^{-5} F_{Fe \times 13 A_{10} M_{M_{\odot}} t_{\text{ill}} t_{5}^{-1}}
\]

The recombination time of an hydrogenic ion of atomic number \( Z \) in a thermal plasma is \( t_{\text{rec}} = (\alpha_e n)^{-1} \) (Verner & Ferland 1996), where \( n \) is the electron density and the recombination coefficient \( \alpha_e \) is given by (Seaton 1959; see also Arnaud & Rothenflug 1985; Verner & Ferland 1996):

\[
\alpha_e(Z, T) = 5.2 \times 10^{-14} Z^{1.7/2} \left[ 0.429 + 0.5 \ln(\lambda) + 0.496/\lambda^{1/3} \right]
\]

where \( \lambda = 1.58 \times 10^5 Z^2 T^{-1} \). During the burst, the Compton temperature \( T_c \) of the plasma is bound to be large due to the high typical energies of burst photons and to the relative inefficiency of radiative cooling processes. The free-free cooling time is of the order of \( 10^7 \) s. For a typical burst spectrum we have \( T_c \sim 10^8 \) K. The recombination time turns out to be \( t_{\text{rec}} \sim 10^7 n^{-1}_{10} \) s, while equation (3), with an illumination time of 100 s, gives \( t_{\text{max,rec}} \sim 10^{-2} \) s.

We conclude that recombination cannot be effective during the burst. During the afterglow, Inverse Compton losses cool the plasma efficiently, leading to a lower Compton temperature. For GRB 970508, the observed optical/X-ray spectrum half a day after the burst gives \( T_c \sim 6 \times 10^8 \) K. This yields a shorter recombination time, \( t_{\text{rec}} \sim 10^{13} n_{10}^{-1} \) s, to be compared with the value \( t_{\text{max,rec}} \lesssim 1 \) s, obtained from equation (3) for a shell of unit solar mass and solar iron abundance. We conclude that, during the afterglow, a shell with several solar masses and/or high iron abundance could produce the observed line through the recombination process.

3.2 Thermal emission from the surrounding shell

This process should become efficient after the burst has passed, leaving behind a thermal plasma with a temperature \( T \sim 10^8 T_8 \) K. This plasma is in the same conditions of the intra cluster medium (ICM) in cluster of galaxies, systems that emit a strong 6.7 keV iron line (Raymond & Smith 1977; Sarazin 1988). A key question to solve if we want to apply ICM computations in this case is whether the collisional ionization equilibrium holds in our plasma. In the very first time, soon after the burst photons have passed, the iron will be almost completely ionized, and a recombination time \( t_{\text{rec}} \) is needed to reach equilibrium. From section 3.1 we have that \( t_{\text{rec}} \sim 100 \) s for standard shell parameters. Since this time is very short compared to the equilibrium cooling time of the plasma (\( t_{\text{cool}} \sim 2.3 \times 10^7 n_{10}^{-1/2} \) s), we can assume collisional equilibrium to compute the iron line intensity.

The equivalent width of the line in a solar abundance plasma has been carefully computed by Bahcall & Sarazin (1978) (see in particular their Figure 1) and ranges from several tens of eV at high (\( 5 \times 10^8 \) K) temperatures to \( \sim 2 \) keV at \( 2.5 \times 10^7 \) K. A very weak line is expected for temperature lower than \( 5 \times 10^6 \) K. For temperatures larger than \( 5 \times 10^7 \) K the EW dependence on temperature can be reasonably approximated as a power law. Assuming an iron abundance 10 times solar we have:

\[
\text{EW}_T \simeq 3.8 T_8^{-1.9} \text{ keV} \quad (T_8 \geq 0.5)
\]

(7)

Taking into account the spectral energy density of the bremsstrahlung continuum at 6.7 keV, we obtain a line luminosity of:

\[
L_{Fe} \simeq 8 \times 10^{44} \exp \left( -0.8 T_8^{-3} \right) \left( \frac{M}{M_{\odot}} \right) \left( T_8 \right)^{-2} V_{47}^{-1} T_8^{-2.4} \text{ erg s}^{-1} \quad (8)
\]

for a shell of volume \( V = 10^{47} V_{47} \) cm\(^3\). For a \( z = 1 \) burst we obtain a flux:

\[
F_{Fe} \simeq 2.5 \times 10^{-14} \exp \left( -0.8 T_8^{-3} \right) \left( \frac{M}{M_{\odot}} \right)^{2} V_{47}^{-1} T_8^{-2.4} \text{ erg cm}^{-2} \text{ s}^{-1} \quad (9)
\]

Therefore a shell of several solar masses, typical for many type II SN (see Raymond 1984; Weiler & Sramek 1988; Woosley 1988; McCray 1993), at a temperature slightly below \( 10^{8} \) K can produce a line flux of \( 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) for \( z = 1 \) bursts. The EW with respect to the underlying bremsstrahlung radiation would be a few keV, but any other emission component (e.g. afterglow emission) would decrease the line EW. Note that the predicted X-ray bremsstrahlung continuum has a flux \( F_{\text{ff}} \sim 6 \times \)
10^{-14} (M/M_\odot)^2 T_8^{1/2} V_{47}^{-1} \text{ erg cm}^{-2} \text{ s}^{-1}, a value comparable with a typical burst afterglow X–ray flux, especially if $M \sim$ a few $M_\odot$. The line emission process can be stopped after about one day, if the afterglow photons enhance the plasma cooling via inverse Compton, lowering the temperature down to less than $10^7$ K. Line emission can also be quenched by the re–heating produced by the incoming fireball.

### 3.3 Reflection

In Seyfert galaxies we see a fluorescence 6.4 keV iron line produced by the relatively cold ($T < 10^6$ K) accretion disk, illuminated by a hot corona, which provides the ionizing photons (e.g. Ross & Fabian 1993). The EW, if the observer receives both the hot corona emission and the line photons, is of the order of 200 eV if the disk intercepts $\sim 1/2$ of the hard X–rays. In such systems the radiation energy density $U_r \sim 10^8 L_{15}/R_{15}^3 \text{ erg cm}^{-3}$, similar to the radiation energy density at $R = 10^{15}$ cm from the burst. It is therefore conceivable that a similar mechanism can work also for GRBs, if there exists a dense material in the vicinity of the burst (Mészáros & Rees 1998b). In the case of GRB, the equivalent width could be much larger, since the reflected component (line and Compton bump) is observed when the burst has faded and only the much weaker afterglow contributes to the continuum. In this case, besides a scattering optical depth $\tau_T > 1$, we require a size large enough to allow the line being emitted even $\sim$ one day after the GRB event (i.e. $R \sim 10^{15}$ cm).

In this model the emission line is produced only during the burst event, but in the observer frame it lasts for a time $R/c$. The observed luminosity of the Compton reflection component is equal to the $\sim 10\%$ of the absorbed energy, divided by the time $R/c$. $L \sim 3 \times 10^{45} E_{abs,51}/R_{15} \text{ erg s}^{-1}$.

### 4 DISCUSSION

We have discussed three possible mechanisms for the production of a strong iron line, visible during the X–ray afterglow emission of GRBs. All mechanisms require the presence of a large amount of iron in a compact region. Both the general constraints derived in section 2 and the limits due to the particular emission processes discussed in section 3 point towards the presence of more than a solar mass of matter, iron rich, in close vicinity with the burst location. The more natural astronomical scenario in which such conditions are found is the young remnant of a supernova, exploded several months before the burst onset. In fact, with a radial velocity of the ejecta $v_{ej} = 10000$ km s$^{-1}$, a monthly lived SNR has a radius of $R \sim 2.6 \times 10^{15}$ cm. A young SNR surrounding the burst is predicted by the Supranova scenario (Vietri & Stella 1998).

The other strong general requirement concerns the special geometry needed if we want to explain the presence, in the same burst, of both a strong iron line and an optical afterglow (if interpreted as due to a decelerating fireball). Since the line emitting plasma receives the burst radiation from a different orientation than our line of sight, the iron emission line is a powerful tool to measure how isotropic the burst emission is.

We find that the multiple ionization and recombi-
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The iron line scenario has difficulties in reconciling the low temperature required to have a fast recombination with the large heating due to the burst flux. However, during the afterglow, the longer illumination time and the lowest plasma Compton temperature allow a stronger emission line produced by recombination, marginally consistent with the Piro et al. (1999) and Yoshida et al. (1999) observations. The two other alternatives (i.e. thermal emission and reflection) are more promising and not mutually exclusive. The prevalence of one over the other mechanism depends on the set up of the system: compact regions, possibly corresponding to very young supernova remnants (~1 month), would produce iron line photons by fluorescent reflection, while somewhat more extended regions, corresponding to less young remnants (~1 year), could produce thermal emission. Much weaker line fluxes, but lasting for a longer time, can be produced by more relaxed systems (i.e. supernovae exploded more than one year before the burst).

If the emission line is produced by a thermal plasma, its duration is of the order of the cooling time, since this is likely to be longer than the light crossing time $R/c$. On the other hand, as discussed above, the iron line emission is quite sensitive to the temperature, and can then be quenched if the emitting material is suddenly heated by the incoming fireball or cooled by the afterglow photons. In the first case, the line flux can decrease rapidly, to increase again later on, once the shell has cooled again to the appropriate temperature. This mechanism would allow relatively short lived ($\sim R/c$) lines even in the thermal emission scenario.

With the available information, it is hard to tell which is the case for GRB 970508 and GRB 970828. The first had a 1 keV equivalent width line whose flux apparently disappeared after half a day, in comconiance with the “rebursrtung” phase in the X-ray and optical bands. The second burst had a $\sim$ 3 keV equivalent width line whose flux, instead, appeared in comconiance with a small “rebursrtung” phase. The continuum spectra should be the sum of the power law afterglow emission and a bremsstrahlung spectrum (in the case of thermal emission) or a harder (in the 10–100 keV band) Compton reflection spectrum (in the case of reflection). The short duration of both lines, if real, corresponds to a size $R \lesssim 10^{15}$ cm, implying a Thomson thick remnant and favoring the reflection model.

As it is often the case, to be more conclusive we must await better spectra of other bursts: a key signature for thermal emission would be the detection of a strong iron $K_{\beta}$ blend. In fact, this line cannot be produced by fluorescence given the lower photoelectric yield and is very weak even in a recombination scenario. At lower energies (1–3 keV, rest frame), L–shell iron lines, Mg, Si and S lines should also be visible (see Sarazin 1988). In the reflection scenario, afterglow spectra should show the typical hardening of the spectrum above a few keV, and line duration should be short.

The possible association of GRB with supernovae has been investigated recently in detail by Bloom et al. (1998), Kippen et al. (1998) and Wang & Wheeler (1998), following the expression of GRB 980425, likely associated with the type Ic SN 1998bw. Among these works, only Wang & Wheeler (1998) find evidence for a connection while the other two limit to a few percent the bursts possibly associated with supernovae. In the Supernova scenario, however, the association of supernovae with bursts should suffer a time delay, variable between few days to some years, which would smear the time correlation between the two phenomena.

Should the iron line possibly detected in GRB 970508 and GRB 970828 be real and confirmed by other cases, then we have a strong case for the connection between supernovae and gamma–ray bursts. The next generation of experiments and satellites, such as XMM, AXAF and ASTRO-E, will provide us with the necessary information to draw more accurate conclusion on the puzzling problem of the gamma–ray burst progenitor.

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