On the anomalous X–ray afterglows of GRB 970508 and GRB 970828

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ABSTRACT

Recently, BeppoSAX and ASCA have reported an unusual resurgence of soft X–ray emission during the afterglows of GRB 970508 and GRB 970828, together with marginal evidence for the existence of Fe–lines in both objects. We consider the implications of the existence of a torus of iron–rich material surrounding the sites of gamma ray bursts as would be expected in the SupraNova model; in particular, we show that the fireball will quickly hit this torus, and bring it to a temperature \( \approx 3 \times 10^7 \, ^\circ K \). Bremsstrahlung emission from the heated up torus will cause a resurgence of the soft X–ray emission with all expected characteristics (flux level, duration and spectral hardening with time) identical to those observed during the reburst. Also, thermal emission from the torus will account for the observed iron line flux. These events are also observable, for instance by new missions such as SWIFT, when beaming away from our line sight makes us miss the main burst, as Fast (soft) X–ray Transients, with durations \( \approx 10^3 \, s \), and fluences \( \approx 10^{-7} - 10^{-4} \, erg \, cm^{-2} \). This model provides evidence in favor of the SupraNova model for Gamma Ray Bursts.

Key words: Gamma rays: bursts – supernova remnants – X–rays: general – line: formation.

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1 INTRODUCTION

The discovery of afterglows from gamma ray bursts has greatly strengthened our confidence in the correctness of the fireball model (Rees and Mészáros 1992). Since then, attention has begun to shift toward the nature of the exploding source, a problem which is conveniently decoupled from the fireball itself and the ensuing afterglow. For this reason, evidence about the nature of the source has to be sought elsewhere. In particular, attention has been called to the possible interaction of the burst with surrounding material, and the possible generation of a detectable Fe line in the soft X–rays (Perna and Loeb, 1998, Boettcher et al., 1999, Ghisellini et al., 1999, Mészáros and Rees 1998).

Recently, a reburst, i.e., a resurgence of emission during the afterglow has been reported in two bursts, GRB 970508 (Piro et al., 1998), and GRB 970828 (Yoshida et al., 1999). In the case of GRB 970508, the reburst occurs about $10^5$ s after the burst, with the soft X–ray flux clearly rising, and departing from its otherwise typical power–law decline. This resurgence lasts a total of $\approx 4 \times 10^5$ s, reaches a typical flux in the BeppoSAX band of $\approx 8 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, after subtraction of the normal afterglow, and shows evidence for a harder spectrum than during the afterglow proper (power law photon index of $\alpha = 0.4 \pm 0.6$, as opposed to $\alpha = 1.5 \pm 0.6$ before the reburst, and $\alpha = 2.2 \pm 0.7$ at the end of the reburst), (Piro et al., 1998, 1999).

Furthermore, possible evidence for the existence of Fe K-shell emission lines has been found in these same two bursts: for GRB 970508 see Piro et al., 1999, while for GRB 970828 see Yoshida et al. 1999. In the first case, a $K_\alpha$ iron line occurs at an energy compatible with the burst’s optically determined redshift, while in the second one, for which no independent redshift determination exists, the line, if interpreted as $K_\alpha$ from neutral, or weakly ionized iron, yields a redshift of $z = 0.33$. What is astonishing are the inferred line fluxes and equivalent widths: for GRB 970508, $F = (2.8 \pm 1.1) \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (EW $\approx 1.1 \text{ keV}$), while for GRB 970828 $F = (1.5 \pm 0.8) \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (EW $\approx 3 \text{ keV}$). In the case of GRB 970508, furthermore, no evidence for the Fe-line was found after about $10^5$ s.

Despite their inferred intensities, these lines are at the limit of BeppoSAX and ASCA detectability, so that further observations are needed to confirm their presence. On the contrary the statistical significance of the rebursts is very robust. In the following, we shall concentrate on the especially well documented case of GRB 970508, keeping in mind that qualitatively similar arguments apply to GRB 970828 as well.
It is the aim of this paper to show that, if enough material of sufficiently high density is present in the surroundings of the gamma ray burst event site, then this reburst is exactly what one ought to expect on theoretical grounds. In particular, it is possible to explain all observed characteristics of the reburst, duration/flux level/spectral hardening, including the (possible) presence of the iron lines. In the next section we shall consider the dynamical interaction of the burst’s ejecta with the torus, and in the following one we shall discuss the thermodynamic state of the torus, and establish the properties of its (thermal) emission. In the discussion, it will also be pointed out that the thermodynamic status of the torus is precisely the same postulated by Lazzati et al. (1999) to explain the properties of the iron line.

2 DYNAMICAL INTERACTION WITH SURROUNDING GAS

Both Piro et al. (1999) and Lazzati et al. (1999) have already argued that the material giving rise to the Fe K-line cannot lie on the line of sight: the ensuing column depths, in H and Fe would give effects easy to observe. Furthermore, this material should be present in large amounts which would spoil the smooth, power–law expansion of the afterglow, which is observed to cover more than a year. We thus begin by assuming that the site of the explosion is surrounded by a thick torus of matter, with an empty symmetry axis pointing roughly toward the observer. The particle density $n$ and distance $R$ from the explosion site will be scaled in units of $10^{10} \text{ cm}^{-3}$ and $10^{16} \text{ cm}$.

A time $R/c$ after the explosion, this torus will be inundated by the burst proper, and a few seconds later ($\delta t \approx R/\gamma^2 c = 30 \text{ s}$, where $\gamma = 100$ is the shell bulk Lorenz factor), it will be hit by the ejecta shell. This crash will generate a forward shock propagating into the torus, and a reverse one moving into the relativistic shell. For any reasonable value of the torus density, the forward shock will quickly rake up as much mass as there is in the shell: we find that this occurs after the shock has propagated a mere distance $d$, with

$$d = 6 \times 10^8 \frac{cm}{10^{51} \text{ erg}} \frac{E}{n} \left(10^{10} \text{ cm}^{-3} \right) \left(\frac{10^{16} \text{ cm}}{R}\right)^2 \frac{100}{\gamma}. \quad (1)$$

As is well–known, this means that the relativistic shell must slow down to sub–relativistic speeds. Thus, after just $d/c \approx 0.1 \text{ s}$, the forward shock has become sub–relativistic. The large pressure behind the forward shock acts to steepen the reverse shock, which will thus slow down the incoming material to sub–relativistic speeds as well. All of this occurs a few seconds after the torus sees the burst.
The total energy released is expected to be of order of the whole kinetic energy of the shell, because post–shock acceleration of electrons occurs at the expense of the shell bulk expansion, in the shocks. If we suppose that the burst generated a total energy release of \( E = 10^{51} \text{ erg} \), that the initial burst is roughly isotropic, and that the torus covers \( \delta \Omega \) radians as seen from the explosion site, the total energy release \( E_{sh} \) will be
\[
E_{sh} = \frac{\delta \Omega}{4\pi} E .
\] (2)

The total emission timescale can also be reliably computed: the reader will have already noticed that this emission scenario is similar to the external shock scenario (Mészáros, Laguna and Rees 1993), except for two differences. First, in the external shock scenario we are seeing the burst from a reference frame which is moving with respect to the shell of shocked gas with large Lorenz factor, while here the observer is sitting in a reference frame in which the shocked gas is moving sub–relativistically. The major consequence of this first difference is that the photon emission will be isotropic, and we shall thus see it, even though the initial shell movement was perpendicular to the line of sight. The second difference is that, in the external shock scenario, it is matter ahead of the forward shock which is moving relativistically with respect to the shocked gas, while matter entering the reverse shock is moving only barely relativistically with respect to it. In this paper, instead, the opposite applies: matter entering the reverse shock is relativistic, while the forward shock is barely, if at all, relativistic.

Still, these two differences do not spoil the fact that electrons accelerated at either shock cool much faster than the shell light–crossing time, as shown by Mészáros, Laguna and Rees (1993), so that the total burst duration is given by the time the reverse shock takes to cross the whole shell. In our model, the shell thickness in the laboratory frame is \( \approx R/\gamma \) (Mészáros, Laguna and Rees 1993), and, since the reverse shock is relativistic with respect to the incoming matter, the shock crossing time, and thus also the duration \( t_{sec} \) of the secondary burst, is given by
\[
t_{sec} = \frac{R}{\gamma c} = 3 \times 10^3 \text{ s} \frac{R}{10^{16} \text{ cm}} .
\] (3)

Together, the total energy release and emission timescale give us the expected bolometric luminosity; the observed flux can be computed, for cosmological parameters \( \Omega = 1, H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( \Lambda = 0 \), and knowing the burst’s redshift \( z = 0.835 \) (Metzger et al., 1997), and is

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\[ F_X = 1.5 \times 10^{-10} \text{erg s}^{-1} \text{cm}^{-2} \frac{\Omega}{4\pi} \frac{E}{10^{51} \text{erg}} \frac{10^{16} \text{cm}}{R} \]  

(4)

We must now establish in which band this emission will end up. As is well-known, bursts’ spectra are highly variable, both from burst to burst and within the same burst, at different moments. Also, the fireball model is not too specific about the spectral characteristics of bursts. We can still get an idea of the spectrum, however, by noticing first that the spectrum will be non-thermal, with the usual power law dependence upon photon energy typical of synchrotron emission, and second that once again we are observing a burst in the external shock scenario, but in the shell frame. In normal bursts, the spectrum has a break at an energy \( \epsilon_b \), which is approximately \( \epsilon_b \approx 1 \text{MeV} \). However, this spectral feature is blueshifted in the observer’s frame by the shell’s bulk Lorenz factor: \( \epsilon_b = \gamma \epsilon_i \). The intrinsic spectral break \( \epsilon_i \), i.e. in the shell frame, is thus given by

\[ \epsilon_i = \frac{\epsilon_b}{\gamma} = 10 \text{keV} \frac{\epsilon_b}{1 \text{MeV}} \frac{100}{\gamma} . \]  

(5)

It is clear why this secondary burst was not observed. First of all, it is dimmer than the original one by a bolometric factor of \( \delta \Omega / 4\pi \gamma < 10^{-2} \), which would push it below detection threshold for both BATSE and the GRBM/WFC instruments of BeppoSAX. Also, it must have occurred sometime between the burst proper and the BeppoSAX detection of the iron line, when, however, BeppoSAX was not observing with its (more sensitive) Narrow Field Instruments.

The further evolution of the shocked shell is as follows. The material that passed through the reverse shock will have an internal energy density higher than the pre-shock one by a factor \( \Gamma^2 \), where \( \Gamma \approx \gamma \) is the Lorenz factor of the reverse shock, as seen by the pre-shocked ejecta shell. For reasonable radiative efficiencies, the post-shocked matter will have a relativistic velocity dispersion even after the secondary burst; then, a rarefaction wave will make it expand at the sound speed \( \approx c/\sqrt{3} \) back into the cavity from which it came. Thus pressure behind the forward shock will be reduced on a time-scale \( \approx \delta R/c \), where we can again take for the post-reverse shock shell thickness, as an order of magnitude, \( \delta R \approx R/\gamma \). Thus the heated gas expansion time-scale is again \( \approx R/\gamma c \approx 3 \times 10^3 \text{ s} \).

As the pressure from the post-reverse shock material is reduced, the forward shock keeps propagating because of momentum conservation. However, even this shock cannot last long, because of the strong counterpressure applied by the pre-shock torus. We shall show in the next section that this material will be brought up to \( T_f \approx 10^8 \text{ °K} \) by heating/cooling
from the primary and secondary bursts. Then it can easily be checked that $\rho_s c^2 \approx m_p n v^2$, where $\rho_s$, the shell baryon density, is given by spreading the total fireball baryon mass, $E/\gamma c^2$, over the shell volume, $4\pi R^3/\gamma$, and the torus’ velocity dispersion $v$ is purely thermal: $v^2 = k T_f/m_p$. Thus the torus counterpressure will halt the forward shock as soon as it becomes subrelativistic.

We now make a small detour to discuss an interesting point about the kinematics. As seen from the observer, the part of the shell moving toward him will have moved a long distance ($\approx R$, taking the torus to be perpendicular to the line of sight) toward him before the torus is reached by the burst, and thus starts emitting. At that point, photons start travelling away from the torus, and they will catch up with the part of the expanding matter shell moving toward the observer at a rate

$$\delta R = (c - v) \delta t$$

(6)

where $v \approx c(1 - 1/2\gamma^2)$ is the matter speed. However, the time appearing in the above equation is the time in the reference frame of the exploding object, which is related to that of the observer, $t_o$, by $\delta t_o = \delta t (1 - v/c)$, and thus, the distance by which the photon catches up with the matter shell, in an observer’s time interval $\delta t_o$ is

$$\delta R = c \delta t_o$$

(7)

which is identical to the expression when relativistic effects are not present. This immediately allows us to estimate the distance of the torus: in fact, since the reburst was present in the observations made $\approx 10^5$ s after the burst, and this can only occur after the bursts’ photons have reached the torus, we deduce that $R(1 - \cos \theta) < 3 \times 10^{15} cm$, where $R$ is the torus distance from the line of sight, and $\theta$ is the angle away from the line sight of the torus symmetry plane. For the total distance, we shall take $R \approx 10^{16} cm$.

3 THERMAL HISTORY OF THE TORUS

In order to proceed, we need first to determine the torus thickness, which we do by using a constraint from the observations of the iron line. When the torus is reached by the burst proper, the ionization parameter is

$$\xi = \frac{L}{n R^2} = \frac{10^9 L}{10^{51} \text{ erg s}^{-1}} \frac{10^{10} \text{ cm}^{-3}}{n} \left( \frac{10^{16} \text{ cm}}{R} \right)^2$$

(8)

For these large values, we expect that all iron will be completely ionized, so that the generation of the iron line by fluorescence is unlikely. Furthermore, the torus will be hit by the
secondary burst only $R/\gamma^2 c \approx 30\, s$ later: thus fluorescence with afterglow photons cannot be invoked either. The remaining mechanisms, multiple recombination/ionizations and thermal processes, both require the torus Thomson optical depth $\tau_T \approx 1$ for maximum efficiency, and to avoid line smearing (fluorescence, instead, requires $\tau_T \gg 1$). In such a thin shell, the torus temperature is quickly brought up by the primary burst photons to a temperature close to its Inverse Compton value, given by $4kT_{IC} = \bar{\epsilon}$, with $\bar{\epsilon}$ the average burst photon energy. Taking this to be of order the break photon energy $\epsilon_b \approx 1\, MeV$, we find $T \approx \frac{\epsilon_b}{4k} \approx 3 \times 10^9\, \circ K$. However, at this temperature, pair creation will quickly give $\tau_T \gg 1$, and the ensuing thermal cooling will badly limit the temperature, to a value close to the pair creation limit,

$$T_{IC} \approx 5 \times 10^8\, \circ K.$$  \hfill (9)

At such large temperatures, the bremsstrahlung cooling time–scale is quite long $t_{br} \approx 5 \times 10^5\, s (10^{10}\, cm^{-3}/n) (T/5 \times 10^8\, \circ K)^{1/2}$. However, the torus may cool due to Inverse Compton cooling off the photons produced by the crashing of the ejecta onto the torus, which have a typical photon energy $\epsilon_i$ (Eq. 5) much below the torus temperature. For ease of reference, we shall call these secondary photons. The Inverse Compton cooling time–scale $t_{IC} = 3m_e c^2 / 8c \sigma_T U_{ph}$ (where $m_e$ is the electron’s mass, and $\sigma_T$ the Thomson cross–section), can be computed using the fact that the photon energy density $U_{ph} = L/cA$, where $L$, the secondary photons’ luminosity, was given above as $L = E\Omega/4\pi t_{sec}$, and the total area is roughly twice the shock area, $A \approx 2R^2\Omega$. We find thus $U_{ph} = E\gamma/8\pi R^3$, independent of the solid angle subtended by the torus. The ratio of the Inverse Compton cooling time to the duration of the secondary burst is then given by

$$\frac{t_{IC}}{t_{sec}} = \frac{3\pi m_e c^2 R^2}{\sigma_T E} = 1.3 \left( \frac{R}{10^{16}\, cm} \right)^2 \frac{10^{51}\, erg}{E}. \hfill (10)$$

We see that this ratio is very sensitive to the torus location, and to the total energetics. For $t_{IC} \geq t_{sec}$, the torus matter will remain hot (Eq. 9), while for $t_{IC} < t_{sec}$, its temperature will cool to the new Inverse Compton temperature of the secondary photon bath:

$$T_{IC}^{(2)} \approx \frac{\epsilon_i}{4k} \approx 3 \times 10^7\, \circ K.$$ \hfill (11)

For the parameters assumed here, $t_{IC} \approx t_{sec}$, so that the torus will probably settle to a value intermediate between $T_{IC}^{(2)}$ and $T_{IC}$. We scale the value of $T$ to $T_f = 10^8\, \circ K$, but see the next section for a discussion.
The bremsstrahlung cooling time, at this lower temperature, is given by \( t_{br} \approx 1.3 \times 10^5 \text{s} (10^{10} \text{cm}^{-3}/n) \), comparable to the total duration of the reburst observed by Piro et al., 1998. Also, the expected flux level is

\[
F_{br} = 1.1 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \left( \frac{M}{1M_{\odot}} \right)^2 \frac{10^{46} \text{cm}^3}{V} \left( \frac{T}{10^8 \text{K}} \right)^{1/2},
\]

(12)

provided the torus cooling time is longer than the torus light crossing time, \( t_{lc} \approx R/c \). Otherwise, the observed flux \( F_{br}^{(obs)} \) would be related to the previous formula by

\[
F_{br}^{(obs)} = F_{br} \times \frac{t_{br}}{t_{lc}}
\]

(13)

Furthermore, when, initially, the temperature is rather large, \( \approx 10^8 \text{K} \), the spectral slope between the BeppoSAX’ Low and Medium Energy concentrator optics/spectrometers should be rather flat, while later, as the torus cools and its flux decreases, the spectral slope should also increase. Piro et al. (1999) find that, at the point where the reburst is (fractionally) highest over the smooth afterglow, \( \alpha = 0.4 \pm 0.6 \) (i.e., consistent with a flat bremsstrahlung spectrum), while later they find \( \alpha = 2.2 \pm 0.7 \). Though there are large errors, the steepening of the spectrum through the reburst appears to be significant. In view of the agreement of the duration timescale, flux level, and steepening of spectral slope, we suggest that the observed reburst in GRB 970508 is thus bremsstrahlung radiation from a torus of hot material, heated up, and then cooled down, by the photons produced by the impact of the burst ejecta.

We now need to cover our tracks by determining whether there are values of the total torus mass and volume which satisfy, together with \( F_{br}^{(obs)} = 1 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \), also \( \tau_T \approx 1 \), \( n \approx 10^{10} \text{cm}^{-3} \) which we assumed throughout. We assume a geometry whereby the torus has a volume \( V = \delta \Omega R^2 \delta R \), with the torus thickness \( \delta R \leq R \), the torus distance from the explosion site. Since \( \tau_T = 0.6(\text{M}/1M_{\odot})(10^{16} \text{cm}/R)^24\pi/\delta \Omega \), we see that for \( M = 5M_{\odot} \), \( R = 10^{16} \text{cm} \), \( V = 10^{47} \text{cm}^3 \), \( \delta R = 10^{14} \text{cm} \) and \( \delta \Omega \approx 4\pi \), we satisfy all constraints simultaneously: \( \tau_T \approx 2 \) and \( n = 4 \times 10^{10} \text{cm}^{-3} \). From this we see that the torus need not be thin (\( \delta \Omega \approx 4\pi \)), which certainly agrees with expectations about the nature of exploding sources. Also, we notice that \( t_{br}/t_{lc} \approx 4 \), so that the duration of the bremsstrahlung cooling radiation is diluted by light crossing time effects.

Thermal expansion of the shell during the cooling phase is negligible, since the cooling time is of order of the light crossing time, which is certainly shorter than the sound crossing time.
It is well-known that GRB 970508 had an early optical detection, $\approx 0.2^d$ after the burst, which was dimmer than later ($>1^d$) detections (Sahu et al., 1998). Typical fluxes throughout the first 2 days are around $30 \mu Jy$, which far exceed the optical component of the bremsstrahlung emission from the torus, which is in the range of $\approx 0.03 \mu Jy$. Thus the observed nearly simultaneous rise of X-ray and optical fluxes remains, within this model, a coincidence.

4 DISCUSSION

Beyond explaining the observed X-ray reburst (and the Fe line, see below), the current model makes a number of interesting predictions. First, the secondary burst may be observable. We may expect these events to last a few thousand seconds, with fluxes in the range of $10^{-11}$ to $10^{-10} erg s^{-1} cm^{-2}$. The spectra of these sources are also interesting: we argued above that the torus temperature is limited by pair-creation, which would otherwise cause excessive radiative losses; thus we may expect the torus to reach a limiting temperature such that $\tau T \approx 1$, and a temperature $5 \times 10^8 \circ K$, which correspond to a Compton parameter $y \approx 0.5$. We thus expect significant departures from the usual, power-law like spectra of bursts. In particular, from sources which do not have time to cool down to $T_f$ (Eq. [10]), so that the Comptonization of the secondary burst spectrum is time-independent, we expect to see a cutoff $\propto \exp(-h\nu/kT)$ beyond $h\nu = kT \approx 50 keV$, with a complicated, time-dependent non-power-law behavior below this point (Rybicki and Lightman 1979). This exponential cutoff can be used as signature of unsaturated Comptonization, typical of the present model.

Another interesting consequence of this model is that the secondary burst may be seen even without its being preceded by the main gamma ray burst. This would occur whenever we would missed the (beamed) emission from the burst proper, but would see the isotropic emission from the reburst. This might occur because in many models, the beaming of the main burst is expected to be rather smooth, and one may conjecture that, while the total output may be $\approx 10^{52} erg$ close to the major axis, a total of $10^{51} erg$ remains to be emitted nearly isotropically. This would amply satisfy the energy requirements of the reburst. The total expected fluences (up to $\approx 10^{-4} erg cm^{-2}$ for distances smaller than GRB 970508’s)) and durations ($\approx 10^3 s$) strongly remind one of the so-called Fast X-ray Transients, many of which last through several satellite orbits and have no identified counterparts (Grindlay

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A bevvy of these events should become observable with planned new telescopes such as SWIFT.

An interesting question one may ask is why the observation of the rebursts is so rare: up to now, GRB 970508 and GRB 970828 are the only two bursts for which such phenomenon has been observed. So long as the torus is optically thin to bremsstrahlung, we see from Eq. 12 that the expected flux scales with distance from the explosion site as $R^{-q}$, where $q = 2 - 3$. Since we ignore the torus thickness, we consider the two limiting cases: $q = 3$, uniformly filled sphere, and $q = 2$, infinitely thin shell. This flux will appear with a time–delay $R/c$ with respect to the burst, simultaneously with an afterglow which scales as $t^{-p}$, with $p \approx 1.3$. We see that the torus to afterglow flux ratio scales as $t^{p-q}$, with $p-q = -(0.7 - 1.7) < 0$. Thus, the more distant the torus is, the easier it is to detect it. However, since we supposed that $\tau_T \approx 1$ for $R \approx 10^{16} cm$, further shrinking of the torus will make it less bright, not more; but it will have to compete with a simultaneously emitted afterglow which is brighter and brighter. So $R = 10^{16} cm$ is an ideal distance at which the torus could be located.

For the same parameters as above, Lazzati et al. (1999) have shown that the iron line can be interpreted as due to purely thermal processes. Actually, Lazzati et al. showed that also fluorescence and multiple ionization/recombinations can account for the line, given suitable (but different!) thermodynamic conditions for the emitting plasma. However, we showed in this paper that the thermodynamic conditions of the emitting torus are not free, but are essentially fixed by the requirement that the reburst be fitted. We wish to stress that this is a much more demanding requirement, since the reality of the reburst cannot be doubted, while that of the iron line is more questionable. It is however satisfying that the thermodynamic parameters thusly determined ($T = 10^8 ^\circ K$, $n = 4 \times 10^{10} cm^{-3}$) are precisely those that Lazzati et al. (1999) had to assume, in order to fit the line.

As a corollary, one may then understand why it is difficult to observe the iron lines. Lazzati et al. (1999) have derived the luminosity of the line as a function of the torus temperature: $\propto \exp(-8 \times 10^7 \ ^\circ K/T)T^{-2.4}$. This luminosity has a peak for $T = T_m = 3 \times 10^7 ^\circ K$, and decreases steeply with increasing $T$. We see that $T^{(2)}_{IC} \approx T_m$, while $T_{IC} \gg T_m$. Thus, it is only when the torus manages to cool down, that it will find itself in ideal conditions for producing a bright iron line; we see from Eq. 10 that this occurs only for material that lies close to the explosion site. Otherwise, the torus material will remain into a hot state in which the line equivalent width is very small: $\approx 20 eV$ at $T = T_{IC}$ (Bahcall and Sarazin 1978). We also remark that, even in the case in which the torus has managed to cool down to...
After a time $t_{br}$, it will further cool below $T_m$, and the line flux will promptly decrease, thereby explaining the disappearance of the iron line in the observations of GRB 970508 (Piro et al., 1999).

Should the torus be located at larger radii, then we would expect that the material be hotter (from Eq. [10]), and that the Fe–line should not be observable, from the argument above. We thus expect inverse correlations of the time–delay with which the reburst appears with the luminosity, and with the Fe–line equivalent width.

An alternative model for the anomalous behaviour of GRB 970508 has been proposed (Panaitescu, Mészáros and Rees 1998). In their model there is no external material to cause a resurgence of the X–ray flux, and the peculiarities in the time–evolution of the optical afterglow are explained as a consequence of beaming. However, the anomalous variations in the X–ray flux can hardly be followed (see especially their Fig. 2), and certainly there is no allowance for either the observed spectral variations of the X–ray flux during the first two days, nor for the existence of an iron line.

Lastly, we would like to comment on the fact that we require a dense, and abundant amount of iron–rich (for a redshift of $z = 0.835$!) material, at close distance from the explosion site: $5M_\odot$ at $R = 10^{16}$ cm. This is clearly incompatible with all existing models of GRBs, neutron star–neutron star/neutron star–black hole/ black hole–white dwarf mergers, and hypernovae, except for SupraNovae (Vietri and Stella 1998), which are preceded by a SuperNova explosion occurring between 1 month and 10 years before the GRB. With an average expansion speed of 3000 $km$ $s^{-1}$, this implies an accumulated distance of $R = 10^{15}–17$ cm. At this distance, one should find several solar masses (McCray 1993) with densities of order $10^{10}$ cm$^{-3}$, exactly as required by this independent set of observations.

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