A NEW MODEL FOR IRON EMISSION LINES AND RE-BURST IN GRB X-RAY AFTERGLOWS

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ABSTRACT

Recently iron emission features have been observed in several X-ray afterglows of GRBs. It is found that the energy obtained from the illuminating continuum which produces the emission lines is much higher than that of the main burst. The observation of SN-GRB association indicates a fallback disk should be formed after the supernovae explosion. The disk is optically thick and advection-dominated and dense. We suggest that the delayed injection energy after the initial main burst, much higher than energy of the main burst, causes the re-burst appearance in GRB afterglow and illuminates the region of the disk surface with \( \tau \approx 1 \) (\( \tau \) is the optical depth for the Thomson scatter) and produces the iron emission line whose luminosity can be up to \( 10^{45} \) ergs\(^{-1}\). The duration of the iron line emission can be \( 10^4 - 10^5 \) s. This model can explain the appearance of re-burst and emission lines in GRB afterglow and disappearance of the iron emission lines, and also can naturally solve the problem of higher energy of the illuminating continuum than that of the main burst. This scenario is different from the models put forward to explain the emission lines before, that can be tested by SWIFT satellite.

Subject headings: gamma rays:bursts-line:profiles-accretions disks-supernovae:general

1. Introduction

Recently evidence is mounting that ‘long duration’ GRBs are associated with a rare type of supernovae event such as a ‘failed supernova’, ‘Hypernova’ or ‘Collapsar’ (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; MacFadyen, Woosley and Herger 2001; Proga et al. 2003). In this model, the time between the supernovae explosion and the GRB is very short, nearly simultaneous. Another model called ‘Supranova model’ was proposed by Vietri & Stella (1998), in which the supernova (SN) explosion initially results in the formation of a comparatively massive, magnetized neutron star endowed with rapid rotation. This supramassive neutron star is envisioned to
gradually lose rotational support through a pulsar-type wind until it eventually becomes unstable to gravitational collapse, leading to the formation of a BH and the triggering of a GRB. In 'Supranova model', the time between the supernovae explosion and the GRB can range from several weeks to several years.

After the supernovae explosion, the fallback material will form a disk around the newly central black hole in either 'collapsar model' or 'supranova model', and this disk is advection-dominant and hot and dense even after the GRBs (e.g. Chevalier 1989; Mineshige et al. 1997).

X-ray emission lines observed in X-ray afterglow of GRBs provide important clues for identifying the nature of the progenitors of long (t \( \geq \) 2 s) GRBs. The first marginal detection of an emission line was in the X-ray afterglow of GRB 970508 with the BeppoSAX NFI (Piro et al. 1999). Later emission lines were also detected in the X-ray afterglows of GRB 970828 (Yoshida et al. 2001) with ASCA; GRB 991216 (Piro et al. 2000) and GRB020813 (Butler et al. 2003) with Chandra; GRB 011211 (Reeves et al. 2002), GRB 001025A (Watson et al. 2002) and GRB 030227 (Watson et al. 2003) with XMM-Newton; GRB 000214 (Antonelli et al. 2000) with BeppoSAX. The detailed properties of the X-ray emission features can be found in several papers (Lazzati 2002; Böttcher 2003; Gao & Wei 2004). The energy of the emission line found in the X-ray afterglows of GRB 970508, GRB 970828, GRB 991216 and GRB 000214 is roughly consistent with Fe K\(_\alpha\) at the redshift of the hosts. It is adduced as evidence that the environment of the burst is heavily enriched in iron as the result of a recent supernova explosions (e.g. Lazzati et al. 1999; Ghisellini et al. 1999). We would have observed Fe line if the time delay is more than several months such as models of Supranova (Vietri & Stella 1998).

The standard model for gamma-ray burst afterglows assumes that relativistic material is decelerating on account of interaction with the surrounding medium, with a nearly impulsive injection energy. But perhaps the ejecta consists of many concentric shells moving at different speeds, slow moving material carries most of the system’s energy. The delayed injection energy can be more than that of the main burst. It is proposed to be refreshed shock scenario. In the refreshed shock scenario, assuming the source ejects a range of Lorentz factors with the mass \( M(\gamma) \propto \gamma^{-3} \) (Rees & Mészáros 1998; Sari & Mészáros 2000).

The re-burst phenomena have been found in the afterglow of GRB970508 (Piro et al. 1998) and GRB970828 (Yoshida et al. 1999). It has been considered that energy of delayed injection with more than that of the initial burst caused the re-burst appearance (Panaitescu et al. 1998; Kumar & Piran 2000; Sari & Mészáros 2000).

The energy contained in the illuminating continuum that is responsible for the line production is much higher than that of the collimated GRBs (Lazzati 2002; Ghisellini et al. 2002; Gao & Wei 2004). In this letter we consider the illuminating continuum which produces the emission line...
comes from the delayed injection energy, which illuminates the fallback disk and produces the emission lines.

2. Delayed energy injection and Fe emission line feature in X-ray afterglow

The re-burst of emission during the afterglow has been reported in two GRBs, GRB970508 (Piro et al. 1998) and GRB970828 (Yoshida et al. 1999). At the same time possible evidence for the existence of Fe \(K\alpha\) line has also been found in these two GRBs (GRB970508, Piro et al. 1999; GRB970828, Yoshida et al. 1999). Delayed energy injection (or refreshed shock model) can well explained the resurgence emission in these two GRBs (Panaitescu et al. 1998; Kumar & Piran 2000). The delayed injection energy more than the initial fireball energy can produce the observed re-burst in the afterglow about 0.5 day after \(\gamma\)-ray burst. Here we model that the delayed injection energy illuminates the fallback disk around the central black hole and photonionizes the layer of the disk with \(\tau\) = 1, and iron line emission can be produced by the recombination process.

Considering an engine that emits both an initial impulsive energy input as well as a continuous luminosity, the latter varying as a power law in the emission time. The differential energy conservation relation in the observer’s frame can be expressed as (Cohen & Piran 1999; Zhang & Mészáros 2001)

$$\frac{dE}{dt_\odot} = L_0(t_\odot/t_0)^q - k(E/t_\odot), t_\odot > t_0. \quad (1)$$

The first term on the right side is \(L = L_0(t_\odot/t_0)^q\) which is the intrinsic luminosity of refresh shock, \(t_0\) is a characteristic timescale for the formation of a self-similar solution, \(E\) and \(t_\odot\) denote the energy and time measured in the observer frame, \(q\) and \(k\) are dimensionless constants.

In the refreshed shock scenario, following Rees & Mészáros (1998), Kumar & Piran (2000), Sari & Mészáros (2000), one can obtain the relationship between the temporal index \(\alpha\) and the spectral index \(\beta\), where \(F_\nu \propto t_\odot^{\alpha} \nu^{\beta}\). For the X-ray afterglow, considering the forward shock in the slow-cooling regime (Sari, Piran, & Narayan 1998), \(\alpha = (1-q/2)\beta + 1 + q\) (Zhang & Mészáros, 2001). Since no spectral information was available for GRB970508 in the first several days of the afterglow, in the calculation of Panaitescu et al. (1998), \(s = 1.5\) is needed. For the forward shock in the slow-cooling regime in the refreshed model, \(\alpha = \frac{6-6\beta-24\beta}{2(7+\beta)}\) (Sari & Mészáros 2000, for the uniform medium environment). So \(\beta = (17\alpha - 3)/24\). In the X-ray afterglow observations of GRB970508, the temporal index \(\alpha\) changes from -1.1 (before the re-burst) to +1.7 (at the beginning of the re-burst) to -0.4 (during the re-burst) and then to -2.2 (after the re-burst) (Piro et al. 1999).

From above in the refreshed shock scenario one can obtain the delayed energy injection as \(L \propto t_\odot^{q}\), \(q \sim -0.8\), which ends after about \(10^5\) s. We assume the delayed energy is isotropic, that is reasonable from the observations. On the observational side, Pedersen et al. (1998) have found
the optical light curve of GRB970508 afterglow can be explained in terms of an isotropic outflow. The radio observation of GRB991216 afterglow also showed there was an isotropically energetic fireball\(10^{54}\text{erg}\)(Frail et al. 2000). From the numerical work of Panaitescu et al.(1998), the injection energy injects into the GRB outflow up to be \(E_{\text{inj}} = 3E_0\) into the external medium, whose solid angle is \(\Omega_\gamma\), \(\Omega_\gamma\) is the solid angle of the GRB collimated jet. We name this energy as Injection Energy, that is only a fraction of the whole delayed energy. The whole delayed energy is about \(E_{\text{del}} = \frac{4\pi}{\Omega_\gamma} E_{\text{inj}}\). Luminosity varies as about \(t^{-0.8}\). At the beginning of the re-burst, \(t_i \sim 6 \times 10^4\) s, the Injection Energy has been as much as that of the initial burst \(E_0 \sim 4 \times 10^{50}\text{ergs}\)(Bloom et al. 2003). After that time, the residual Injection Energy \(2E_0\) has been exhausted in about \(10^5\) s(Piro et al. 1999).

\[
E = \int_{t_i}^{t_e} L_i \left(\frac{L}{L_i}\right)^{-0.8} dt
\]

\(t_i\) means the time at which the re-burst appears, \(t_e\) means the time when the re-burst ends, \(L_i\) is the luminosity at the time of re-burst emergence, \(E\) means the energy injecting into the external medium. After the emergence of the re-burst, the residual Injection Energy is about \(2E_0\), and time duration is about \(10^5\) s, we can obtain that \(L_i \sim 10^{46}\text{ergs}^{-1}\). From \(L \propto t^{-0.8}\) and about energy of \(E_0\) has been exhausted before the re-burst, we can get \(L \sim 10^{47}\text{ergs}^{-1}\), at \(t \sim 3 \times 10^3\) s.

An advection-dominant disk can exist around a stellar black hole even after the \(\gamma\)-ray bursts(Kohri & Mineshige 2002; Janiuk et al 2004)(Fig.1). For the ’collapsar model’, SN explodes at almost same time with the GRBs, or about a minute to few hours prior to the \(\gamma\)-ray bursts. Whereas for ’supranova model’, the time delay between the SN explosion and GRB is perhaps several months or even longer. In this case almost all the fallback nickel has been decayed to iron.

The evolution of fallback disk around the black hole has been considered by, eg., Meyer & Meyer-Hofmeister(1989), Cannizzo et al.(1990), Mineshige et al.(1993), and Mineshige et al.(1997). From the work of Mineshige et al. (1997),we can draw the accretion rate of the disk result from the fallback material. Since the radioactivity time scale is about 85 days for nickel decaying to iron, here we adopt ’Supranova model’(Vietri & Stella 1998), and assume \(\gamma\)-ray bursts take place about 100 days after the SN explosion.

\[
\dot{M} \sim 10^{25}\text{gs}^{-1}\left(\frac{M_{BH}}{3M_\odot}\right)\left(\frac{\Delta M}{0.1M_\odot}\right)\left(\frac{\alpha}{0.01}\right)\left(\frac{t}{100\text{day}}\right)^{-1.35}
\]

where \(\Delta M\) is the amount of fallback material of the disk and \(\alpha\) is the viscosity parameter.We adopt that the mass of the black hole to be \(3 M_\odot\). \(\Delta M\) has a large range for the different mechanism of the SN explosion and the evolution of the disk (eg. Woosley 1993; Chevalier 1989). Here we adopt \(\Delta M\) to be \(0.1 M_\odot\).

While about one hundred days after the SN explosion, the accretion rate would be decreasing to about \(10^{-8}M_\odot\text{s}^{-1}\). At this time the radiation pressure is dominant in the disk (eg. Mineshige et
al.1997). The relations of $T \Sigma$ and $\dot{M} \Sigma$ are as following (Kohri & Mineshige 2002):

$$T = 4.87 \times 10^1 \alpha^0 \Sigma^{\frac{1}{2}} r^{-\frac{1}{2}} M_{BH}^\frac{1}{2}$$  \hspace{1cm} (4)

$$\Sigma = 3.3 \times 10^3 \dot{M} \alpha^{-1} r^{-\frac{1}{2}} M_{BH}^\frac{1}{2}$$  \hspace{1cm} (5)

The total mass of the disk is

$$\Delta M = \int_{R_{in}}^{R_o} 2\pi R \Sigma dR$$  \hspace{1cm} (6)

$R_{in}$ and $R_o$ represent the innermost radius and the outermost radius respectively. From eq.(3), eq.(5) and eq.(6), adopting $\Delta M=0.1 M_\odot$, we can obtain the radius of the outermost disk, $R_o \sim 2 \times 10^{12}$cm.

So we can get the results about surface density $\Sigma$ and temperature $T$ at the outermost radius:

$$\Sigma = 4.5 \times 10^7 g cm^{-2}(\frac{\dot{M}}{10^{25} g s^{-1}})(\frac{\alpha}{0.01})^{-1}$$  \hspace{1cm} (7)

$$\times (\frac{r}{10^6 r_s})^{-\frac{1}{2}} (\frac{M_{BH}}{3M_\odot})^{\frac{1}{2}}$$

and

$$T = 2 \times 10^6 K(\frac{r}{10^6 r_s})^{\frac{1}{2}} (\frac{M_{BH}}{3M_\odot})^{\frac{1}{2}}$$  \hspace{1cm} (8)

Then the average density of the disk at this time at the outermost radius $r=10^6 r_s$ is:

$$\rho = \frac{\Sigma}{2H} = 7.2 \times 10^{-5} g cm^{-3}(\frac{\Sigma}{4.5 \times 10^7 g cm^{-2}})^2$$  \hspace{1cm} (9)

$$\times (\frac{T}{2 \times 10^6 K})^{-\frac{1}{4}} (\frac{r}{10^6 r_s})^{-3} (\frac{M}{3M_\odot})$$

At the outermost radius which is about $r=10^6 r_s=8.85 \times 10^{11}$cm, temperature $T$ is about $2 \times 10^6$K and the number density $n$ is about $4 \times 10^{19} cm^{-3}$ in the disk.

The ionization parameter is $\xi = \frac{\dot{\omega}_i}{nR_s^2} = 2.5 \times 10^3 (\frac{\dot{\omega}_i}{10^{10} ergs^{-1}}) (\frac{n}{4 \times 10^{19}})^{-1} (\frac{R}{10^{12} cm})^{-2}$. At this ionization parameter, iron emission is very efficient(Lazzati et al. 2002). The recombination time for hydrogenic iron in the outer disk photoionized by the nonthermal delayed energy is(Lazzati et al. 1999)

$$t_{rec} = 1.5 \times 10^{-8} T^{\frac{1}{2}} n_{17}^{-1} s$$  \hspace{1cm} (10)
The temperature parametrization used here is consistent with the range expected from photoionization equilibrium (Lazzati et al. 1999).

The optical depth at outer radius \( r = 10^{12} \) cm is optically thick: \( \tau_T = 2n_H\sigma_T \sim 10^7 \). So the number of Fe nuclei in the layer of the disk with \( \tau = 1 \) is

\[
N_{Fe} \sim \chi_{Fe}M/(\tau_T 56m_p) \sim 10^{47} \chi_{Fe}.
\]

(\( \chi_{Fe} \) is the iron mass fraction of the disk). The Fe line luminosity is

\[
L_{Fe} \sim \chi_{Fe} 10^{47}(1+z)^{-1} \text{ergs}^{-1}
\]

(11)

For SN1987A, \( \chi_{Fe} \) can be about 2% when all the nickel have decayed to iron (Chevalier 1989). So the luminosity of iron line can be obtained: \( L_{Fe} \sim 2 \times 10^{45}(1+z)^{-1} \text{ergs}^{-1}. \)

After the emergence of the re-burst, luminosity decays from about \( 10^{46} \) ergs\(^{-1} \) at the rate of \( t^{-0.8} \). So the luminosity of the iron line should decrease and disappear during the re-burst, consistent with the observations of iron line (Piro et al. 1999).

It is noticed that we assume the delayed energy is almost isotropic. The energy obtained by the disk is

\[
E_{disk} = \frac{\Omega_d}{4\pi}E_{del}, \quad \Omega_d \text{ is the solid angle subtended by the fallback disk as observed at the location of central engine.}
\]

For the advection disk, \( H/R \approx 0.77 \) (Narayan et al. 2001). We can get \( E_d \approx 0.37E_{del} \). For GRB970508, the open half angle of the GRB collimated jet is 16.7° (Frail et al. 2001). So the energy obtained by the disk is \( E_d \sim 60E_0 \). Even if only 10% fraction of the energy was reflected by the disk (e.g. Zycki et al. 1994), It is about 3\( E_0 \) reflected by one surface of the disk, that is sufficient for the line emission production.

### 3. Discussion and Conclusions

It is found that the energy contained in the illuminating continuum which is responsible for the line production is much higher than that of the collimated main GRBs. Here we model that the energy obtained from the delayed injection energy, higher than that of the collimated \( \gamma \)-ray bursts, illuminates the fallback disk which is formed after the supernovae explosion, photoionizes the disk region of \( \tau = 1 \), then produces the observed iron line feature.

**In our model the delayed energy comes from the central engine, which can be the magnetic energy from the declining magnetic field of the superpulsar (Rees & Mészáros 2000) or the magnetic dipole radiation of the magnetar (Dai & Lu 1998). It could be primarily in a magnetically driven relativistic wind (which would be super-Eddington). The magnetized wind would develop a shock before encountering the disk. The nonthermal electrons would be accelerated behind the shock in the outflow material. The shock-accelerated electrons could cool promptly, and would yield a power-law X-ray continuum. It is similar to what**
has been proposed by Rees and Mészáros (2000). This X-ray continuum illuminates the fallback disk and produces the iron line. The surface of the disk can be accelerated outward by this super-Eddington flux of the illuminating continuum (e.g. Vietri et al. 2001), so usually an outward velocity can be seen in the lines (e.g. Reeves et al. 2002). In our model, the delayed energy emission and the GRBs could come from different physical processes. The delayed energy could be from magnetic wind of the magnetar, so the energy emission is almost isotropic. However, from the observation of the GRBs, the GRB prompt emission should be intrinsically collimated. So there should exist a transition from a collimated to an uncollimated energy release in the engine.

The Injection Energy must be higher than that of the initial main burst so that the effect can be observed in the GRB afterglows (Cohen & Piran 1999; Zhang & Mészáros 2001). For GRB970508, at $t \sim 3 \times 10^3$s after the GRB, the delayed illuminating continuum decays to be $10^{47}\text{ergs}^{-1}$, and the ionized iron ion recombines, Fe line appears and the line luminosity is about $10^{44} - 10^{45}\text{ergs}^{-1}$. At the time $t \sim 6 \times 10^4$s, the re-burst emerges. And after that time, the luminosity of the delayed illuminating continuum decays to be less than $10^{46}\text{ergs}^{-1}$, the iron line would decrease and disappear. The duration of the Fe line $t_d \sim 10^4 - 10^5$s, longer than the cooling time of thermal disk $t_{\text{cool}} \sim 10^{-4}n_{10}^{-1}$s. All above are consistent with the observations of the Fe line in GRB970508 X-ray afterglow.

The re-burst phenomenon has not been observed in GRB991216 afterglow. It can be explained that the Injection Energy is as much as or less than that of the main burst, or the re-burst was missed in the observation though it had happened. In the former case, the line duration should be $10^4$s or less, consistent with what has been observed, adopting the energy of the main burst $E \sim 10^{51}\text{ergs}$ (Bloom et al. 2003).

Above scenario is based on the supernova model in which the time delay between the SN explosion and the $\gamma$-ray bursts can be several months or even longer. Our model supports the ‘supernova model’ because it must have enough time to let nickel decay to iron (about $10^{-3}M_\odot$ Fe in the disk). In our model we assume the time between the SN explosion and the GRB is about 100 days, so the fallback disk that we consider has evolved for about 100 days after the SN explosion. In this case, the lines and the SN bump can not be seen in the same events.

In our model, the disk was in place before the GRB occurred, so it may produce a high level of pre-GRB activity of the source.

Different values of the ionization parameter, $\xi$, could produce the different reflection spectra. When $\xi \sim 10^2$, the spectra will show luminous lines from light metals and a depressed $K_\alpha$ iron line; while $10^3 < \xi < 10^5$, a luminous iron line will be observed in the spec-
tra (Lazzati et al. 2002). In our model the fallback disk with different properties, such as different of number density of the electrons in the disk surface and the outermost radius, will have different ionization parameter. In this paper, $\xi \sim 2.5 \times 10^3$, so luminous $K_\alpha$ iron line can be observed in the spectra.

Vietri et al. (1999) has suggested a thermal model that a relativistic fireball associated with the GRB might hit the pre-GRB supernova remnant within $\sim 10^3$ s and heat the ejecta to $T \sim 10^7 - 10^8$ K. At such temperature the plasma emission shows thermal bremsstrahlung emission as well as iron line emission. In their model the thermal bremsstrahlung and recombination continuum from the thermal disk can account for the re-burst observed in GRB970508 and GRB970828. While in our model, the delayed injection energy from the central engine after the main burst, more than the energy of the main burst accounts for the re-burst and produces the iron line emission.

Our model is also different from the decaying magnetar model in which Rees & Mészáros (2000) suggested that iron line could be attributed to the interaction of a continuing but decaying post-burst relativistic outflow from the central engine with the progenitor stellar envelope at distances less than a light-hour. In their model bumps should be found in less than several hours after the GRBs (Gao & Wei 2004).

In conclusion, We suggest that the delayed injection energy that causes the re-burst in the GRB afterglow, illuminates the fallback disk which is formed after the supernovae explosion, photonizes the fallback disk, then produces iron line feature. This scenario can well explain the production of the re-burst and the emission lines, that can be tested by the observations of SWIFT satellite in the near future.

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Fig. 1.— This is just a cartoon picture of the geometry of the fallback disk. The central engine is a magnetar or a black hole.