CERENKOV LINE EMISSION AS A POSSIBLE MECHANISM OF X-RAY LINES IN GAMMA-RAY BURSTS

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ABSTRACT

The recent discoveries of X-ray lines in the afterglows of gamma-ray bursts (GRBs) provide significant clues to the nature of GRB progenitors and central environments. However, the interpretation of iron lines as resulting from fluorescence or recombination requires a large amount of iron material. We argue that the very strong iron line could be attributed to an alternative mechanism: Cerenkov line emission, since relativistic electrons and dense medium exist near GRB sites. Therefore, broad iron lines are expected, and the line intensity will be nearly independent of the iron abundance; a medium with anomalously high Fe abundance is not required.

Subject headings: gamma rays: bursts — line: profiles — X-rays: general

1. INTRODUCTION

Recent gamma-ray burst (GRB) observational reports have shown broad emission line features during the X-ray afterglows of four GRBs (GRB 970508: Piro et al. 1999; GRB 970828: Yoshida et al. 1999; GRB 991216: Piro et al. 2000; GRB 000214: Antonelli et al. 2000). X-ray lines of similar energies are usually interpreted as iron emission lines from fluorescence or recombination. According to the variability and very large flux and equivalent width, we can estimate that there are large iron masses of 0.01–1.0 M⊙ in the emission region, with sizes of ∼1015 cm. This much Fe would have to come from the surrounding medium rather than from GRB progenitors to avoid the famous baryon contamination problem.

However, an iron-rich medium may not be consistent with the normal interstellar medium (ISM) observed, even in the dense regions of stellar formation. Mészáros & Rees (1998) have shown that the circumbust environment created by the stellar wind before the hypernova (Paczynski 1998) could yield a line of substantial intensity. A similarly favorable situation is expected in the supernova (Vietri & Stella 1998), where a GRB is preceded by a supernova explosion for several months to years with ejection of an iron-rich massive shell. In these scenarios, high density in excess of 1010 cm−3 is expected, and Fe absorption features of strength comparable to those in the progenitor stellar envelope at a distance of less than a light hour, and only a small mass of Fe is required. Another idea is provided in the frame that the lines are not interpreted as iron emission but rather as the strongly Doppler-blueshifted Lyα line emissions by jets of highly relativistic cannonballs (Dar & De Rújula 2001).

In this Letter we propose a new mechanism for the lines in X-ray afterglows: Cerenkov line emission. As we know, Cerenkov radiation is produced when the particle velocity exceeds the light speed in the medium. Furthermore, You & Cheng (1980) argued that for relativistic electrons moving through a dense gas, the Cerenkov effect produces peculiar atomic/molecular emission lines: Cerenkov lines. They presented a series of formulae to describe the properties of peculiar Cerenkov lines (You et al. 1984, 1986), and extended formulae can be applied to X-ray lines, such as Fe K-edge lines (You et al. 2000). Elegant experimental confirmation of Cerenkov lines in O2, Br2 gas, and Na vapor using an 85Sr β-ray source has been obtained in the laboratory (Xu et al. 1981, 1988, 1989). Cerenkov line emission has the following remarkable features: it is broad and asymmetrical, has Cerenkov redshift, and is polarized if relativistic electrons have an anisotropic velocity distribution.

We emphasize the special importance of the Cerenkov redshift, which markedly strengthens the emergent intensity of the Cerenkov emission line. For an optically thick dense gas, the emergent line is determined by both the emission and the absorption. The absorption mechanisms for normal and Cerenkov lines are extremely different. The intensity of the normal line, Iν, is greatly weakened by the strong resonant absorption kν,ν′,ν″ (the subscripts ν, ν′, and ν″ denote the lower and upper levels) due to the fact that the normal line is located exactly at the position of the intrinsic frequency ν, where kν is very large. In the extreme case of a very dense gas, the emergent flux has a continuum with a blackbody spectrum, and the normal line disappears: Iν ~ 0. However, the Cerenkov line, located at ν < ν, owing to the redshift, can avoid the resonant absorption because kν,ν′,ν″ → 0. The main absorption mechanism that affects the intensity of the Cerenkov line is the photoionization absorption kν, which is very small compared with kν,ν′. Thus, the Cerenkov line photons can easily escape from deep inside a dense gas cloud, causing a strong emergent line flux, only if the density of relativistic electrons Nν is high enough. In other words, the dense gas appears to be more transparent for the Cerenkov line than for the normal line, which makes it possible for the Cerenkov line mechanism to dominate over the normal line mechanisms when the gas is very dense and there exist abundant relativistic electrons in the emission region.

In the astrophysical processes of GRBs, a large amount of relativistic electrons and dense gas regions could exist. For the long burst afterglows localized so far, the host galaxies show signs of star formation activity where the high-density environment is expected. Recent broadband observations of the afterglows of GRB 000926 (Piro et al. 2001; Harrison et al. 2001) and statistical analysis (Reichart & Price 2002a, 2002b) imply evidence for a fireball in a dense medium. When the ultrarelativistic blast waves interact with the dense regions, very
strong Cerenkov line emission in X-ray bands will be observed, and the Cerenkov mechanism may dominate in the case of the optically thick gases. The advantage of the Cerenkov mechanism lies in that the Cerenkov line in the optically thick case is naturally broad and the emergent intensity is nearly independent of the abundance of iron, as elaborated in the following section.

2. CERENKOV LINE EMISSION: BASIC FORMULAE

The essential point of the calculation of Cerenkov radiation is the evaluation of the refraction index \( n \) and the extinction coefficient \( \kappa \). At a given frequency \( \nu \), the larger the index \( n \), the larger the condition \( v > c/n \), to be satisfied and the stronger the Cerenkov radiation at \( \nu \), where \( v \) is the particle velocity and \( c \) is the light speed. We adopt simplified approximate formulae when we are concerned only with the neighborhood of a given atomic line, \( \nu \sim n_{\nu, u} \) (You et al. 2000):

\[
n^{2} - 1 = \frac{c^{3}}{16\pi^{3}}\nu_{\nu, u}^{3}A_{\nu, u}g \frac{S_{u}}{g_{u}} \frac{S_{l}}{g_{l}}, \tag{1}
\]

\[
\kappa = \frac{c^{3}}{128\pi^{3}}\nu_{\nu, u}^{3}G_{\nu, u}g \frac{S_{u}}{g_{u}} \frac{S_{l}}{g_{l}}, \tag{2}
\]

where the damping constant \( G_{\nu, u} \) is related to Einstein’s coefficient \( A_{\nu, u} \); \( g \) is the statistical weight; \( N \) is the number density of the concerned atoms, e.g., for the calculation of iron \( K \) and \( L \) lines, \( N = N_{Fe} \), \( n_{Fe} \) represents the density of iron. \( S_{u} \) and \( S_{l} \) represent the actual occupation number of electrons at levels \( u \) and \( l \), respectively, and \( y \) represents the fractional energy displacement defined as \( y \equiv -\Delta\epsilon/\epsilon_{s, u} \), where \( \epsilon_{s, u} \equiv h\nu_{\nu, u} = \epsilon_{u} - \epsilon_{l} \) and \( y \ll 1 \) because we are interested in the neighborhood of \( n_{\nu, u} \).

It is known from the usual theory of Cerenkov radiation that the spectral power \( P_{\nu} \) emitted in a unit frequency interval by an electron moving with velocity \( \beta = v/c \) is

\[
P_{\nu} = 4\pi \frac{e^{2}}{c}(1 - \beta^{-2}n^{-2})\beta\nu. \tag{3}
\]

Let \( \mathcal{N}(\gamma)d\gamma \) be the number of relativistic electrons per unit volume with energies \( \gamma = (1 - \beta^{-2})^{-\nu/2} \) in the interval \( d\gamma \), assuming lower and upper energy cutoffs \( \gamma_{1} \) and \( \gamma_{2} \). Hence, the emissivity in unit volume, unit solid angle, and unit frequency interval is

\[
J_{\nu} = \frac{1}{4\pi} \int_{\gamma_{1}}^{\gamma_{2}} P_{\nu} \mathcal{N}(\gamma)d\gamma \approx \frac{\pi e^{2}}{c}N_{\nu}(n^{2} - 1 - \gamma_{-2})\nu, \tag{4}
\]

where \( \gamma_{-2} \) represents the characteristic energy of electrons, \( J_{\nu}^{\gamma}/N\mathcal{N}(\gamma)d\gamma/\gamma^{2} = \gamma_{-2}N_{\nu} \). Replacing \( \nu \) with \( y \) \((J_{\nu}^{\gamma}d\nu = J_{\nu}^{\gamma}dy)\), we have

\[
J_{\nu}^{\gamma}dy = \frac{\pi e^{2}}{c}N_{\nu}(n^{2} - 1 - \gamma_{-2})dy. \tag{5}
\]

Setting \( n^{2} - 1 - \gamma_{-2} = 0 \), we get the Cerenkov line width:

\[
\gamma_{lim} \equiv \frac{\Delta\nu_{lim}}{\nu_{\nu, u}} = c\delta\gamma^{2}, \tag{6}
\]

With equations (1), (5), and (6), the spectral emissivity becomes

\[
J_{\nu}^{\gamma}dy = C_{i}(\gamma_{-1} - \gamma_{lim}^{2})dy, \tag{7}
\]

\[
C_{i} = \frac{c^{3}}{16\pi^{3}}\nu_{\nu, u}^{3}G_{\nu, u}g \frac{S_{u}}{g_{u}} \frac{S_{l}}{g_{l}}. \tag{8}
\]

In an optically thick dense gas, the Cerenkov line mechanism may be efficient, and the final intensity \( J^{\nu} \) is determined by the competition between the emission \( J^{\nu} \) and absorption \( k \). The main absorption mechanisms that affect the emergent intensity of Cerenkov lines are the line absorption \( k_{\nu, u} \) and photoionization absorption \( k_{s, u} \) (free-free absorption can be neglected in the X-ray band). Then, the total absorption coefficient is \( k = k_{\nu, u} + k_{s, u} \). \( k_{\nu, u} \) can be easily obtained \((k_{\nu, u} = 4\pi \nu_{\nu, u}k_{\nu, u}/c)\) using equation (2):

\[
k_{\nu, u} = C_{2}y^{-2}, \tag{9}
\]

The photoionization absorption coefficient is \( k_{s, u} = \sum s N_{s, u} \sigma_{s, u}(s) \), where \( \sigma_{s, u}(s) \) is the photoelectric cross section of level \( s \). If we investigate it in Fe K-edge lines, the dominant absorbers should be the iron atoms or ions rather than other elements. Thus, for the Fe K\( \alpha \) line,

\[
k_{s, u} = N_{Fe} S_{2} \sigma_{s, u}(2) = 8.4 \times 10^{-6}N_{Fe} S_{2} \epsilon_{21}^{-3}, \tag{10}
\]

where \( \epsilon_{21} = 6.4 \) keV. Only the \( s = 2 \) energy level is considered due to the fact that around 6.4 keV, \( \sigma_{s, u}(s) \gg \sigma_{s, u}(s > 2) \).

Finally, we can estimate the Cerenkov line intensity in the optically thick case:

\[
J_{\nu} \equiv \frac{J_{\nu}}{k} = \frac{J_{\nu}^{\gamma}}{k_{\nu, u} + k_{s, u}} = \frac{N_{\nu}C_{i}(\gamma_{-1} - \gamma_{lim}^{2})}{C_{2}y^{-2} + k_{s, u}}. \tag{10}
\]

From the above equation we see that both the emissivity and absorption are proportional to the density of iron atoms \( N_{Fe} \); then, the emergent intensity is only weakly dependent on \( N_{Fe} \), owing to the existence of the factor \( \gamma_{lim} \) in the expression. The property of independence of iron density could be used to resolve the puzzle of the excessive amount of iron in the ISM. Integrating equation (10), the total intensity of Cerenkov lines
is obtained as

$$I' = \int_0^{\gamma_{\text{lim}}} I'_x dy = Y \left[ \ln (1 + X^2) + 2 \left( 1 - \frac{\arctan X}{X} \right) \right],$$

(11)

where $Y \equiv (N_e/2) C_1/k_{\text{sd}}$ and $X \equiv (k_{\text{sd}}/C_2)^{1/2} \gamma_{\text{lim}}$.

3. X-RAY LINES IN GAMMA-RAY BURSTS

We believe in the existence of the Cerenkov line mechanism operating in GRBs because there definitely exist dense gas regions and abundant relativistic electrons, both of which are just the right conditions to produce the Cerenkov line emission. We first relist the parameters, such as a very strong magnetic field, and therefore the ultrastrong iron lines in the X-ray afterglows can be explained probably without an additional request for the initial and external conditions of the iron-rich torus.

We also can estimate the relativistic electron density required for X-ray lines from four GRB afterglows. In the computations, we assume that the X-ray lines in GRB 970828 and GRB 000214 are also Fe Kα lines, and the line with a central energy of 3.49 keV in GRB 991216 is considered (the other in 4.4 keV is explained as the recombination continuum of H-like iron in 9.28 keV). Taking the standard cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 1$, and $\Lambda = 0$ and letting $C_{0,1} = D_n = 1$, our final results and the GRB line parameters are displayed in Table 1. We notice the electron densities $N_e \sim 10^{60} - 10^{61} \text{ cm}^{-3}$ are similar to those estimated for the delayed energy injection (Rees & Mészáros 2000) and the supranova model (Vietri et al. 2001). We first simply estimate the relativistic electron density from the fireball, $N_e \sim 10^{80} - 10^{81} \text{ cm}^{-3}$, and taking the isotropic energy $E \sim 10^{53} \text{ ergs}$, $\gamma \sim 100$, and $\Delta_0 \sim \gamma T$ ($T$ is the duration $\sim 10 \text{ s}$), we obtain the density $N_e \sim 10^{63} \text{ cm}^{-3}$, which is lower than our requirement in the model. So we think the relativistic electrons should come from other processes. Here we propose that the electrons may be produced by a pulsar wind from the central millisecond magnetar (Thompson 1994) or by $e^-e^+$ outflow from the Kerr black hole with magnetized torus (MacFadyen & Woosley 1999) as the delayed injection after GRB events. Our interpretation is similar to that of Rees & Mészáros (2000), but we consider the $e^-e^+$ outflow instead of electromagnetic flux. The luminosity is required to be as high as $L \sim 4\pi D_n^2 N_e c \gamma p c^2 \sim 10^{48} \text{ ergs s}^{-1}$, where we take $N_e \sim 10^{60} \text{ cm}^{-3}$, $\gamma \sim 10$ at a distance of $10^{26} \text{ cm}$. The luminosity could be satisfied by the central compact objects with acceptable parameters, such as a very strong magnetic field.

Because the scattering cross section of relativistic electrons will be near zero owing to the Klein-Nishina formula in the very high frequency (due to the Doppler effect), we need not worry that the electron-scattering process will greatly affect the line profile and intensity. The line width is also comparable to the one observed in GRBs, which is displayed in Figure 5 of the previous work (You et al. 2000).

4. DISCUSSION

The recently detected X-ray lines in the afterglows of GRBs give us important information on the nature of GRB progenitors by imposing significant constraints on models, and the severe
problem may be how to arrange a huge amount of iron-rich material close to GRB sites while avoiding a very large opacity at the same time. In this Letter we have presented an alternative model of the X-ray spectral features by a Cerenkov line mechanism, which would not have the above problems.

The broad feature of Cerenkov line emissions is consistent with the observations. Owing to the Cerenkov redshift, the Cerenkov mechanism can avoid strong absorption and may dominate the line mechanism in the optically thick medium. What is more, in §3 we have estimated the Cerenkov line luminosity in GRBs. We find that it is nearly independent of iron abundance and that a large amount of Fe is not required, as in the model of Rees & Mészáros (2000), so additional physical mechanisms involving the iron-rich medium before triggering GRBs are not needed in our interpretation. The line intensity can be comparable to the observed value with the relativistic electron density around $10^{10} - 10^{11} \text{ cm}^{-3}$, which could be satisfied in the environment of GRBs as the delayed injection from central objects.

Furthermore, we present a few arguments for fluorescence and recombination mechanisms. The fluorescence model predicts positive correlation of both line curves and flux between the Kα line and X-ray continuum, which needs further observations to confirm. Besides, the prediction of the marked absorption dip ($>7 \text{ keV}$) at the edge that always accompanies the fluorescent Kα line (Young, Ross, & Fabian 1998) has not been observed. The recombination mechanism also involves serious problems. Recombination lines require a very high temperature, which should be considered by further theoretical models. Because of a very large optical depth, the ionization edge at 9.28 keV would appear as an absorption rather than an emission feature (Rees & Mészáros 2000). Up until now, the discovery of a transient absorption edge in the X-ray spectrum of GRB 990705 (Amati et al. 2000) has been reported; however, it is still surprising that no absorption features are observed in X-ray afterglows in such a dense medium. The problems need more detailed investigations.

We have shown that fluorescence and recombination are not the only possible mechanisms for producing the observed lines in X-ray afterglows of GRBs. Then a question is put forward: how to discriminate between the Cerenkov line mechanism and these other mechanisms? Cerenkov lines have some interesting features: broadness, asymmetry, Cerenkov redshift, and polarization with the anisotropic velocity distribution of electrons. Therefore, we expect that future observations of high spectral resolution missions, such as Chandra, XMM-Newton, and the future mission Swift, could address these important issues, providing us with more information on GRB progenitors and the circumburst environment.

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