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X-ray Emission Lines in GRB Afterglows: Evidence for a Two-component Jet Model *

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Abstract X-ray emission lines have been observed in X-ray afterglows of several γ-ray bursts (GRBs). It is a major breakthrough for understanding the nature of the progenitors. It has been proposed that the X-ray emission lines can be well explained by the Geometry-Dominated models, but in these models the illuminating angle is much larger than that of the collimated jet of the GRB. For GRB 011211, we have obtained an illuminating angle of about $\theta \sim 45^\circ$, while the angle of the GRB jet is only 3.6°. So we propose that the outflow of GRBs with emission lines should have two distinct components: a wide component that illuminates the reprocessing material and produces the emission lines and a narrow one that produces the GRB. Observations show the energy for producing the emission lines is higher than that of the GRB. In this case, when the wide component dominates the afterglows, a bump should appear in the GRB afterglow. For GRB 011211, the bump should occur within 0.05 days of the GRB, which is obviously too early for the observation to catch it. Alongside the X-ray emission lines there should also be a bright emission component between the UV and the soft X-rays. These features can be tested by the $Swift$ satellite in the near future.

Key words: gamma rays: bursts — line: profiles — ISM: jets and outflows — supernovae: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are commonly interpreted in terms of a relativistic outflow emanating from the vicinity of a stellar neutron star or black hole (e.g. Piran 2004; Zhang & Mészáros 2004). Highly collimated narrow jets can be inferred from the presence of achromatic breaks in the afterglow lightcurves (Rhoads 1999).

Recently X-ray emission lines have been observed in the X-ray afterglow of several GRBs. They can provide important clues for identifying the nature of the progenitors of long ($t \geq 2\,$s)

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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; in GRB 991216 (Piro et al. 2000) and GRB020813 (Butler et al. 2003) with Chandra; in GRB 011211 (Reeves et al. 2002), GRB 001025A (Watson et al. 2002) and GRB 030227 (Watson et al. 2003) with XMM-Newton; in 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 locations of the emission lines found in the X-ray afterglows of GRB 970508, GRB 970828, GRB 991216 and GRB 000214 are roughly consistent with Fe K_α at the redshift of the hosts, while the emission lines were identified as blueshifted light elements lines of S, Si, Ar, Mg, and Ca in the afterglow of GRB 011211, GRB 020813 and GRB 030227.

Two types of models have been put forward to interpret the emission lines: one is Geometry-Dominated (GD) models (e.g. Vietri et al. 2001; Lazzati et al. 1999; Reeves et al. 2002), the other is Engine-Dominated (ED) models (e.g. Rees & Mészáros 2000; Mészáros & Rees 2001). In the ED models, the lines are created by reprocessing material very close to the explosion site ($R \sim 10^{13}$ cm). The ionizing continuum is believed to be provided by a post-burst energy injection (Rees & Mészáros 2000; Mészáros & Rees 2001; Gao & Wei 2004, 2005). The duration of the line emission is determined by the time interval of the post-burst energy injection. On the other hand, in the GD models the reprocessing material is located at some large distance ($R \sim 10^{16}$ cm), and is illuminated by the burst and early afterglow photons. In the GD models, the duration of the emission lines is set by the size of the reprocessor. The reprocessing material is compact and metal enriched, similar to supernova remnant, as predicted in the supernova model (Vietri & Stella 1998). It has been argued that the production of the emission lines strongly favors the GD models (e.g. Lazzati et al. 2002; Reeves et al. 2002). However, in these models, whether in the reflection model version or in the thermal model version a large collimation angle of the illuminator is needed (e.g. Lazzati et al. 1999; Reeves et al. 2002).

The half opening angle of the GRB jet was obtained from the presence of the achromatic break in the afterglow lightcurve (Frail et al. 2001; Bloom et al. 2003). It is much smaller than the illuminating angle obtained with the GD models. If the photons illuminating the reprocessing material come from bursts and early afterglows with small collimation angles, the duration of the emission lines will be much shorter than is observed. It also contradicts the fact that much higher energy is needed for the illuminating continuum that is responsible for the lines production than that of the collimated GRBs (Lazzati 2002; Ghisellini et al. 2002; Gao & Wei 2004). To solve the energy problem, we have explained it as continuous post-bust energy injection from the magnetar (Gao & Wei 2004), or delayed energy injection from the central engine (Gao & Wei 2005). A similar model can also explain the early flare in X ray afterglow light curve (Fan et al. 2002; Fan & Wei 2005).

Recently, two distinct components in the GRB outflow have been proposed for several gamma-ray bursts. On the observational side, Frail et al. (2000) proposed that the γ-rays, early X-rays and optical afterglow of GRB 991216 could be attributed to a narrow ultra-relativistic outflow component and the longer-wavelength afterglow such as radio afterglow originated in a wide component that is only mildly relativistic. A similar picture was proposed for GRB 970508 (Pedersen et al. 1998) and GRB 030329 (Berger et al. 2003; Sheth et al. 2003). A two-component model was also suggested as an explanation for the observed re-brightening of the X-ray flash source XRF 030723 (Huang et al. 2004). In their numerical simulations of collapsar model, the narrow component has a Lorentz factor $\gamma_{\rm n} \geq 100$ and a half opening angle $\theta_{\rm n} \sim 3° - 5°$, while for the wide component, $\gamma_{\rm w} \sim 15$ and $\theta_{\rm w} \sim 10°$ (Zhang et al. 2004). In his GRMHD models of jet formation, McKinney (2005) has found a two-component jet with a quite broad component out to 25° and a core component within 5°.

In this paper, we reconsider the Geometry-Dominated models, and investigate the angle of the illuminator in the GRB 011211 afterglow. A large illuminating angle is obtained. Here we propose a two-component outflow model to solve the angle problem. It is suggested that the outflow in the GRB whose afterglow shows the line emission has two components, the angle of the wide component is about several tens degrees, and the energy of the wide component is high enough to illuminate the material to produce the emission lines.

2 THE ILLUMINATING ANGLE AND THE TWO-COMPONENT JET MODEL

In this paper the Geometry-Dominated models are used to explain the line production (e.g. Lazzati 2002; Lazzati et al. 2002). In these models the line emission comes from an extended region and its duration arises from light-travel time effects. So the geometry of the dense material is important because it dominates the time duration of the line emission. Lazzati et al. (1999) have investigated the relations between the geometry of the reprocessing material and the theoretical models.

We investigate the illuminating angle in the reflection model and thermal model. In the reflection model, the photons are reflected by the funnel-shaped material. The geometry of the reprocessing material we adopt here is similar to that adopted by Tavecchio et al. (2004). This geometry of material is efficient for reflection and we called it funnel-shaped reprocessing material (Fig. 1a). In the first subsection below, we re-calculate the illuminating angle in the reflection model. The detailed calculation of the physical quantities can be found by Tavecchio et al. (2004).

In the thermal model, similar to the geometry taken up by Lazzati et al. (1999), we adopt the shell-shaped reprocessing material (Fig. 1b). This geometry of the material is efficiently heated to high temperature and produces the emission lines by collision-ionization and recombination. Though Reeves et al. (2002) have explained the production of the emission lines with the thermal model, they assumed rather than calculated an illuminating angle of 20°. In the second subsection below we calculate the illuminating angle of the burst source in the thermal model.

2.1 The Illuminating Angle in the Reflection Model

Here we reconsider the reflection model similar to the calculation of Tavecchio et al. (2004). In this model with the funnel-shaped reprocessing material (Fig. 1a) the time at which lines become visible can be defined as follows (the time intervals are measured in the frame of the burst source):

$$t_{\rm app} = \frac{R}{c}(1 - \cos\theta), \tag{1}$$

where θ is the half opening angle of the illuminator, R is the distance between the burst source and the reprocessing material.

The duration of the line $t_{\rm line}$ is given by

$$t_{\rm line} \sim \frac{\Delta R}{c}\cos\theta, \tag{2}$$

where ΔR is the width of the reprocessing material, which can be expressed as (Tavecchio et al. 2004).

$$\frac{\Delta R}{R} = \frac{1}{5\pi}\xi\zeta\frac{W_i m_p}{A_i \epsilon_i \sin\theta \alpha_r}, \tag{3}$$

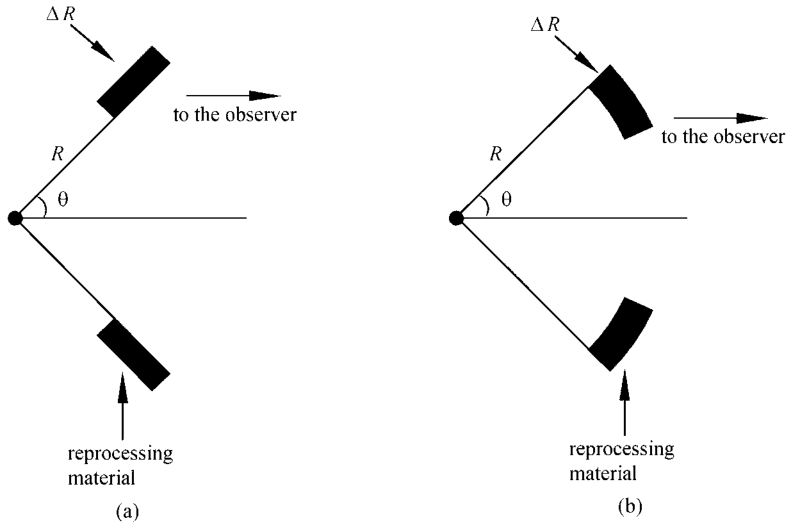

Fig. 1 Sketch of the geometry assumed for the reprocessing material in Geometry-Dominated models. (a) the funnel-shaped material in the reflection model. (b) the shell-shaped material in the thermal model.

where W_i is the atomic weight of the element (the subscript i denotes a specific line) and ξ is the ionization parameter. For soft X-ray lines, ξ is about 10^2 for efficient emission (Lazzati et al. 2002). For GRB011211, the ionization parameter is

$$\xi = \frac{L_{\rm ill}}{n_e R^2} \simeq 10^2, \tag{4}$$

where $L_{\rm ill}$ is the luminosity of the X-ray illuminating continuum, n_e is the number density of the electron, ζ is the efficiency in producing the lines (Ghisellini et al. 2002),

$$\zeta = \frac{E_{\rm line}}{E_{\rm ill}} \simeq 10^{-2}. \tag{5}$$

A_i is the mass abundance of the emitting element, ϵ_i is the energy of the line, α_r is

$$\alpha_r = 5.2 \times 10^{-14} Z \lambda^{1/2} \Big[0.429 + 0.5 \ln(\lambda) + \frac{0.496}{\lambda}^{1/3} \Big], \tag{6}$$

where $\lambda = 1.58 \times 10^5 Z^2 T^{-1}$, Z is the atomic number of the element and T is the electron temperature. For GRB 011211, the temperature T of a photoionized plasma illuminated with $\xi = 100$ is predicted to be in the range $10^5 - 10^6\,$K (Kallman & McCray 1982). So here we assume $T = 5 \times 10^5\,$K. Combing Eqs. (1)–(3), it can be found

$$\tan\theta(1-\cos\theta) \sim \frac{1}{5\pi} \xi \zeta \frac{W_i m_p}{A_i \epsilon_i \alpha_r} \frac{t_{\rm app}}{t_{\rm line}}. \tag{7}$$

For GRB 011211, the observation shows that the emission lines appear at time $t_{\rm app} \leq 4 \times 10^4/(1+z)s \sim 1.3 \times 10^4\,$s, the time duration of the lines $t_{\rm line} \simeq 5 \times 10^3/(1+z)s \sim 1.7 \times 10^3\,$s, $\xi \simeq 100$ and $\zeta \simeq 0.01$. For solar abundance of the elements (Anders & Grevesse 1989) we know the value of A_i. Here ϵ_i is the center energy of the line, for instance $\epsilon_{\rm CaXX}$ is 4.70 keV (in the burst source frame). In this case, the illuminating angle can be obtained to be about $\theta \sim 45^\circ$.

2.2 The Angle of the Illuminator in the Thermal Model

In the thermal model, for the shell-shaped reprocessing material (Fig. 1b), the duration of the lines observed in the GRB afterglow is

$$t_{\rm line} = \frac{R}{c}(1 - \cos\theta). \quad (8)$$

The X-ray lines luminosity is

$$L_i = [N_i \epsilon_i / t_{\rm rec}](1+z)^{-1}, \quad (9)$$

where N_i is the number of nuclei of the given element and $t_{\rm rec}$ is the recombination time scale. When the reprocessing material is heated to thermal equilibrium, close to the Compton temperature $T_C \sim 10^7$ K (Reeves et al. 2002), we have $t_{\rm rec} \sim 10^{11} T_7^{1/2} n_e^{-1}$.

The number of nuclei in the material layer within Thomson optical depth $\tau_T = 1$ (in $\tau = 1$ layer that absorbs enough energy without smearing the lines very much (see Gao & Wei 2005)) is

$$N_i \sim A_i M/(\tau_T W_i m_p), \quad (10)$$

where M is the total mass of the material that is illuminated by the illuminator. $M = n_e m_p V$, V is the volume of the illuminated material, $V = 2\pi R^2(1-\cos\theta)\Delta R$, and τ_T is the Thomson optical depth of the reprocessing material, $\tau_T = n_e \Delta R \sigma_T$. For GRB 011211, the ionization parameter $\xi \simeq 10^2$ (Lazzati et al. 2002), the X-ray luminosity illuminating the material is of the order $L_{\rm ill} \sim 10^{47}$ erg s^{-1}. The luminosity of the line is about 10^{45} erg s^{-1}, $t_{\rm line} \sim 1.7 \times 10^3$ s. According to these, we have $\theta \sim 45°$.

We have obtained an angle of the illuminator of about 45°. Obviously it is much larger than the half opening angle of the GRB jet, which is only 3.6° (Frail et al. 2001; Bloom et al. 2003).

Therefore, we propose that the GRB outflow with the X-ray lines has two distinct components: a narrow one that produces the prompt GRB emission, and a wide component that illuminates the reprocessing material and produces the emission lines. The illuminator's angle is $\theta \sim \theta_{\rm w}$.

3 PRODUCTION OF BUMP IN THE TWO-COMPONENT OUTFLOW

It has been found that the energy obtained from the lines emission is higher than that of the γ-ray burst (Ghisellini et al. 2002; Gao & Wei 2004). So in the two-component outflow model the energy of the wide component illuminating the reprocessing material should be $E_{\rm ill} \sim E_{\rm w} \geq E_{\rm n}$, $E_{\rm n}$ is the energy of the narrow component which is the same as that of the γ-ray burst, $E_{\rm n} = E_\gamma$.

In the theory of GRB afterglow, the interaction of the jet with the ambient medium drives a reverse shock into the GRB ejecta, which decelerates the ejecta. The energy given to the swept-up external medium is $\sim \eta^2 M_{\rm sw} c^2$ (here η is the Lorentz factor of the outflow, $M_{\rm sw}$ is the rest mass of the swept-up external medium). The Lorentz factors of the narrow and wide component are taken to be $\eta_{\rm n} \sim 300$ and $\eta_{\rm w} \geq 30$, respectively. The energy of the wide component is assumed to be higher than that of the narrow one, i.e., $E_{\rm w} \geq E_{\rm n}$. The density of the medium is assumed to be same for both components. So we obtain $\eta_{\rm w} \geq 30$ ($\eta_{\rm w}$ is the Lorentz factor of the wide component).

From the work of Peng et al. (2005), for $E_{\rm w}/E_{\rm n} > 1$, we expect that a bump should appear in the afterglow at time $t_{\rm dec,w}$ (the deceleration time of the wide component) when the wide component dominates the afterglow. That is

$$t_{\rm dec,w} \leq 0.05 \Big(\frac{E_{\rm iso,52}}{n_0}\Big)^{1/3} \Big(\frac{\eta_{\rm w}}{30}\Big)^{-8/3} {\rm days}. \quad (11)$$

So we should observe a bump at some time within 0.05 days after the GRB. Now the GRB 011211 X-ray afterglow was observed some 11 hours after the burst (Reeves et al. 2002). So the bump was obviously too early to have been observed.

If the energy of the wide component is less than or comparable with that of the narrow component, then the lightcurve of the afterglow will not be dominated by the wide component, and there will appear no bump. Only when the energy of the wide component is much higher than that of the narrow one, would a distinct bump emerge (Peng et al. 2005; Wu et al. 2005).

4 DISCUSSION AND CONCLUSIONS

The Geometry-Dominated models have been proposed to explain the X-ray emission lines observed in the X-ray afterglows (e.g. Lazzati et al. 2002; Reeves et al. 2002). In these models, the time duration is set by the geometry of the reprocessing material. In this paper, we investigate the Geometry-Dominated models and calculate the illuminating angle of the illuminator.

Generally the iron line can be well explained by a reflection model while the soft X-ray lines prefer a thermal model interpretation. However, this is not always the case. Tavecchio et al. (2004) have claimed that emission lines in GRB 011211 afterglow also can be well explained by a reflection model. Therefore, we will calculate the illuminating angle both for a reflection model and a thermal model.

For GRB 011211, in the GD models, an illuminating angle $\theta \sim 45^\circ$ is obtained. However from the presence of the break in the light curve of the GRB afterglow, a jet with an angle of only $\theta_j \sim 3.6^\circ$ was obtained (Frail et al. 2001; Bloom et al. 2003). Since the physical parameter of X-ray lines is comparable on the whole (Lazzati 2002), we assume that the illuminating angle in other GRBs has the same value as GRB 011211.

It should be noted that the solar abundance of the elements is adopted in our calculation. The angle would be smaller than 45° if we adopt a greater abundance. For instance, if we adopt 10 times the solar abundance, we will obtain $\theta \sim 22^\circ$. However, in any case it will be larger than the half opening angle of GRB 011211.

Therefore, we propose a two-component outflow model for the γ-ray burst with X-ray emission lines. The angle of the wide component is comparable with that of the illuminator, $\theta \sim 45^\circ$; while the collimated jet of the GRB is comparable with the narrow component, $\theta_j \sim 3.6^\circ$.

For GRB 011211 the energy for illuminating the reprocessing material obtained from the X-ray lines is more than 5×10^{50} erg (Gao & Wei 2004; Ghisellini et al. 2002), which is higher than that of the γ-ray bursts. In this case, the wide component will dominate the afterglow, and a bump will appear in the lightcurve of the afterglow. Our calculation shows that it should be seen some time within 0.05 days after the burst in the X-ray afterglow. Unfortunately it was too early to be caught by the observations.

In this two-component outflow model, when the wide component dominates the lightcurve of the afterglow, an approximate isotropic component of the X-ray afterglow should be observed. In the X-ray band observation of GRB 011211 afterglow, no break in the afterglow was reported (Reeves et al. 2002).

For GRB 991216, a narrow half opening beaming angle $\theta_j \sim 3^\circ$ has been claimed from the optical observation (Halpern et al. 2000). However, recently Ruffini et al. (2005) claimed that the data analysis in 2–10 keV of GRB 991216 afterglow confirmed spherical symmetry. We have calculated the energy of the illuminator obtained by the emission lines. It is between 3×10^{51} and 3.8×10^{52} erg (Gao & Wei 2004). This energy is much higher than that of the burst. So the bump should appear in the lightcurve of the afterglow. It was too early to be observed. When the wide component dominates X-ray afterglow, an afterglow with spherical symmetry would be obtained. So the result obtained by Ruffini et al. (2005) is consistent with our two-component outflow model.

In the same way, our two-component model is also consistent with the observation of GRB 970508, whose afterglow could be explained in terms of a narrow jet surrounded by an isotropic outflow (Pedersen et al. 1998).

In the low-ionization condition discussed here, about 90% of the total incident luminosity is absorbed by the reprocessing material (e.g. Zicky et al. 1994), and then re-emitted. The reprocessed luminosity $L_{\rm repr}$ is

$$L_{\rm repr} = 0.9 \frac{L_{\rm line}}{\zeta} \sim 9 \times 10^{46} \frac{L_{\rm line,45}}{\zeta_{-2}} \ {\rm erg\ s^{-1}}. \quad (12)$$

The surface of the slab illuminated by the incident continuum will be heated to high temperature, close to the Compton temperature $T_C \sim 10^7$K (e.g. Reeves et al. 2002). The emission from these outer layers will peak in the X-ray region, at energies around 1 keV. Gas in the layers deeper in the material will be close to thermal equilibrium: the temperature of these region will be close to the black-body temperature corresponding to a black-body emission with a luminosity of the order $L_{\rm bb} = L_{\rm repr}$. Tavecchio et al. (2004) have obtained that the maximum of the emission falls at the frequency $\nu_{\rm bb} \sim 10^{15}$ Hz, i.e. in the near UV.

The actual emergent spectrum will be a complex integral over the emission from different layers, in time-dependent conditions. The detailed calculation of the spectrum is beyond the scope of this paper. So, alongside the X-ray emission lines there should be a bright component between the UV and the soft X-rays that is 100 times greater than the line luminosity (Tavecchio et al. 2004).

In conclusion, we have assumed that the outflow of GRBs has two components. The wide component illuminates the reprocessing material and produces the emission lines; while the narrow component corresponds to the jet of the GRB. We have obtained that for GRB 011211 a bump should occur within 0.05 days after the burst because of the higher energy of the wide component, but it was too soon after the burst for the bump to be observed. A bright component between the UV and the soft X-rays should also be observed alongside the X-ray emission lines.

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