Modeling and Implications of the Transient Absorption Feature in GRB 990705

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Abstract

A transient Fe absorption edge during the prompt phase of a GRB has recently been observed for the first time. This has been interpreted as evidence for photoionization of the GRB environment by the burst radiation, which allows diagnostics of the density structure and element abundances in the vicinity of the burst. Assuming that the observed absorption feature is caused by photoelectric absorption, we model the time-dependent photoionization and X-ray radiation transport, and deduce constraints on the size and matter distribution of the photoionized region responsible for the absorption edge. If the density of the region is $\lesssim 10^{10}$ cm^{-3}, then we find that the intervening material would have to contain $\sim 44\,\Omega\,M_\odot$ of iron within $\sim$ 1.3 pc of the burst source, assuming the measured best-fit $\sim$ 75-fold overabundance of iron. Alternatively, and more plausibly, the observed absorption feature could be caused by photoelectric absorption in dense clouds of radius $r_c \lesssim 10^{12}$ cm at $\sim 10^{17}$ cm from the burst source, containing $\lesssim 0.7\,\Omega\,M_\odot$ of iron. In such an environment, recombination would compete with photoionization, until the clouds are effectively heated to the Compton equilibrium temperature of the ionizing GRB continuum. We also briefly discuss the recent suggestion that the absorption feature may be due to resonant scattering by Fe XXVI in a highly ionized, clumpy high-velocity outflow.

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1) Introduction

Recently, Amati et al. (2000) have reported the detection of a transient, redshifted Fe K edge in the prompt X-ray emission from GRB 990705. This is the second time (after GRB 980329; Frontera et al. 2000) that X-ray spectroscopy during the prompt phase of a GRB revealed evidence for excess absorption above the Galactic hydrogen column, and the first time that evidence for a time-dependence of such absorption has been found. The transient nature of the absorption feature has been interpreted as unmistakable evidence for photoionization of the absorber by the prompt burst emission (Amati et al. 2000, Böttcher et al. 2001). The corresponding time-dependent photoionization and radiation transfer problem had been simulated before by Böttcher et al. (1999) who predicted that excess absorption features are either transient on time scales of $\lesssim 1$ minute, or do not change appreciably as the burst evolves, depending primarily on the average distance of the absorbing material from the GRB source.

In this paper, we review the results of detailed modeling of the time-dependent photoionization and radiation transfer problem in quasi-isotropic, intermediate-density media obtained in Böttcher et al. (2001) and in small, dense clumps in which photoionization is balanced by rapid recombination. We also discuss the possibility that the absorption feature is a blue-shifted resonance scattering feature in an inhomogeneous high-velocity outflow, as recently suggested by Lazzati et al. (2001). The implications of these results for GRB progenitor models will be discussed briefly.

2) Model representation of the GRB emission

The prompt burst emission from GRB 990705 can be reasonably well represented by a FRED-type single-pulse burst if one neglects the sub-second-scale variability, which is irrelevant for the photoionization problem which we are modeling in this paper. We can thus describe the GRB spectral evolution by the parametrization of Dermer et al. (1999), based on the external shock model for GRBs. GRB 990705 had a γ-ray duration of $t_d \sim 40$ s and a 2 – 700 keV fluence of $(9.3 \pm 0.2) \times 10^{-5}$ erg cm^{-2}. At a redshift of $z = 0.86$, as determined from the transient Fe absorption edge, this corresponds to an isotropic energy output in X- and γ-rays of $E_{X\gamma} \approx 2.2 \times 10^{53}$ ergs. During the early phase of the GRB, the 2 – 700 keV continuum was consistent with a power-law of photon index , ≈ 1.1 (i.e. νF_ν spectral index $\upsilon = 0.9$). No evidence for a high-energy spectral break or turnover in the early 2 – 700 keV spectrum was found, implying that the νF_ν peak energy is beyond 700 keV. For our modeling, we assume $\epsilon_0 \equiv E_{\rm pk}/(m_e c^2) = 1.5$. All the above observables can be reproduced in the framework of the Dermer et al. (1999) parametrization using the following parameters:

$$
\begin{aligned}
E_0 &= 10^{54}\ \mathrm{erg} \\
,_0 &= 440\, n_0^{-1/8} \\
\upsilon &= 0.9 \\
\delta &= 0.5 \\
g &= 1.8 \\
q &= 2.5 \cdot 10^{-3}
\end{aligned}
$$

3) Photoelectric absorption in an intermediate-density homogeneous shell

The most straightforward interpretation of the transient absorption feature would be photoelectric absorption in a homogeneous cloud or an isotropic shell of intermediate density, in which recombination is slow compared to photoionization. In this case, we model the absorbing material as a uniform shell with inner radius $r_{\rm in}$, density $n_{\rm sh}$ [cm^{-3}], and radial column density N_H, which also determines the thickness of the shell. The element abundances are fixed to the values found through spectral analysis of the BeppoSAX WFC spectrum of GRB 990705 by Amati et al. (2000), i.e. standard solar-system abundances for all elements except iron for which an overabundance of $A_{\rm Fe} = X_{\rm Fe}/X^0_{\rm Fe} = 75$ w.r.t. the standard solar-system iron abundance $X^0_{\rm Fe}$ was deduced. The material in the shell is assumed to be neutral before the onset of the burst.

We are using the code developed in Böttcher et al. (1999) to simulate the time-dependent photoionization and radiation transfer problem in the CBM. The modeling is done by varying the initial column density N_H, the radius $r_{\rm in}$, and the density $n_{\rm sh}$.

Fig. 1 shows sample results of some of our simulations for various values of the column density N_H, the radius $r_{\rm in}$, and the density $n_{\rm sh}$. Plotted is the absorption depth $\tau_{\rm FeKedge}$ of the iron K edge as a function of observed time. The shaded regions indicate the measured depth of the iron line (with 1 σ error) during the first four time intervals after the onset of GRB 990705. We find that the measurements place rather tight constraints on the three fitting values N_H, $r_{\rm in}$, and $n_{\rm sh}$. Good agreement is achieved for

$$N_H = 1.8 \times 10^{22} \text{ cm}^{-2}$$
$$r_{\rm in} = 1.3 \text{ pc}$$
$$n_{\rm sh} = 10^5 \text{ cm}^{-3}$$

These values are in good agreement with a simple analytical estimate based on the assumption that the decay time scale of the absorption feature, $t_{\rm abs} \sim 10$ s corresponds to the time scale $t_{\rm ion}$ of photoionization of the CBM by the prompt GRB radiation, which yields

$$t_{\rm ion} = \frac{36}{\Phi_0 \, E_{\rm thr} \, \sigma_0}$$

where $\Phi_0 \approx (1.2 \times 10^{56} / r_{\rm in}[cm]^2)$ photons cm^{-2} s^{-1} keV^{-1} is the illuminating photon flux at $E = m_e c^2$, $E_{\rm thr} \sim 8$ keV is an average value of the ionization threshold and $\sigma_0 \sim 3.5 \times 10^{-20}$ cm^2 is an average value of the photoelectric absorption cross section at threshold for the various ionization stages of iron. $t_{\rm ion} \sim 10$ s is achieved for $d \sim 1$ pc.

This result implies that the absorber would have to contain a total mass of $M_{\rm CBM} = 365 \, \Omega \, M_{\odot}$, where Ω is the solid angle subtended by the absorber. The amount of iron contained in this cloud would be $M_{\rm Fe} = 44 \, \Omega \, M_{\odot}$. Even if the cloud were strongly anisotropic, $\Omega \lesssim 1$, it appears very unlikely that such an extreme mass and concentration of iron could be produced in the context of any reasonable GRB progenitor model.

However, we find that even with this huge mass of iron, the flux of a Fe Kα line which would be expected to result in the course of the on-going photoionization of the CBM would remain far below detectable levels. This is in excellent agreement with theoretical modeling of the iron lines observed in other GRBs, which strongly favors highly anisotropic scenarios in which the line-emitting material is located outside the line of sight from the GRB source to the observer, e.g. a torus of dense material around an anisotropic burst source (Ghisellini et al. 1999; Böttcher 2000), an evacuated funnel in a beamed GRB scenario (Weth et al. 2000), or a nonrelativistic shock wave interacting with a disk of pre-ejected material (Böttcher & Fryer 2001).

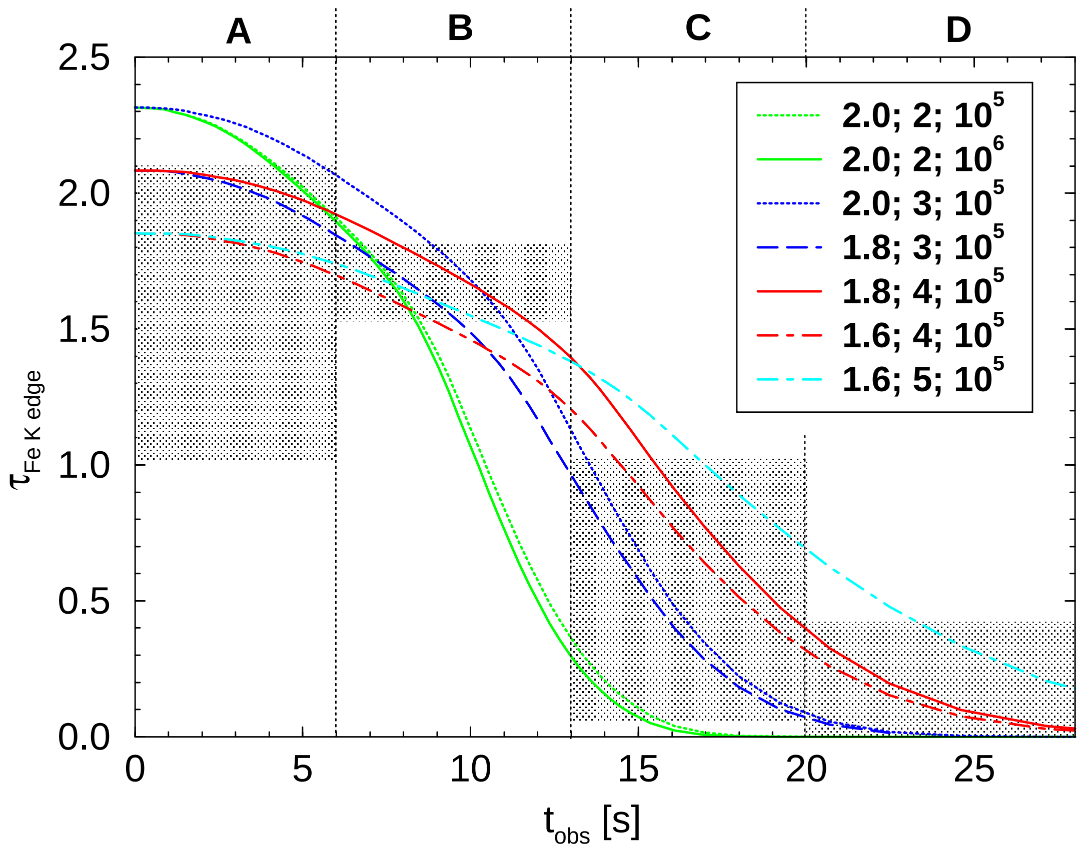

Fig. 1: *Simulated time evolution of the Fe K edge in GRB 990705 for various combinations of column density, N_H, radius, $r_{\rm in}$, and density, $n_{\rm sh}$, of the absorbing material. The shaded regions show the values allowed by the measurements of Amati et al. (2000). The curves show the model results, using the parameters quoted in Section 3 and in the legend, where the first number is N_H [10^{22} cm^{-2}], the second number is $r_{\rm in}$ [10^{18} cm], and the third number is $n_{\rm sh}$ [cm^{-3}].*

4) Photoelectric absorption in dense clouds

In a medium of moderate density, where recombination is inefficient, each iron atom absorbs ~ 12 ionizing photons (taking into account Auger ionization) before being completely ionized. The amount of iron required to reproduce the observed absorption feature in terms of photoelectric absorption could be reduced if the material is so dense that the recombination time scale is of the order of the ionization time scale, so that each iron atom absorbs more than ~ 12 ionizing photons.

To estimate the conditions under which this is the case, we assume that a fraction ζ of the CBM is contained in these clouds, i.e. the total mass in the clouds is $M_c = \zeta M_{\rm ej}$, and we write $M_{\rm ej} = m_{\rm ej}\, M_\odot$. These clouds are covering a fraction $a_c \sim 1$ of the sky as seen from the burst source. The radius of the clouds is $r_c = 10^{10}\, r_{10}$ cm, and their distance from the central source is $x = 10^{17}\, x_{17}$ cm. The cloudy ejecta subtend a solid angle Ω_s around the GRB source. Assuming that the electron density in the cloud is dominated by free electrons from ionized hydrogen, the recombination timescale of fully ionized hydrogen may be estimated as

$$t_{\rm rec,Fe}^{-1} \sim 2.13 \times 10^3 \, \frac{\zeta\, m_{\rm ej}}{T_4^{3/4}\, x_{17}^2\, r_{10}\, a_c} \ {\rm s}^{-1},$$

where T_4 is the electron temperature in units of 10^4 K.

To estimate the photoionization time scale, we assume that during the first ~ 10 s the GRB spectrum is approximately constant in flux and spectral shape. The average spectrum of GRB 990705 during this time interval, at the redshift of the burst, is well characterized by

$$\Phi(E) = 4 \times 10^{22}\, x_{17}^{-2}\, h_{17}^{-2}\, E_{\rm keV}^{-1.1} \, \frac{\rm photons}{\rm cm^2\, s\, keV},$$

where $E_{\rm keV}$ is the photon energy (in the GRB rest frame) in units of keV. This results in a photoionization time scale for iron of

$$t_{\rm pi,Fe}^{-1} \sim 97\, x_{17}^{-2}\, h_{70}^{-2}\ {\rm s}^{-1}.$$

Furthermore, we require that the column density of iron through the cloud layer is $N_{\rm Fe} \sim 2.2 \times 10^{20}$ cm^{-2}, as indicated by the depth of the observed absorption feature. Finally, we assume that the decline of the absorption depth is due to ongoing Compton heating of the electrons in the cloud (note that the recombination rates scales as $t_{\rm rec}^{-1} \propto T_e^{-3/4}$), and estimate the Compton heating time as

$$t_{\rm heat}^{-1} \sim 0.52\, x_{17}^{-2}\, h_{70}^{-2}\, T_4^{-0.1}\ {\rm s}^{-1}.$$

Now, setting $t_{\rm heat} = 10$ s, and $t_{\rm rec,Fe} = t_{\rm ion,Fe}$, we find the following physical conditions for the material in the clouds:

$$x \sim 2 \times 10^{17}\, h_{70}^{-1}\, T_4^{-0.05}\ {\rm cm}$$

$$r_c \sim 8 \times 10^{11}\, \frac{\zeta}{(\zeta_{\rm Fe}/75)\, T_4^{0.85}\, a_c}\ {\rm cm}$$

$$n_c \sim 8 \times 10^{10}\, T_4^{0.85}\ {\rm cm}^{-3}$$

$$M_{\rm ej} \sim 3.5\, \frac{\Omega_s\, h_{70}^{-2}\, T_4^{-0.1}}{(\zeta_{\rm Fe}/75)}\ M_\odot$$

$$M_{\rm Fe} \sim 0.7\, \Omega_s\, h_{70}^{-2}\, T_4^{-0.1}\ M_\odot$$

Here, $\zeta_{\rm Fe}$ is the overabundance of iron w.r.t. standard solar-system abundances. As a consistency check, we require that the Thomson depth through ejecta be $\tau_{\rm T} < 1$ in order to avoid a very low transmission efficiency and smearing of the millisecond variability in GRB 990705. We find

$$\tau_{\rm T} \sim \sigma_{\rm T}\, r_c\, n_c\, a_c \sim 4.3 \times 10^{-2}\, \frac{\zeta}{(\zeta_{\rm Fe}/75)}.$$

5) Resonance Scattering by Fe XXVI

(Lazzati et al. 2001)

Lazzati et al. (2001) have recently suggested that the transient absorption feature in GRB 990705 could be due to resonant scattering by Fe XXVI in highly ionized clumps in a high-velocity outflow from the burst source. In order to reproduce the observed width of the absorption feature, an outflow velocity of $v_0 \sim 4 \cdot 10^9$ cm s^{-1}, and a velocity dispersion of $\Delta v \sim v_0$ was required in order to produce the observed energy and width of the absorption feature (recall that resonance scattering in a stationary medium would produce a very narrow absorption line).

Parameters inferred from the requirements that the material is highly ionized, but a significant fraction of iron remains in the Fe XXVI state through balance between photoionization and recombination, and that the transient nature of the iron line is due to Compton heating of the plasma, they infer typical CBM parameters:

$$x \sim 2.6 \times 10^{16}\, L_{51}^{1/2} \mathrm{cm}$$

$$r_c \sim 2 \times 10^{13}\, \tau_{\mathrm{T}}^2\, (\zeta_{\mathrm{Fe}}/10)\ \mathrm{cm}$$

$$n_c \sim 8.3 \times 10^{10}\, T_4^{5/3}\, \tau_{\mathrm{T}}^{-1} (\zeta_{\mathrm{Fe}}/10)^{-1}\ \mathrm{cm}^{-3}$$

$$M_{\mathrm{ej}} \sim 6.1\ M_{\odot}$$

$$M_{\mathrm{Fe}} \sim 0.16\ M_{\odot}$$

where L_{51} is the burst luminosity in units of 10^{51} ergs s^{-1} and the Thomson depth through the CBM is restricted to $\tau_{\mathrm{T}} \leq 1$.

6) Summary and Discussion

We have investigated different scenarios for the production of the transient absorption feature seen in GRB 990705. We found that an unreasonable amount of iron in the circumburster material (CBM) would be required if the transient nature of the absorption feature was due to photoionization, not effectively balanced by recombination.

More plausible CBM parameters are found assuming that the absorption is photoelectric absorption in dense clouds with covering factor ~ 1 around the burst source, although rather extreme clumping ($r_c/x \sim 4{\cdot}10^{-6}$) is required.

As an alternative to photoelectric absorption, Lazzati et al. (2001) have suggested resonant scattering by Fe XXVI in a high-velocity outflow with large velocity dispersion. This model requires less extreme clumping than the photoelectric-absorption scenario only if the Thomson depth through the CBM is assumed to be $\tau_{\rm T} \sim 1$. Also it appears to require a rather extreme mean outflow velocity of $v \sim 0.13$ c, which also implies a rather huge kinetic energy in the ejecta of $\sim 10^{53}\,\Omega$ ergs.

Both versions of the clumpy-CBM scenario seem to point towards progenitor models in which the GRB is preceded by a supernova, which ejects several solar masses of highly iron-enriched material into the environment. If photoelectric absorption is the principal absorption mechanism, then the delay between supernova and GRB can be estimated to $\Delta t \sim$ several years, while in the case of resonant scattering by Fe XXVI, $\Delta t \sim$ a few months.

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