

Discovery of a Transient Absorption Edge in the X-ray Spectrum of GRB 990705

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We report the discovery of a transient equivalent hydrogen column density with an absorption edge at ~ 3.8 kiloelectron volts in the spectrum of the prompt x-ray emission of gamma-ray burst (GRB) 990705. This feature can be satisfactorily modeled with a photoelectric absorption by a medium located at a redshift of ~ 0.86 and with an iron abundance of ~ 75 times the solar one. The transient behavior is attributed to the strong ionization produced in the circumburst medium by the GRB photons. The high iron abundance points to the existence of a burst environment enriched by a supernova along the line of sight. The supernova explosion is estimated to have occurred about 10 years before the burst. Our results agree with models in which GRBs originate from the collapse of very massive stars and are preceded by a supernova event.

The nature of the progenitors of celestial GRBs is an open issue of key astrophysical importance. Collapse of massive fast-rotating stars—the hypernova model (1)—or delayed collapse of a rotationally stabilized neutron star—the supranova model (2)—are among the favored scenarios for the origin of these events. Both models predict that the preburst environment is characterized by a high gas density, either as a result of strong winds from the massive progenitor in the case of a hypernova or because of a supernova (SN) event in the case of the supranova model (3). In the latter case the environment is expected to be enriched in heavy elements. The progressive photoionization of the circumburst material (CBM) by the GRB photons should produce in the burst x-ray spectrum transient low-energy cut-off and K-edge absorption features of the elements in the CBM (4). The detection of such features may allow us to estimate the density and composition of the CBM, the GRB redshift,

and, ultimately, the nature of the GRB progenitor. Owing to the coalignment of two detection units of the gamma-ray burst monitor (GRBM, 40 to 700 keV) (5, 6) with the

two wide-field cameras (WFCs, 2 to 26 keV) (7), the Italian-Dutch x-ray mission BeppoSAX can provide not only arc minute localizations of GRBs, but also measurements of their spectra in a broad (2 to 700 keV) energy band (8). Among the GRBs detected by the BeppoSAX WFC and GRBM, the event of 5 July 1999 (GRB 990705) is the second brightest in γ -rays (40 to 700 keV) after GRB 990123 and ranks in the top 15% in x-rays (2 to 26 keV). This burst triggered the GRBM on 5 July at 16:01:25 universal time and was positioned with an error radius of 3 arc min at right ascension $\alpha(2000) = 05^{\text{h}}09^{\text{m}}52^{\text{s}}$ and declination $\delta(2000) = -72^{\circ}08'02''$, in a direction close to the edge of the Large Magellanic Cloud. Optical and near-infrared observations of the GRB 990705 location led to the discovery of a reddened fading counterpart and a possible host galaxy (9). Recently, Holland *et al.* (10) have imaged the GRB 990705 field with the Hubble Space Telescope, detecting a spiral galaxy at the position of the GRB. Although the distance of this galaxy is not known, its size and brightness are compatible with a redshift $z \leq 1$ (11).

A 120,000 s follow-up observation with the BeppoSAX narrow-field instruments (12) was also performed starting ~ 11 hours after the GRBM trigger. In the first 7 hours of observing time, an x-ray source of 3.3σ significance, corresponding to $1.9 (\pm 0.6) \times$

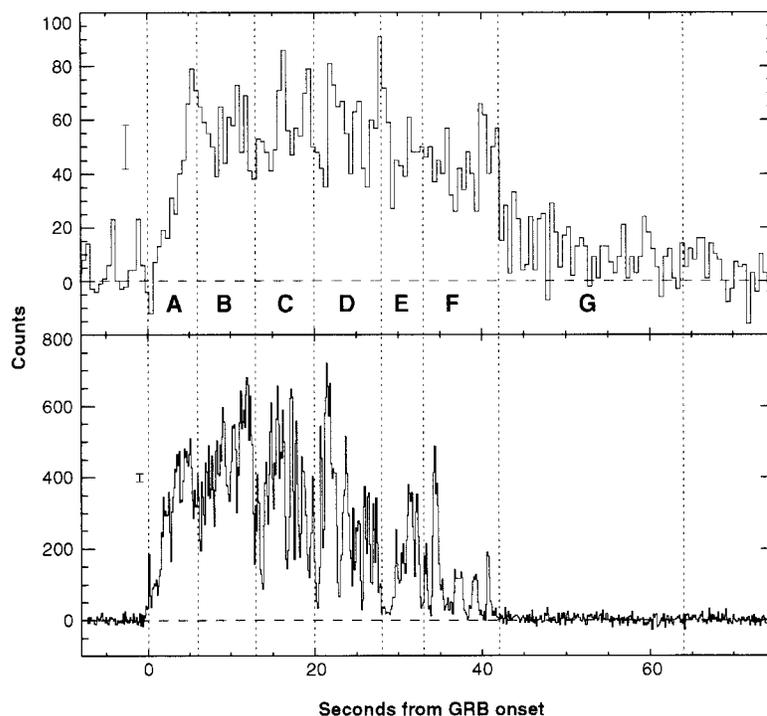


Fig. 1. (Top) WFC light curve (2 to 28 keV) with 0.5-s time resolution. (Bottom) GRBM light curve (40 to 700 keV) with 0.128-s time resolution. The vertical dotted lines limit the seven intervals in which spectral analysis was performed. The typical error is shown for each light curve on the left of the panel.

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10^{-13} erg $\text{cm}^{-2} \text{s}^{-1}$, was detected from a 2-arc min radius region centered on the near-infrared counterpart position. The source, 1SAX J0509.9-7207, was not visible after this time. On the basis of the fading behavior, 1SAX J0509.9-7207 is the most likely candidate of the GRB 990705 x-ray afterglow.

The event exhibits a highly structured pulse, a duration of 42 s in γ -rays and a longer duration (~ 60 s) in x-rays (Fig. 1). Following the investigation results obtained with a sample of BeppoSAX GRBs (8), we observed the spectral evolution of the GRB prompt emission by accumulating WFC and GRBM spectra in seven adjacent time intervals (Fig. 1). The 2- to 700-keV spectra of time intervals from C to G can be fit with a simple power-law model [$I(E) \propto E^{-\Gamma}$] with a continuously variable photon index in the range from 1.22 ± 0.02 to 2.24 ± 0.28 (the uncertainties quoted hereafter are 1 standard deviation). This hard-to-soft evolution is typical of GRB prompt emission spectra (8). Instead, the spectra of the first two time intervals (A and B in Fig. 1), of 6 s and 7 s duration, respectively, cannot be described

either by this model (see Fig. 2) or by the smoothed broken power-law model proposed by Band *et al.* (13) for GRB spectra. The description with a power-law photoelectrically absorbed by a gas with cosmic abundance (14) within our galaxy ($z = 0$) provides a good fit ($\chi^2/\text{df} = 5.55/9$) for the slice A with equivalent hydrogen column density $N_{\text{H}} = 8.7 (\pm 3.6) \times 10^{22} \text{ cm}^{-2}$ and power-law photon index $\Gamma = 1.08 \pm 0.03$. However, for time slice B the same model does not provide a good description ($\chi^2/\text{df} = 29.9/9$); the depression between 4 and 6 keV, which is apparent in this spectrum (Fig. 2, middle panel), is still present. A possible description of the feature ($\chi^2/\text{df} = 5.8/7$) is obtained by adding to the photoelectrically absorbed power law, whose best-fit parameter values are $N_{\text{H}} = 3.5 (\pm 1.4) \times 10^{22} \text{ cm}^{-2}$ and $\Gamma = 1.08 \pm 0.02$, an absorption edge of energy $E_{\text{edge}} = 3.8 \pm 0.3 \text{ keV}$, and optical depth $\tau = 1.4 \pm 0.4$. More naturally, the best fit of the time slice B spectrum ($\chi^2/\text{df} = 5.5/7$) is obtained with a photoelectrically absorbed power law with iron relative abundance with respect to the solar (15), $\text{Fe}/\text{Fe}_{\odot}$, and z of the absorbing medium left free to vary. In Fig. 3 we show the result; we obtain a photon index $\Gamma = 1.09 \pm 0.02$, an absorption column density of $N_{\text{H}} = 1.32 (\pm 0.30) \times 10^{22} \text{ cm}^{-2}$, a relative abundance $\text{Fe}/\text{Fe}_{\odot} = 75 \pm 19$, and a redshift $z = 0.86 \pm 0.17$. The value of the photon index agrees with the spectral hardness expected at the early times of the event. We have also tested other elements such as Ca, Cr, Co, and Ni with K-edge close to or higher than 3.8 keV. With Ca we still obtain a satisfactory fit, but the abundance required ($\text{Ca}/\text{Ca}_{\odot} = 1083 \pm 285$) is higher than the values found in Ca-rich astrophysical media (16).

We investigated whether the best model found for the B spectrum can also give a good description of the spectrum measured during the time interval A. The result is positive, but the statistics of the data do not allow us to

constrain all the model parameters. Assuming the best-fit values of $\text{Fe}/\text{Fe}_{\odot}$, z , and N_{H} found for the time interval B, the A spectrum is equally well described ($\chi^2/\text{df} = 8/10$) by this model with best-fit photon index $\Gamma = 1.09 \pm 0.02$ coincident with that found for the time interval B. Leaving only $\text{Fe}/\text{Fe}_{\odot}$ free to vary, the best-fit ($\chi^2/\text{df} = 7.9/10$) is found for $\text{Fe}/\text{Fe}_{\odot} = 71 \pm 22$. We can conclude that the best-fit model parameters found for the B spectrum also give a good description of the data during the first time interval.

The total 2- to 700-keV fluence of GRB 990705 calculated with the time-averaged spectrum is $9.3 (\pm 0.2) \times 10^{-5} \text{ erg cm}^{-2}$. Assuming the best-fit value of z , a standard cosmology with Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and deceleration parameter $q_0 = 0.5$ and isotropic emission, it corresponds to a released energy of $\sim 1.2 \times 10^{53} \text{ erg}$. For comparison, in the time intervals A + B, the 2- to 700-keV fluence is $\sim 3.8 \times 10^{-5} \text{ erg cm}^{-2}$, corresponding to a released energy of $\sim 4.7 \times 10^{52} \text{ erg}$, with almost all of it emitted above the energy of the absorption feature (3.8 keV).

The iron abundance inferred above points to the existence of an environment iron-rich for a SN along the line of sight. The most likely location for this material is in the immediate surroundings of the burst (see below), and we shall neglect the possibility of a chance alignment along the line of sight. Metal enrichments by a factor of about 100 above the solar value are considered typical of SNe (and of no other astrophysical environment). This is true for type I SNe, and for type II SNe with massive progenitors, especially in the case of strong mass loss during the main-sequence phase (17). Assuming the SN progenitor to have a mass $M_{\text{pr}} = 10 m_1 M_{\odot}$, and the supernova remnant (SNR) to be distributed in a spherical shell around the origin of the GRB site, we can estimate the ejecta distance D from the burst location from $M_{\text{pr}}/m_{\text{p}} = 4\pi D^2 N_{\text{H}}$ (where m_{p} is the proton mass). For the value $N_{\text{H}} = 1.3 \times 10^{22} \text{ cm}^{-2}$ derived above, we get $D \approx 3 \times 10^{17} d_{17}^{1/2} m_1^{1/2} \text{ cm}$, where d_{17} is the distance in units of $3 \times 10^{17} \text{ cm}$. This distance is actually an upper limit. Should the SNR be highly ionized even before the burst, N_{H} , which only measures the neutral column depth, would be a poor approximation for the total hydrogen column depth, pushing D to smaller values. For this value of D , one can estimate the time elapsed between the SN explosion and the burst. Assuming a SN ejecta speed of $10^4 v_4 \text{ km s}^{-1}$, we get $\delta t \sim 10 d_{17}/v_4 \text{ years}$. But the major test comes from showing that the absorption edge must disappear within a few seconds after the burst onset. To show that this is indeed the case, we notice first that the large optical depths $\tau \approx 1.4$ inferred from our observations imply that most photons above

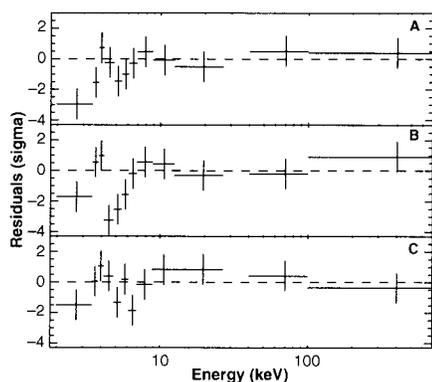


Fig. 2. Distribution of the residuals of the count spectra from the best-fit power-law model in the time intervals **A** (top), **B** (middle), and **C** (bottom). The major deviations of the data from the model are apparent in the lowest energy bin for the A spectrum and in the 3- to 6-keV band for the B spectrum, whereas no statistically significant deviations from a power-law are apparent for the C spectrum. The probability that the observed deviations are due to chance is 2.3×10^{-2} for time interval A and 9.0×10^{-6} for time slice B. The higher chance probability obtained for the deviations in the time interval A is likely due to the lower statistical quality of these data (see text). The possibility that instrumental effects caused the depression in B spectrum were investigated with negative results. The cross-calibration between the two instruments was verified by measurements of the Crab Nebula spectrum (22). The depression is also found in the ratio between the GRB count rate spectrum of the time interval B and the Crab Nebula spectrum taken with the same instrumentation. The depression is not apparent in the spectra accumulated over the successive time intervals (see bottom panel for the time slice C).

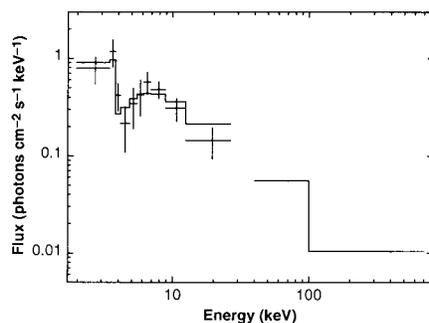


Fig. 3. Photon spectrum in the time slice B. The continuous plot shows the best-fit curve obtained with a power-law plus a photoelectric absorption by a medium at redshift $z = 0.86$, column density $N_{\text{H}} = 1.3 \times 10^{22} \text{ cm}^{-2}$, and iron abundance 75 times that of the sun.

the ionization threshold will be captured as they fly through the SNR, until near complete photoionization is achieved. The required number of photons for the complete photoionization of iron can be estimated, from the above parameters, as $\approx 5 \times 10^{56} m_1$, taking into account Auger ionization (4) and including the exceptional iron abundance detected here, 75 times higher than the solar value. On the other hand, during the first 13 s (duration of the time intervals A+B), this burst emits a time-averaged photon spectrum $dn = 4.2dE/E$ photons $\text{cm}^{-2} \text{s}^{-1}$ in the observer's frame. Within this time interval, and for a standard cosmology, this corresponds to a total of 3.6×10^{57} ionizing photons, where every photon above the threshold has been weighted with the ratio of its cross section to that at the threshold. Furthermore, the density due to a $10 m_1 M_\odot$ star dispersed in a volume of radius D is about 10^5 cm^{-3} , implying long recombination time scales ($>10^5$ s), depending on the exact, but rapidly varying, temperature. Thus, we conclude that the burst has about the right number of photons to cause the complete photoionization of iron within the B time interval, with recombination providing no real countereffect. A similar conclusion, with a more elaborate computation, has been reached, for generic parameters, by Böttcher *et al.* (4).

The implication of the above discussion is that the iron-rich material is, most likely, located around the burst site and cannot be located by chance along the line of sight. In fact, from the column density and iron abundance derived from the B spectrum, we have found that the absorbing material has an iron content ~ 75 times that of the solar value, and we have deduced that only a SNR can be responsible for this absorption. Calling R_{SNR} the radius of the SNR, and D its distance from the burst site, if the SNR were really located by chance along the line of sight, it would intercept only a fraction $\delta\Omega \sim (R_{\text{SNR}}/D)^2$ of all bursts photons. For a chance alignment, $R_{\text{SNR}} \ll D$, so that $\delta\Omega \ll 1$; however, this reduced number of burst photons would still have to ionize the whole SNR, i.e., several solar masses of matter. Because we have determined above that this is just about feasible for $D \approx 10^{17}$ cm, it follows that this cannot be accomplished for a chance alignment, where of course $D \ll 10^{17}$ cm, and we should be able to see the absorption edge through the entire burst duration. Given that this is not the case, we deduce that the SNR cannot be located by chance along the line of sight.

Lastly, the nondetection of an iron line (3σ upper limit of $1.5 \text{ photons cm}^{-2} \text{ s}^{-1}$) from the SNR is consistent with our model. Indeed, at least three factors may contribute to making the iron line weak. First, the burst may be beamed, whereas the line reemission certainly is not. Second, although we see the whole SNR, yet line reemission is diluted with respect to the

burst duration T_B by the light transit time D/c in the ratio cT_B/D . Third, although fluorescence may be fast, recombination must be slow, owing to the low overall material densities on the order of 10^5 atoms/cm^3 . Still, such a line should be present at later times, when the afterglow decreases sufficiently; four cases of this kind have been reported [GRB970508 (18), GRB970828 (19), GRB991216 (20), GRB000214 (21)].

Our results favor models in which GRBs originate from the collapse of very massive stars and are preceded by a supernova-like explosion.

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Observation of X-ray Lines from a Gamma-Ray Burst (GRB991216): Evidence of Moving Ejecta from the Progenitor

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We report on the discovery of two emission features observed in the x-ray spectrum of the afterglow of the gamma-ray burst (GRB) of 16 December 1999 by the Chandra X-ray Observatory. These features are identified with the Ly_α line and the narrow recombination continuum by hydrogenic ions of iron at a redshift $z = 1.00 \pm 0.02$, providing an unambiguous measurement of the distance of a GRB. Line width and intensity imply that the progenitor of the GRB was a massive star system that ejected, before the GRB event, a quantity of iron ~ 0.01 of the mass of the sun at a velocity ~ 0.1 of the speed of light, probably by a supernova explosion.

The nature of the progenitors of GRBs is an unsettled issue of extreme importance (1). The merging of a binary system of compact objects (such as black holes, neutron stars, and white dwarfs) or the collapse of a massive star (hypernova or collapsar) could deliver the energy required by a GRB, but observational evidence favoring a particular model is still missing. This evidence can be gathered through the measurement of lines produced by the medium surrounding the GRB (2–4). However, although observations

of GRB afterglows have provided much information on the broadband spectral continuum and its origin (5, 6), they have not yet given results of comparable importance on spectral lines. In the optical range, current measurements are inconclusive, because all of the spectral emission lines observed so far are produced by the host galaxy rather than at the burst site. The x-ray range appears more promising because theoretical computations show that only a dense, massive medium close to the GRB site—such as that expected