On the X-ray lines in the afterglows of GRBs

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ABSTRACT

The observation of X-ray lines in the afterglow of GRB 011211 has been reported, and challenged. The lines were interpreted as blue-shifted X-rays characteristic of a set of photoionized "metals", located in a section of a supernova shell illuminated by a GRB emitted a couple of days after the supernova explosion. We show that the most prominent reported lines coincide with the ones predicted in the "cannonball" model of GRBs. In this model, the putative signatures are Hydrogen lines, boosted by the (highly relativistic) motion of the cannonballs (CBs). The corresponding Doppler boost can be extracted from the fit to the observed I-, R- and V-band light-curves of the optical afterglow of GRB 011211, so that, since the redshift is also known, the line energies are –in the CB model– absolute predictions. We also discuss other GRBs of known redshift which show spectral features generally interpreted as Fe lines, or Fe recombination edges. The ensemble of results is very encouraging from the CB-model's point of view, but the data on each individual GRB are not good enough to draw (any) objectively decisive conclusions.

Subject headings: gamma rays: bursts—X rays: Lines

Introduction

There is mounting evidence from late-time observations of the optical afterglows (AGs) of relatively nearby (redshift $z < 1$) gamma ray bursts (GRBs) that long duration GRBs are produced in the explosions of supernovae akin to SN1998bw (Galama et al. 1998), by the ejection of ordinary baryonic matter –essentially ionized Hydrogen– in the form of plasmoids or "cannonballs" (CBs), with very highly relativistic Lorentz factors ($\gamma \sim 10^3$) (Dar and De Rújula 2000a,b, Dado et al. 2002a,b,c), but otherwise similar to the ones observed in quasars (Marscher et al. 2002) and microquasars (e.g., Mirabel and Rodriguez 1994; Belloni et al.

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1997; Mirabel and Rodriguez 1999; Rodriguez and Mirabel 1999 and references therein). The ejection of these cannonballs (CBs) close to the line of sight makes their sky-projected motion appear extremely superluminal[3].

On Dec. 11, 19:09:21 UT 2001 the long duration (~ 270 s) GRB 011211 was detected in the constellation Crater by BeppoSAX (Gandolfi et al. 2001). Approximately ten hours after the GRB, its optical afterglow was detected by Grav et al. (2001) and was followed by measurements of its declining light-curve by Bloom et al. (2001), Jensen et al. (2001), Holland et al. (2002), Bhargavi et al. 2001; and Fruchter et al. (2001), who also measured its redshift: $z = 2.141$, confirmed in turn by Gladders et al. (2001). The GRB's host galaxy was detected, with a red magnitude $R_{host} = 25.0 \pm 0.3$, by Burud et al. (2001).

Observations with XMM-Newton of the X-ray afterglow of GRB 011211 started at 06:16:56 UT on December 12, 2001, 11 h (39.6 ks) after burst, and lasted 27 ks (Reeves et al. 2002a). The analysis of the X-ray spectrum revealed significant evidence for emission lines only in the first 10 ks of observations. The emission lines that were fitted to the first 5 ks data had energies of 1.40 ± 0.05 keV, 2.19 ± 0.04 keV, 2.81 ± 0.04 keV, 3.79 ± 0.07 keV, and 4.51 ± 0.12 keV, in the GRB rest frame. They were interpreted by the observers as Kα lines from MgXI, SiXIV, SXVI, ArXVIII and CaXX, blueshifted by the motion at $\beta = v/c = 0.086 \pm 0.04$ of a shell ejected by a massive GRB progenitor in a supernova (SN) explosion having occurred a couple of days prior to the GRB. In this interpretation, a section of the SN shell near the line of sight was illuminated and reheated to a temperature of $T \sim 4.5 \pm 0.5$ keV by the beamed GRB, and it emitted the blueshifted X-ray lines.

Borodzin and Trudolyubov (2002) have criticized the above interpretation by noticing that the data showing the lines were accumulated during the first 5 ks of observations, while the source was located near the edge of a CCD chip, and that the lines disappeared as the satellite was subsequently repositioned. Moreover, the background data collected over the edge of the CCD show a very significant peak at the position of the most prominent alleged line. Rutledge and Sako (2002) have also criticized the significance of these data on statistical grounds. Reeves et al. (2002b) have responded to these critiques and insisted on the significance of their results, though they find that a fit without the two lines of minimum and maximum energy (attributed to MgXI and CaXX) is as good, or even a little better, than the fit with all five lines.

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[3]With the exception (Dar and De Rújula 2000a) of the very close-by GRB 980425, associated to SN1998bw, this "hyperluminal" motion is not directly observable, but it was suggested (Dado et al. 2002d) that it gives rise to the observed scintillations in the GRB radio afterglows (Taylor et al. 1997) and may thereby be measurable.

We cannot enter into the above controversy. In what follows, we discuss the data in Reeves et al. (2002a) at face value for, even if their significance is weakened, they constitute a good stage within which to discuss the predictions of the CB model (Dar and De Rújula 2000a) concerning X-ray lines in GRB afterglows. We concentrate on GRB 011211 because it has, so far, the best measured X-ray spectrum, but we also discuss other GRBs of known redshift (970508, 970828 and 991216) in which Fe lines and/or a recombination edge have been claimed to be observed. In all cases these "lines" or "recombination edges" are not truly observationally established; we shall often refer to them as spectral *features,* for the sake of precision.

The interpretation of the X-ray features in Reeves et al. (2002a) as metal lines is not without problems. First, the non-detection of the Fe Kα line was argued to be due to the relatively long time it takes the β decay chain $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ to produce Fe^{56} in supernova explosions. This appears to be inconsistent with the fact that the only X-ray lines with large flux and equivalent width previously claimed to be detected in GRB afterglows were attributed to Fe lines: the BeppoSAX results for GRB 970508 (Piro et al. 1998) and GRB 000214 (Antonelli et al. 2000), the ASCA observations for GRB 970828 (Yoshida et al. 1999; 2001) and the Chandra data on GRB 991216 (Piro et al. 2000). Second, the fitted blueshift of the X-ray lines is supposedly due to the beaming of the GRB radiation that illuminates only a small section of the expanding SN shell, near the line of sight. The energy deposition time in such a segment is very short *in the observer frame*: the GRB ejecta is moving initially with a large Lorentz factor γ, and it overtakes a SN shell with an estimated radius $R_{SNS} \sim 10^{15}$ cm in $t \sim (1+z)\, R_{SNS}/c\, \gamma^2 \leq 10$ sec of observer's time, for $\gamma > 100$. The radiative cooling time of an optically thin SN shell with an electron density $n_e \sim 10^{15}\, cm^{-3}$ and a temperature of 4.5 keV is also extremely short: $\tau \ll 1$ s. The arrival times (in the observer frame) of recombination photons from the SN shell sector illuminated by a GRB jet of opening angle $\theta = 20^o$ are spread over $t = R_{SNS}\, (1+z)\, (1-\cos\theta)/c = 1.75$ h after the GRB, while the putative XMM lines were observed 11 h after burst. These, and other puzzling geometrical and physical details of the model, leave ample room for other interpretations of the observations, should they be real.

An alternative interpretation (Dar and De Rújula 2001a) is that the spectral features observed in the X-ray afterglows of GRBs are optical Hydrogen-recombination lines from the CBs that produce GRBs, Doppler shifted to the X-ray band by the CBs' highly relativistic motion ($\gamma \sim 10^3$) and observed[4] at very small angles ($\theta \sim 1/\gamma$).

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[4]Doppler-shifted Lyman, Balmer and HeI lines have been detected from the mildly relativistic jets of SS433 (e.g. Margon 1984; Kotani et al. 1996; Eikenberry et al. 2001).

In this paper we show that the energies of the X-ray emission lines perhaps detected in the afterglow of GRB 011211 happen to coincide with the energies of Hydrogen's Balmer and Lyman lines, redshifted by $1 + z = 3.141$ due to the cosmic expansion, and blueshifted by a Doppler factor $\delta \sim 840$. This value of δ is, as we shall see, that of the CBs at the time of the observation of the putative X-ray lines (some 11h after burst) obtained from a Cannonball-Model fit to the light-curve of the optical afterglow of GRB 011211, prior to the reported X-ray observations. What this means is that the positions of the X-ray lines —*predicted* in the CB model— coincide with the observed positions of the most prominent spectral features in the data.

In discussing the previous indications for "Fe" lines in the AGs of GRBs 970508, 970828 and 991216 (Dar and De Rújula 2001a) we argued that they were compatible with Lyα emission, though the data were insufficient to make a decisive distinction between a highly boosted hydrogen line and a merely redshifted Fe line. Here, we rediscuss this issue in more detail, now that we also have independent a-priori determinations of the values of δ in each individual GRB at the time of the corresponding X-ray observations. As for the case of GRB 011211, all prominent features in the spectra coincide in energy with lines that can be expected in the CB model.

The CB model predicts that the X-ray lines should be relatively narrow and move in time from higher to lower frequencies, as the CBs decelerate while ploughing though the interstellar medium (ISM). The blending of the emissions from unresolved CBs with somewhat different Doppler factors, and/or a poor energy resolution, may broaden the lines considerably and conceal the time-dependence of their energy. In the current data, the limited energy resolution and the required integration over relatively long time-intervals would certainly have precluded the observation of the predicted line motion.

CB model fit to the AG of GRB 011211

We do not give here a detailed description of the CB model, which we have discussed *at nauseam* elsewhere (Dar and De Rújula 2000a,b, Dado et al. 2002a,d). We simply reproduce the formulae required for the analysis at hand.

In the CB model the afterglow has three origins: the ejected CBs, the concomitant SN explosion, and the host galaxy (HG). These components are usually unresolved in the measured GRB afterglow, so that the corresponding light curves and spectra are measures of the cumulative energy flux density:

$$\mathrm{F_{AG}} = \mathrm{F_{CBs}} + \mathrm{F_{SN}} + \mathrm{F_{HG}}\,. \tag{1}$$

The contribution from the host galaxy dominates the light-curve at late times and was fitted (in each band) to the late afterglow. The contribution of the supernova was modelled by assuming an SN1998bw-like contribution placed at the GRB redshift, z = 2.141. In this particular GRB, as in all the ones with redshift z > 1.2, the SN contribution is too dim to be observable (Dado et al. 2002a).

In the CB model the jetted cannonballs are made of ordinary matter, mainly hydrogen. For the first $\sim 10^3$ seconds of observer's time, a CB is still cooling fast and emitting via thermal bremsstrahlung (Dado et al. 2002a), but after that its emissivity is dominated by synchrotron emission from ISM electrons that penetrate in it. Integrated over frequency, this synchrotron emissivity is approximately equal to the energy deposition rate of the ISM electrons in the CB[5]. The electrons from the ISM that enter the CBs are Fermi accelerated there to a broken power-law energy distribution with a "break" energy (or more appropriately a "bend" energy) equal to their incident energy in the CBs' rest frame. In that frame, the electrons' synchrotron emission (prior to attenuation corrections) has an approximate spectral energy density (Dado et al. 2002d):

$$F_{_{CB}}[\nu, t] = E_\gamma \frac{dn_\gamma}{d\,E_\gamma} \sim f_0\, \frac{(p-2)\,\gamma^2}{(p-1)\,\nu_b} \frac{[\nu/\nu_b]^{-1/2}}{\sqrt{1+[\nu/\nu_b]^{(p-1)}}} \tag{2}$$

where $p \approx 2.2$ is the spectral index of the Fermi accelerated electrons prior to the inclusion of radiation losses, f_0 is an explicit normalization constant proportional to the ISM density, $\gamma(t) = 1/\sqrt{1-\beta^2}$ (with $\beta = v/c$) is the Lorentz factor of the CBs, and $\nu_b \simeq 1.87\times 10^3\,[\gamma(t)]^3$ Hz is the "injection bend" frequency in the CB rest frame[6]. The X-ray frequency domain in Eq. (2) is always at $\nu \gg \nu_b$, so that the expected spectrum is $d\,n_\gamma/d\,E_\gamma \approx E^{-\alpha}$, with a slope $\alpha = (p+2)/2 \simeq 2.1$. The radiation emitted by a CB is Doppler-shifted and forward-collimated by its highly relativistic motion, and redshifted by the cosmological expansion. A distant observer sees a spectral energy flux:

$$F_{obs}[\nu, t] \simeq \frac{(1+z)\,\delta(t)^3\,R^2\,A(\nu, z)}{D_L^2}\, F_{_{CB}}\left[\frac{(1+z)\,\nu}{\delta(t)}, \frac{\delta(t)\,t}{1+z}\right] , \tag{3}$$

where R is the radius of the CB (which in the CB model tends to a calculable constant value $R_{max} = \mathcal{O}(10^{14})$ cm, in minutes of observer's time), $A(\nu, z)$ is the total extinction along the

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[5]The kinetic energy of a CB is mainly lost to the ISM protons it scatters; only a fraction $\leq m_e/m_p$ is re-emitted by electrons, as the AG.

[6]This bend frequency does not correspond to the conventional synchrotron "cooling break". It is produced by an *injection bend* in the high energy electron spectrum in the CB at the energy $E_b = \gamma(t)\ m_e\, c^2$ with which the ISM electrons enter the CB at a particular time in its decelerated motion (Dado et al. 2002d).

line of sight to the GRB, $D_L(z)$ is the luminosity distance[7] and $\delta(t)$ is the Doppler factor of the light emitted by the CB:

$$\delta(t) = \frac{1}{\gamma(t)\,(1-\beta(t)\cos\theta)} \simeq \frac{2\,\gamma(t)}{1+\theta^2\gamma(t)^2}\,, \tag{4}$$

where θ is the angle between the CB's direction of motion and the line of sight to the observer. The last approximation is valid in the domain of interest for GRBs: $\gamma^2 \gg 1$ and $\theta^2 \ll 1$. The total AG is the sum over CBs (or large individual GRB pulses) of the flux of Eq. (3).

For an interstellar medium of constant baryon density n_p, the deceleration of the CBs results in a Lorentz factor, $\gamma(t)$, that is given by (Dado et al. 2002a):

$$\begin{aligned}
\gamma &= \gamma(\gamma_0,\theta,x_\infty;t) = \frac{1}{B}\left[\theta^2 + C\,\theta^4 + \frac{1}{C}\right]\,,\\
C &\equiv \left[\frac{2}{B^2 + 2\,\theta^6 + B\,\sqrt{B^2+4\,\theta^6}}\right]^{1/3}\,,\\
B &\equiv \frac{1}{\gamma_0^3} + \frac{3\,\theta^2}{\gamma_0} + \frac{6\,c\,t}{(1+z)\,x_\infty}\,,
\end{aligned} \tag{5}$$

where $\gamma_0 = \gamma(0)$, and $x_\infty = N_{CB}/(\pi\,R_{max}^2\,n_p)$ characterizes the CB's slow-down in terms of N_{CB}, its baryon number and R_{max}, its radius (it takes a distance x_∞/γ_0, typically of $\mathcal{O}(1)$ kp, for the CB to slow down to half its original Lorentz factor).

In Fig. (1), we show that the optical afterglow of GRB 011211 in the IRV bands is very well fitted in the cannonball model of GRBs, by use of Eqs. (2) to (5). Besides the overall normalization, the fit involves three parameters: $\theta = 1.16$ mrad; $\gamma_0 = 834$, and $x_\infty = 0.271$ Mpc. We have fixed the spectral index in Eq. (2) to $p = 2.2$, since that value is compatible with the one fit, in the same manner, to *all* of the optical, X-ray and radio AG light-curves of GRBs of known redshift (Dado et al. 2002a,d).

The X-ray line data of GRB 011211

The X-ray spectrum of this GRB has been well measured, in comparison with previous cases. This is shown in Fig (2), which we have borrowed from the data analysis by Borodzin and Trudolyubov (2002). These authors find that the spectrum is compatible with a power-law of slope $\alpha = 2.14 \pm 0.03$, modified only by absorption in the Galaxy. A slope ~ 2.1 is expected

[7]The cosmological parameters we use are: $H_0 = 65$ km/(s Mpc), $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

in the CB model and —as extracted from the time-dependence of the optical and/or X-ray AGs— it is compatible with the observations for all GRBs of known redshift (Dado et al. 2002a,b,c). In Fig (2) we also show how very compatible with the data at hand the expected $\alpha \approx 2.1$ actually is.

The observation and the properties of the lines reported in Reeves et al. (2002a) are model dependent; they are in particular very sensitive to the continuum underlying the peaks in the data. This can be seen in Fig. (3a), where we have redrawn the data in Fig. 2 of Reeves et al. (2002a) without a model curve to guide the eye (this figure reports data for the 5 ks interval in which the lines were seen). Quite clearly, one can draw a smooth continuum on this figure, above which the alleged lines would lose much of their significance. To draw such a continuum with as little prejudice as possible we have first made a smooth fit to Fig. 1 of Reeves at al. (2002a), which displays the data on the complete 27 ks of observational time, where there are no significant line features. We have then redrawn this continuum[8] on top of the 5 ks data, with a normalization meant to underemphasize the possible non-smooth deviations; the result is shown in Fig. (3b). Clearly, with this continuum "background", the two alleged lines at ~ 1.21 and ~ 1.44 keV are not significant (these are the putative ArXVIII and CaXX lines). Also, the other three smaller-energy lines, particularly the lowest-energy one, are not very prominent[9]. The vertical lines in Fig. (3b) are CB model expectations, which we proceed to discuss.

Line emission in the CB model

As a CB —in a time of $\mathcal{O}(1)$ s after it exits the transparent outskirts of the shell of the SN associated with it— becomes transparent to the bulk of its enclosed radiation, its internal radiation pressure drops abruptly and its transverse expansion rate is quenched by collisionless, magnetic-field-mediated interactions with the ISM (Dado et al. 2002a). During this phase, the ISM electrons that enter the CB cool mainly by synchrotron emission. The synchrotron emission is partially reabsorbed by the partially ionized CB through free-free transitions at low radio frequencies and by bound–free and bound–bound transitions at optical frequencies (in the CB rest frame). The CB plasma cools mainly by line emission from electron–proton recombinations.

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[8]The zig-zag feature around 0.5 keV, also present in Fig. 1 of Reeves et al., (2002a) is presumably the effect of the oxygen absorption edge in our Galaxy, somewhat smoothed by resolution.

[9]Recall that Reeves et al. (2002b) also find that the inclusion of the lowest and highest energy lines does not improve their fits.

Line energies: the case of GRB 011211

At a given time t, the CBs are viewed with a blue-shifting Doppler factor $\delta(\mathrm{t})$, so that a line of laboratory wavelength λ_{i} would be observed at a redshift z to have an energy uplifted by a "boost" factor B(t):

$$\begin{aligned} \mathrm{E_i(t)} &= \mathrm{B(t)\,E_i^{lab}} = \mathrm{B(t)}\,\frac{\mathrm{h\,c}}{\lambda_\mathrm{i}} \\ \mathrm{B(t)} &\equiv \frac{\delta(\mathrm{t})}{1+\mathrm{z}}\,, \end{aligned} \tag{6}$$

with $\delta(\mathrm{t})$ as in Eq. (4). The parameters that we fit to the optical AG of GRB 011211, substituted in Eqs. (4,5), result in $\gamma(\mathrm{t}) = 686$ at $\mathrm{t} \sim 11$ h, the time when the lines were seen. For a redshift $\mathrm{z} = 2.141$, Eq. (4) implies $\delta(\mathrm{t}) \simeq 840$, so that lines at rest in the CBs would be uplifted in energy by a factor $\mathrm{B(t)} \simeq 267$ at the time of the observations.

In Fig. (4) we show the predicted evolution of the energy $\mathrm{E_i(t)} \propto \delta(\mathrm{t})$ of the H lines as a function of time, for the case of GRB 011211. The X-ray observations of Reeves et al. (2002a) lasted too little for the line motion to have an observable effect, given their limited statistics and energy resolution. This is also the case for all the other GRBs to be discussed below.

In normal dense astrophysical plasmas, e.g., plasma clouds in the broad-line region of quasars (see, e.g., Laor et al. 1997 and references therein), the prominent Hydrogen lines are: $\mathrm{H}\alpha[\lambda 6563]$, $\mathrm{H}\beta[\lambda 4861]$, the higher energy Balmer lines accumulating at $\mathrm{H}\infty[\lambda 3647]$, and the $\mathrm{Ly}\alpha[\lambda 1215.7]$ line. The first three of these lines are, as one can see in Fig. (3b), at the positions where there are, perhaps, indications in the data of an excess over a smooth continuum: the predicted energies are 0.50, 0.68 and 0.91 keV, while the fit of Reeves et al. (2002a) results in 0.45 ± 0.05, 0.70 ± 0.02 and 0.89 ± 0.01 keV, respectively. The $\mathrm{Ly}\alpha$ line ought to be uplifted in energy to ~ 2.74 keV, above the range shown in Fig. (3). Interestingly, there is a feature in the 27 ks data (Fig. 1 of Reeves et al. 2002a) which, although it is also not very significant, sits at that very point[10]. All these features have widths comparable with the experimental resolution of somewhat less than 100 eV.

We have argued in Dar and De Rújula (2000, 2001a,b) and Dar et al. (2000) that the ordinary matter constituting cannonballs ought to be shattered by their violent collision with the SN shell, and exit it in the form of unbound baryons and electrons, so that the expected X-ray lines would be merely hydrogenic. But it is quite possible that the collisions

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[10] We do not have access to that figure in an e-friendly format, and it is too complicated to reproduce by hand, or by scanning.

be somewhat "cushioned" (Hubbard and Ferry, in preparation, Hubbard 2002) such as to leave some nuclei unscathed, as the CBs gather SN shell material in their passage: in their collisions with shell nuclei, the baryons or nuclei of the CBs lose a considerable fraction of their initial Lorentz factor (Dar and De Rújula 2001b), but they may do it in many soft collisions, as opposed to a few hard ones. It that case, one may expect to see also He- or even "metal" lines, uplifted in energy by as much as the H lines are. The predicted position of the He$\alpha[\lambda 5875]$ of HeI is also shown in Fig. (3b). One quasi-degenerate example of lines, prominent in the broad line region of quasars, is the pair MgII[λ2796.3; λ2803.5], which in the case at hand should appear at 1.19 keV, see Fig. (3b). This is where Reeves et al. (2002a) claim to see Ar XVIII, at 1.21 ± 0.02 keV. But the possible choices (other than for H and perhaps He and Ni lines) are far too vast to draw definite conclusions from these very scant data. This is even more so in the "standard" interpretation, in which the overall line-shift is a free parameter.

Other GRBs with X-ray spectral "features"

There are GRBs of known redshift in whose X-ray data the observation of "Fe" lines or recombination edges has been claimed; in chronological order: GRB 970508 (Piro et al., 1999), GRB 970828 (Yoshida et al. 1999, 2001 and references therein) and GRB 991216 (Ballantyne et al. 2002 and references therein). The corresponding data are shown in Figs. (5, 6, 7), from which we have, as for GRB 011211 in Fig. (3), eliminated theoretical lines that unavoidably "guide the eye". It is clear from these figures, without further ado, that without a very good knowledge of the shape and magnitude of the smooth continuum underlying the putative lines, it is not possible to claim the observation of statistically convincing effects. The evidence for a line is more convincing in the case of GRB 000214 (Antonelli et al. 2000), but its redshift is not known, precluding an explicit analysis.

The case for the observation of line features is presumably weakest for GRB 970508, see Fig. (5). The upper panel is the spectrum of the "early" X-ray AG, extending for some 30 ks after the start of the observations, at 6 hours after the GRB. The lower figure shows the later data around 1 day after the burst. The feature at E $\sim$ 3.4 keV in the upper panel has been interpreted as an Fe line at the GRB's redshift z = 0.835 (Piro et al. 2000). In Dado et al. (2002a) we have fit the optical AG of this GRB in the CB model, the resulting parameters are $\theta = 3.51$ mrad, $\gamma_0 = 1123$ and $x_\infty = 0.293$ Mpc[11]. With these parameters,

[11]The value of x_∞ is for the early part of the AG, the time at which the X-ray line was possibly observed, which preceds the abrupt rise in this AG at ~ 1 day, discussed in Dado et al. (2002a).

we obtain $\delta(\mathrm{t_{obs}}) \simeq 142$ and $\mathrm{B(t_{obs})} = 78$, nearly constant through the X-ray observation time, as in Fig. (4). Boosted by this $\mathrm{B(t_{obs})}$, one of the potentially strong lines, the $\mathrm{n} = 2$ to $\mathrm{n} = 1$ transition in HeII would be at 3.17 keV, where the feature is in the upper panel of Fig. (5). For this particular GRB, which is viewed at a relatively large angle, δ and B are quite small, and other putative lines are at sub-keV energies, where absorption appears to be very strong. The data, however, are not good enough to extract conclusions from the coincidence of the observed feature and the He line, nor from its Fe-line interpretation.

GRB 970828, in spite of its being well localized (Remillard et al. 1997, Smith et al. 1997, Marshall et al. 1997, Murakami et al. 1997, Greiner et al. 1997), had no detectable optical AG down to a magnitude $\mathrm{R} \simeq 23.8$ (Groot et al. 1998). Such "orphan" GRBs are expected in the CB model, not only because of possible absorption, but because the time at which the optical AGs begin to decline very fast is extremely sensitive to the circumburst ISM density, and may be as short as $\mathcal{O}(10^{-2})$ days, see Fig. (6) of Dado et al. (2001). In that article, lacking optical data, we fit the X-ray light curve of this GRB in the CB model, with the result that its parameters were $\gamma_0 = 1153$, $\theta = 0.86$ mrad and $\mathrm{x}_\infty = 0.87$ Mpc (these values are not as well determined as in GRBs with well measured optical AGs). Yoshida et al. (1999, 2001) analized the spectra of this GRB in three time intervals, in the middle one of which, at $\mathrm{t_{obs}} \sim 1.2 \times 10^5$ s, they found hints of structure, reproduced in Fig. (6). These authors first ascribed the feature at $\mathrm{E} \sim 4.8$ keV to the Fe K_α line, which resulted in a prediction of a redshift $\mathrm{z} = 0.33$. The subsequently measured redshift of the likely host galaxy is $\mathrm{z} = 0.9578$ (Djorgosvski et al. 2001). More recently Yoshida et al. (2001) attribute the feature to a recombination edge of Fe. The CB model fit results in $\delta(\mathrm{t_{obs}}) \sim 1004$ for which, at the GRBs redshift, $\mathrm{B(t_{obs})} \sim 513$, and a Ly$\alpha$ line would be at a predicted $\mathrm{E} \sim 5.2$ keV which is, as shown in Fig. (6), quite compatible with the position of the apparent feature in the data.

In the case of GRB 991216, Piro et al. (2000) have interpreted the features at ~ 3.4 keV and > 5 keV of the X-ray spectra shown in Fig. (7) as the 6.7 keV K_α line of He-like Fe, and a Fe recombination edge, respectively. Ballantyne et al. (2002) have analized in detail the first of these features in a specific model. They report that the "F-test" significance of the K_α line is 98%, an explicit example of how difficult it is to convince oneself that lines have actually been observed: a $2.33\,\sigma$ effect in a Gaussian distribution has the same significance[12]. For this GRB, the CB model fit to the optical AG results in $\gamma_0 = 906$, $\theta = 0.43$ mrad and $\mathrm{x}_\infty = 0.462$ Mpc, which imply, at the average observational time $\mathrm{t_{obs}} \sim 39$ hours, $\delta(\mathrm{t_{obs}}) \sim 905$ and a boost $\mathrm{B(t_{obs})} \sim 448$ at the GRB's redshift $\mathrm{z} = 1.02$. For that predicted boost, there are no

[12]These authors also find that an extra non-Galactic absorption "is significant *only* at the 97% confidence level" (the emphasis is ours, and 97% is $2.17\,\sigma$).

indications of deviations from a smooth distribution at the positions of the H Balmer lines, except, perhaps, for the corresponding recombination edge. But the n = 3 to n = 2 line of HeII and the H Lyα line very snuggly coincide with the two allegedly significant features of the X-ray spectrum, as shown in Fig. (7) (the alleged Fe line centers at 3.4 keV, the predicted He line is at 3.39 keV). But, once again, the data are not precise enough to extract decisive inferences.

Line intensities

A detailed modelling of the line intensities is a very involved problem. Here we can only offer a qualitative, order-of-magnitude discussion of the subject.

The recombination rate in a hydrogenic CB is (Osterbrock 1989):

$$R_{rec} \simeq 6.0 \times 10^{44}\, x^2 \left[\frac{N_{CB}}{6\times 10^{50}}\right] \left[\frac{n_b}{10^7\,cm^{-3}}\right] \left[\frac{T}{10^4\,K}\right]^{-0.7} s^{-1}\,, \tag{7}$$

where N_{CB} is the total baryon number of the CB, n_b is its baryon density, and x is the fraction of ionized hydrogen in the CB. The line emission luminosity in the CB rest frame is $R_{rec} \times 13.6\,eV$. The corresponding radiation is boosted and relativistically beamed to an observed energy flux:

$$\begin{aligned} F_{lines} &\simeq 2.5\times 10^{-11}\,(1+z)\,erg\,cm^{-2}\,s^{-1} \\ &\times\; n_{CB}\,x^2 \left[\frac{D_L}{2\times 10^{28}\,cm}\right]^{-2} \left[\frac{N_{CB}}{6\times 10^{50}}\right] \left[\frac{n_b}{10^7\,cm^{-3}}\right] \left[\frac{T}{10^4\,K}\right]^{-0.7} \left[\frac{\delta}{10^3}\right]^4, \end{aligned} \tag{8}$$

where n_{CB} is the number of CBs (or prominent GRB pulses), and the luminosity distance D_L is normalized to its reference value for z = 1 and our chosen cosmological parameters.

For the reference parameters to which we have normalized Eq. (8), the flux is comparable to those reported for the X-ray line-emissions in GRB afterglows. Its exact value depends rather weakly on temperature and quite strongly on the ionization fraction x in the CBs, whose qualitative evolution can be assessed as follows. The bound-free cross section for photoionization of atomic hydrogen in its n-th excited state by photons with frequency above the ionization threshold, $\nu_n = 3.29\times 10^{15}/n^2\,Hz$, is given by $\sigma_\nu(n) = n\,\sigma_1\,\bar{g}_n(\nu/\nu_n)^{-3}$, with $\sigma_1 = 64\,\alpha\,\pi\,a_0^2/(3\sqrt{3}) \simeq 7.91\times 10^{-18}\,cm^2$ ($a_0 = 0.53\times 10^{-8}$ cm is the Bohr radius and $\bar{g}_n$ is the Gaunt factor for photo-absorption by hydrogen). Thus, a partially ionized CB with a typical radius $R_{CB} \simeq 2.5\times 10^{14}$ cm, and density $n_b \sim 10^7\,cm^{-3}$, is opaque to optical radiation. The recombination photons are repeatedly reabsorbed and reemitted while diffusing out of the CB. The optical radiation of a CB (X-rays in the observer's frame) is the sum of the line emission and the power-law synchrotron radiation from its surface. In a quasi-equilibrium state the ionization fraction is such as to keep the local recombination rate equal to the joint ionization rate by the synchrotron and recombination radiations[13]. The temperature is controlled by the same equilibrium, by the CBs' surface energy loss and by the energy input from the continuing collision of the CB and the ISM. It is difficult to ascertain without a complete modelling of the problem. In Eq. (8) we have used a reference T so that the maximum of the thermal distribution (at $\sim 3\,\mathrm{T}$) is of the order of magnitude of the line energies of Hydrogen, whose transitions dominate the thermal energy transport within the CB.

Initially, the ionization is close to maximal and the line radiation of Eq. (8) results in a flux comparable to that of the power-law-behaved synchrotron radiation in the X-ray band. Later, when $\gamma(t)$ decreases, equilibrium between the ionization and recombination rates results in a rapid decline of line emission: the recombination rate is $\propto x^2$ and the photo-ionization rate is $\propto (1-x)\,\gamma^2$, so that when x is small, $x \propto \gamma$, and the recombination rate decreases like γ^2. Moreover, the diffusion time of recombination photons becomes very long as $x \to 0$ which results in strong suppression of line emission. The derivation of an exact X-ray spectrum and its time dependence would require very complicated radiation-transport calculations which are beyond the scope of this paper.

Conclusions

We have studied an alternative (Dar and De Rújula 2001a) to the interpretation by Reeves et al. (2002a) of the X-ray data of XMM-Newton on GRB 011211. Unlike the quoted authors, we have not for the moment studied in detail the very involved question of the predicted absolute and relative intensities of the lines, which is very model dependent (the density profile, ionization level and temperature of a CB, as well as their time dependence, are quite complicated issues). But we have shown that, in the CB model, the positions of the lines are predictable and happen to coincide with the meager evidence for most of them. In the CB model long-duration GRBs are associated with SNe that are compatible with an approximately SN1998bw-like standard candle. Reeves et al. (2002a) adduce that their data supports this association; we contend that —if it does— it is not for the reasons they advance, but because their observations are consistent with CB-model expectations.

We have shown that the Fe-line candidates observed in three other GRBs could very

[13]The cooling rate of electrons via bremsstrahlung, $\mathrm{L_{brem}} \simeq 1.43 \times 10^{-27}\,\bar{\mathrm{n}}_\mathrm{e}\,\mathrm{T}^{1/2}\,\mathrm{erg\,s^{-1}}$, is more than three orders of magnitude smaller than the electron cooling rate via recombination and line emission.

well be H or He lines, again predictably boosted by the very fast motion of cannonballs. The individual data on each of the four GRBs that we have discussed is inconclusive, but the overall consistency of the CB-model interpretation of their X-ray spectral features is encouraging. In the CB model the presence of X-ray lines which —case by case— have predictable energies, is a very natural possibility. In contrast, in the other scenarios that have been discussed, the X-ray lines require in every instance the introduction of ad-hoc and sometimes rather exotic hypothesis on the surroundings of the GRB engine.

With better data it ought to be possible to distinguish the lines expected in the CB model from the ones of the standard GRB paradigm(s). Not only the line positions can, in the CB model, be foretold; but also their widths should be narrow, and predictably time dependent (Dar end De Rújula 2001a).

We thank Ehud Behar and Ari Laor for useful comments. The support of the Asher Fund for Space Research at the Technion is gratefully acknowledged.

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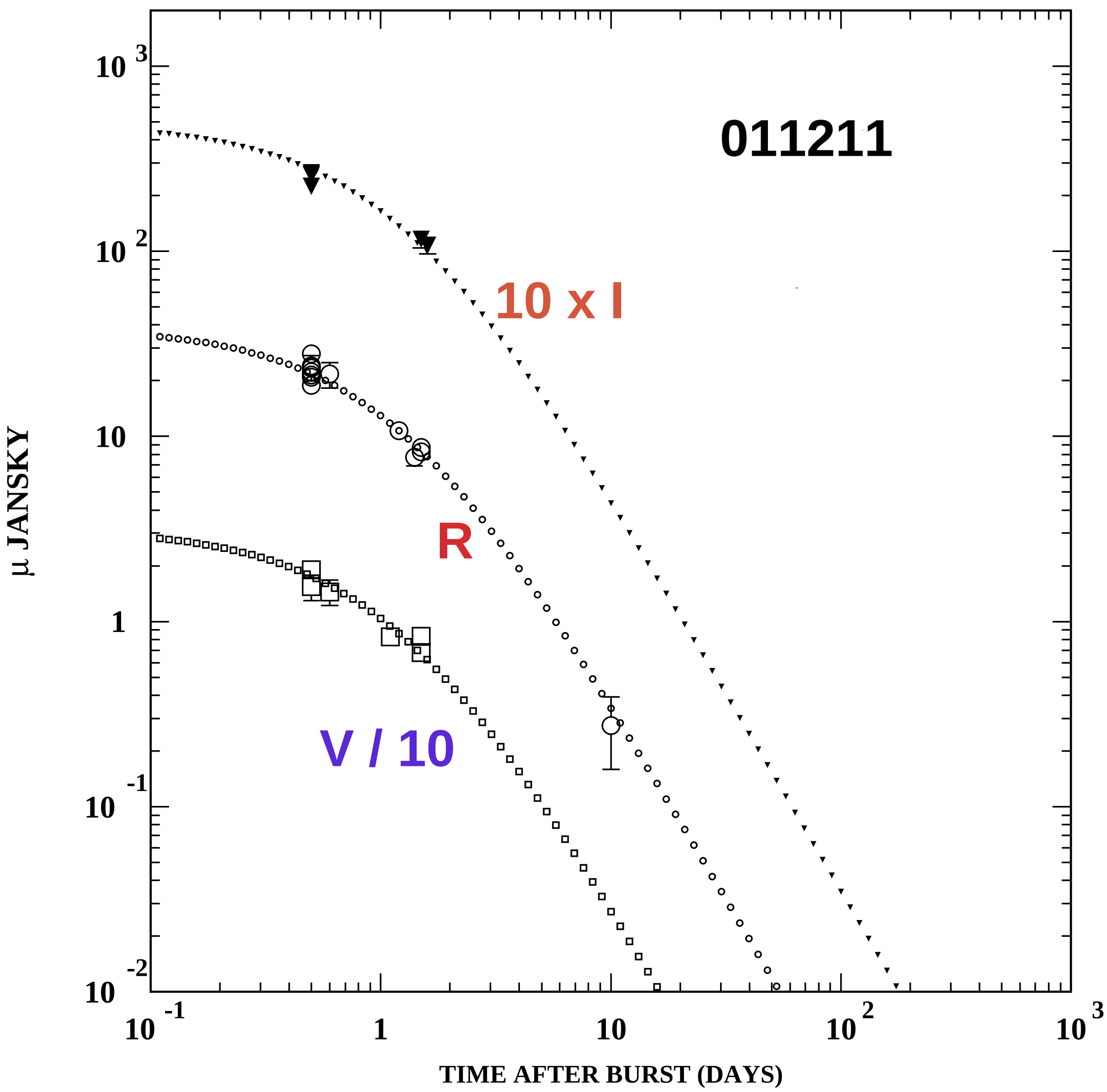

Fig. 1.— Comparison between the observations in the I, R and V bands of the optical afterglow of GRB 011211 and the CB model fit as given by Eqs. (2) to (5), corrected for extinction in our Galaxy. The figure shows (from top to bottom) 10 times the I-band, the R-band and 1/10 of the V-band.

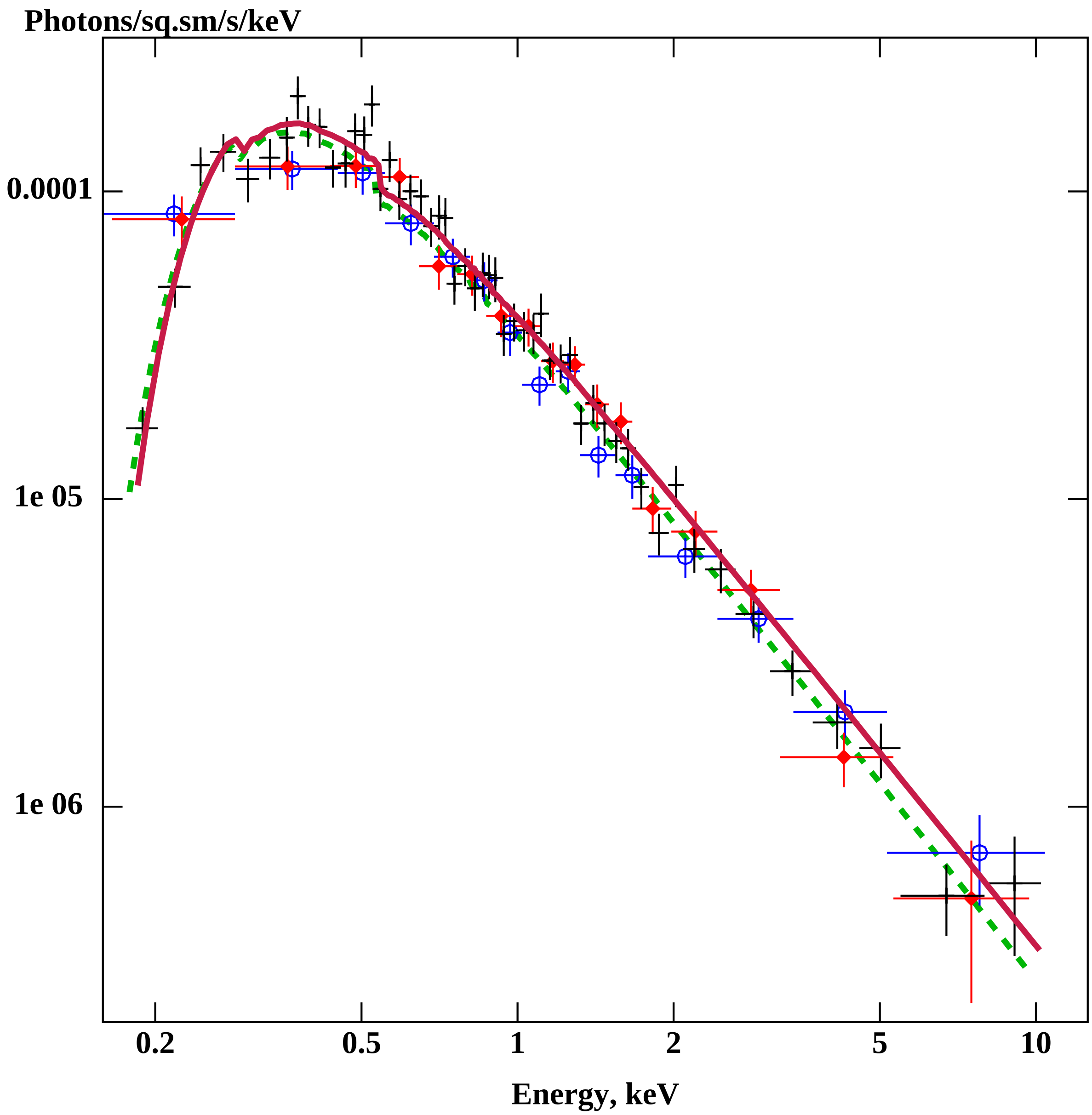

Fig. 2.— X-ray spectrum of GRB 011211, as analized by Borodzin and Trudolyubov (2002). The data are from various detectors on board XXM-Newton: MOS1 (circles), MOS2 (squares) and PN (no added symbols). A power-law is only modified by absorption in the Galaxy. The dashed line is for a best-fit spectral index of 2.14, the continuous line is for the value 2.1 characteristic of the CB model.

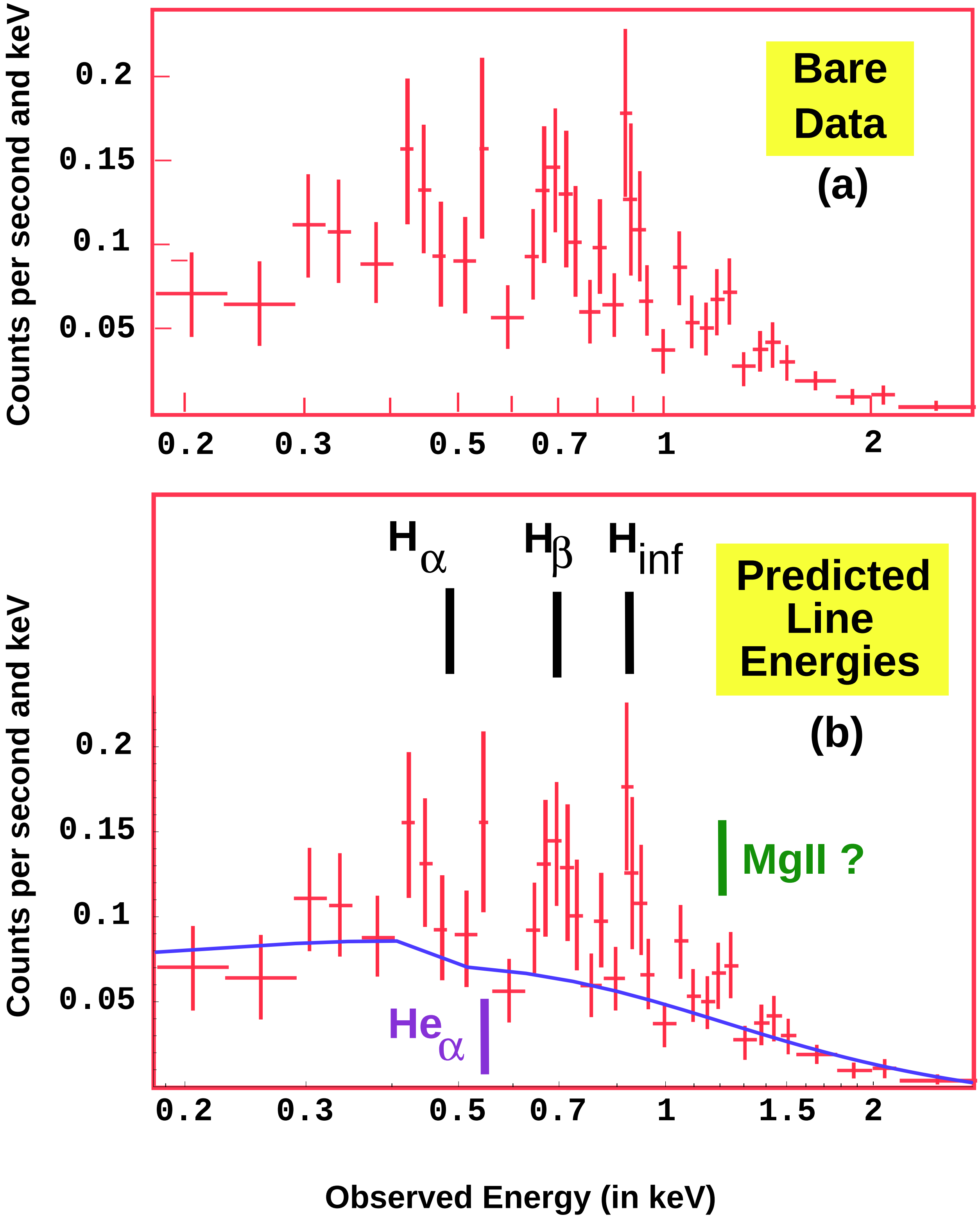

Fig. 3.— (a) X-ray spectrum of GRB 011211 during the 5 ks of observations in which putative line features were observed (Reeves et al. 2002). (b) The same data with a "background" line scaled from a fit to the full 27 ks of observations. The vertical lines are at the predicted positions of lines in the CB model.

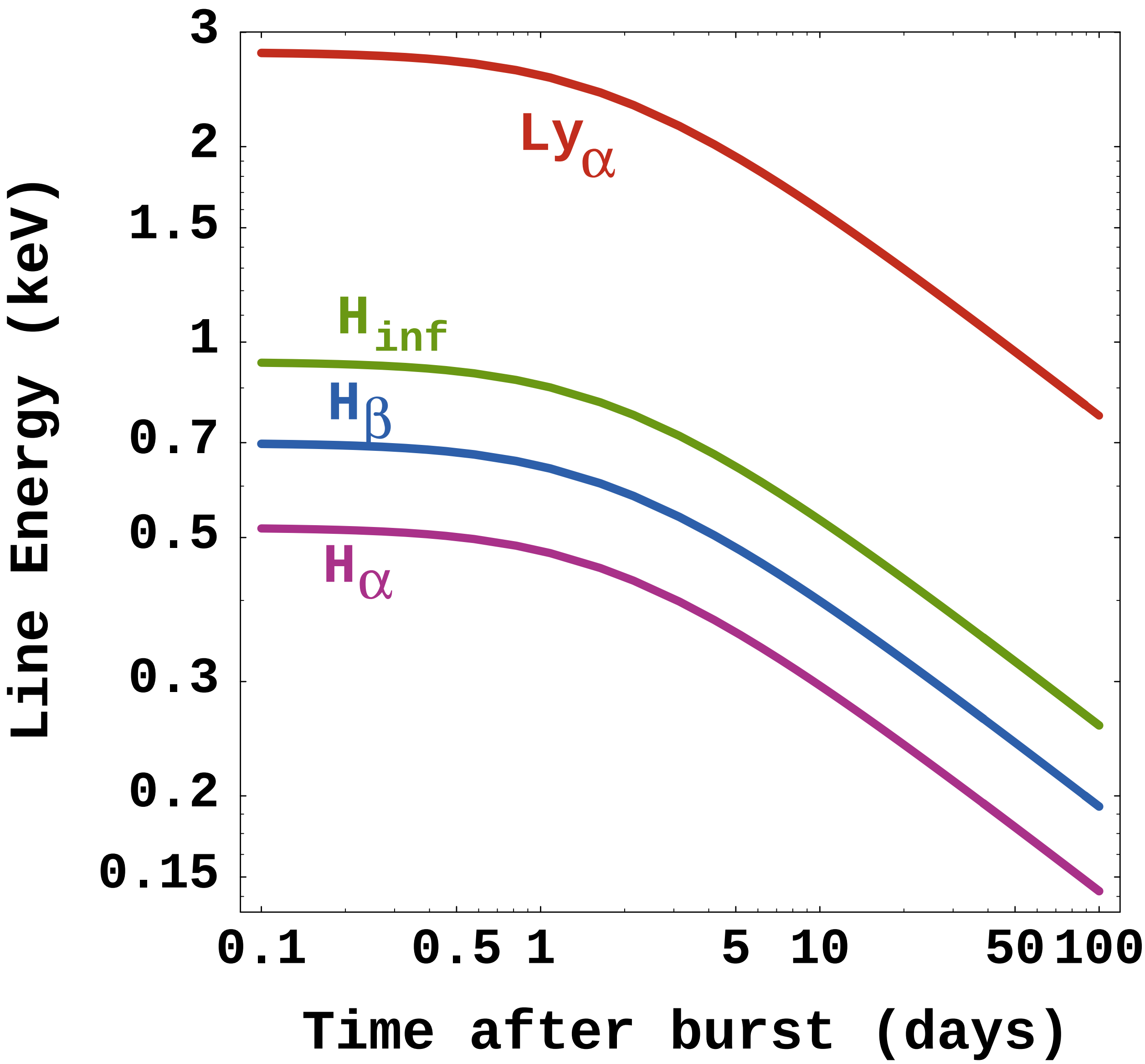

Fig. 4.— Comparison between the predicted energies of the expected prominent lines in the X-ray afterglow of GRB 011211 as function of time after burst, as given by Eq. (6), with the time-dependent Doppler factor obtained from our CB-model fit to its optical afterglow.

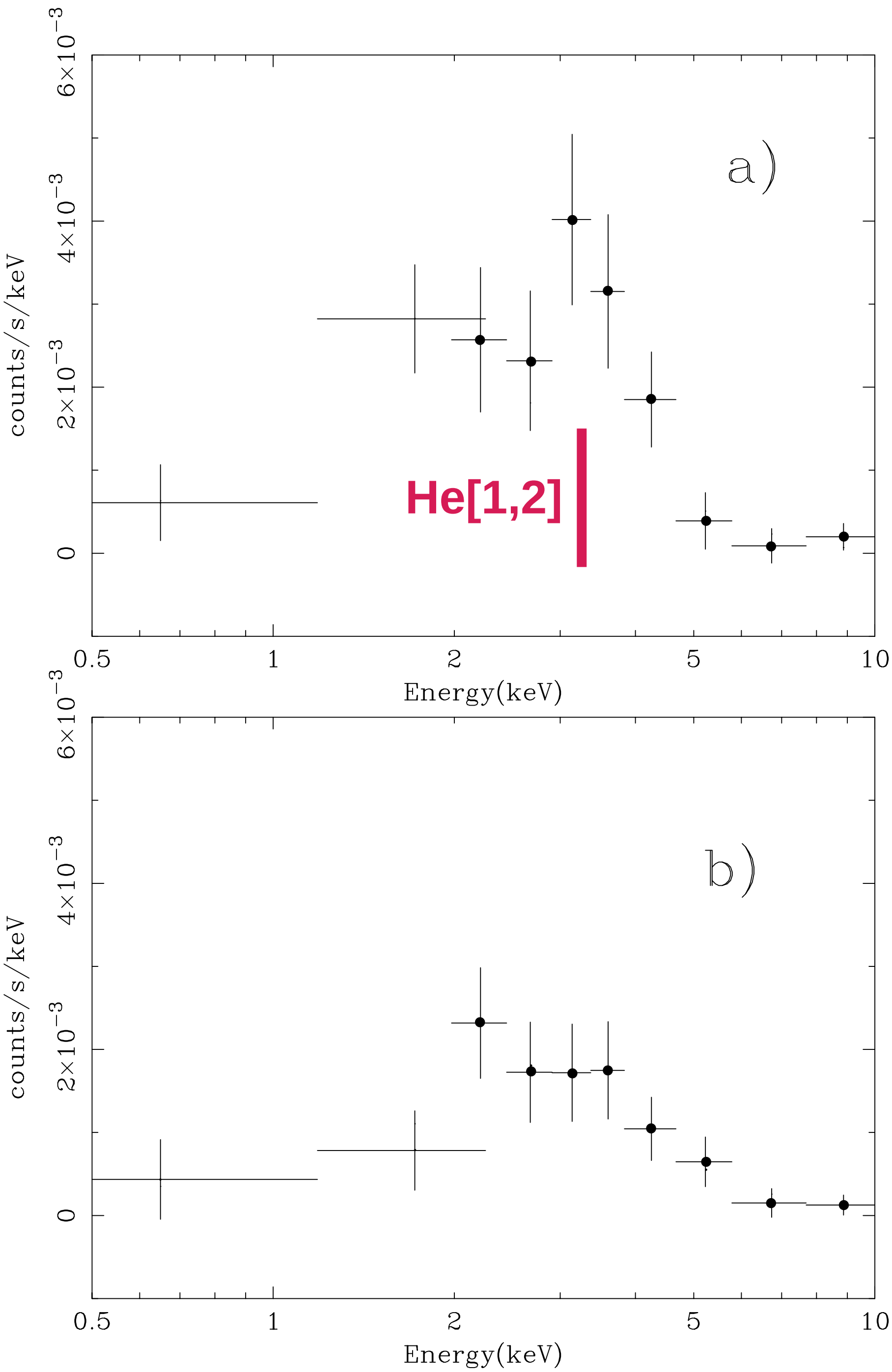

Fig. 5.— The X-ray spectrum of GRB 970508. (a) In the first and (b) in the second part of the observations (Piro et al. 1998). The vertical line is at the position predicted in the CB model for the Lyα-like transition in HeII.

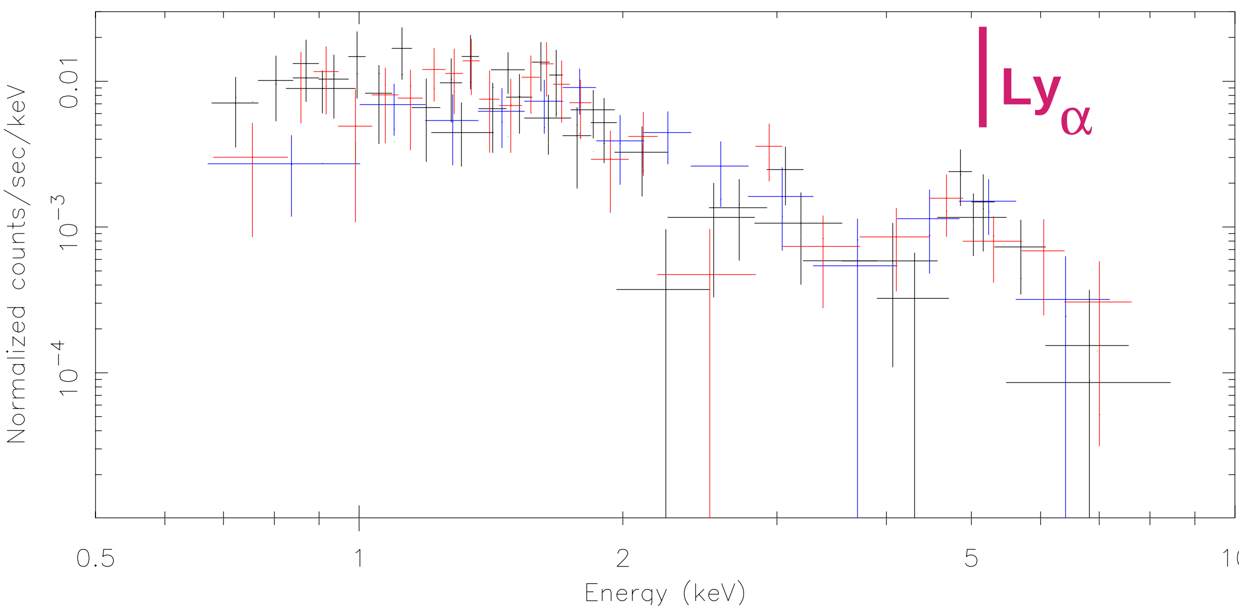

Fig. 6.— The X-ray spectrum of GRB 970828 in the intermediate time-period in which a putative line feature was observed (Yoshida et al. 2001). The vertical line is at the position predicted in the CB-model for the Lyα transition.

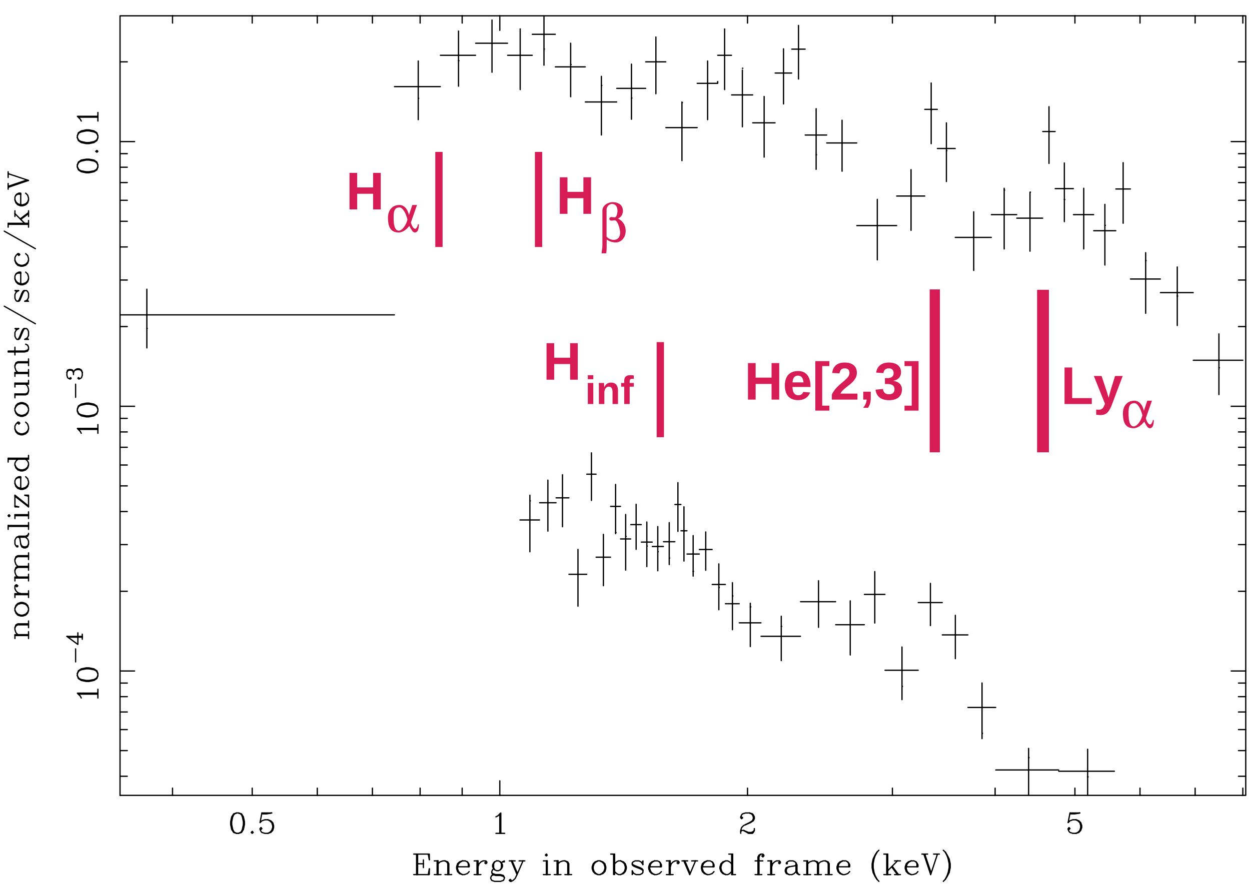

Fig. 7.— The X-ray spectrum of GRB 991216. The top (bottom) spectrum is that of the ACIS-S (HETG) counter of *Chandra* (Piro et al. 1999). The vertical lines are at the positions predicted in the CB model (the He line is the Hα-like transition in HeII).