

# X-Ray Emission of Gamma-Ray Bursts

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## ABSTRACT

X-ray emission can provide a crucial diagnostic of gamma-ray bursts (GRBs). We calculate the X-ray and gamma-ray spectra of impulsive acceleration episodes related to GRB pulses. We use the synchrotron shock model (SSM) as a basis of our calculations. We show that the current data on soft-to-hard emission ratios of GRB pulse emission are in agreement with the SSM. In particular, GRB pulse emission detected by GINGA is in agreement with the SSM low-energy spectra. We deduce that GINGA detected the majority of bright GRBs detectable by BATSE. These results indicate that the physical environment surrounding the GRB emission site is optically thin to X-ray photon energies. We also calculate emission ratios in the *Einstein*, ROSAT, SAX and HETE energy bands, and discuss how future information on simultaneous soft/hard GRB emission can contribute in distinguishing different emission models. Two different components of X-ray emission may simultaneously exist in a fraction of GRBs. One component is clearly associated with the individual GRB pulses, and an additional component may be related to the pulse X-ray spectral upturns and/or the precursors/tails occasionally observed. We also show that a meaningful search of GRB-driven X-ray flashes in Andromeda (M31) can be carried out with existing ROSAT PSPC data and future SAX WFC observations.

*Subject headings:* Gamma-ray bursts – Relativistic shock theory

## 1. Introduction

GRBs are characterized by a relatively low fluence in the X-ray energy band as compared to the hard X-ray/gamma-ray band (Trombka *et al.* 1974, Wheaton *et al.* 1973, Katoh *et al.* 1984, Laros *et al.* 1984, Yoshida *et al.* 1989, hereafter Y89, Murakami *et al.* 1991). The soft/hard energy ratio (e.g., 1-10 keV/30-1000 keV) of GRB fluences is of order of few percent. The “X-ray paucity” feature is a fundamental characteristic of GRBs, and a well established observational fact.

We calculate in this paper the X-ray spectrum of GRBs using the synchrotron shock model (SSM) which has been recently shown to successfully reproduce the broad-band spectra of bright GRBs (Tavani 1995; Tavani 1996a,b,c, hereafter T96a,b,c). We show that in the absence of absorption processes (due to opacity and/or synchrotron self-absorption) in the X-ray band or spectral distortions due to inverse Compton scattering, the X-ray/gamma-ray emission ratios can be reliably computed. The observed emission ratios are dependent on the underlying particle energy distribution function, and we calculate the X-ray/gamma-ray emission ratios for different spectral assumptions.

We compare our results with the previously determined simultaneous X-ray/gamma-ray emission ratios from the joint data of the XMOS *P78-1* and the *Pioneer Venus Satellite* (PVO) instruments (Laros *et al.* 1984), the GINGA GRB monitor (Y89), and the WATCH instrument (Castro-Tirado 1994). We also calculate observable emission ratios appropriate to current high-energy missions, BATSE, ROSAT, SAX and HETE.

This paper is organized as follows. Sect. 2 provides a summary of the GRB emission model used here, and a discussion of the most relevant theoretical points addressed in the analysis.

A first goal of our paper is to use simultaneous soft/hard emission ratios to constrain the GRB emission mechanism. We show in Sect. 3 that a definite correspondence between X-ray/gamma-ray emission ratios and peak energy of the  $\nu F_\nu$  spectrum ( $E_p$ ) can be established. Simultaneous broad-band spectroscopy of GRBs detected by different instruments can provide useful information to test the SSM.

Our second goal is to discuss the possible existence of an additional low-energy component in the GRB spectrum (Sect. 4). This extra component, most likely observable in the X-ray energy range, might be easily detectable as a low-energy excess during the GRB pulse emission, or as a component preceding or following GRB main pulses. Our analysis allows to easily identify spectral components additional to the SSM pulse emission.

We discuss in Sect. 5 attenuation and absorption processes possibly affecting the detection of X-ray from GRBs.

We finally discuss in Sect. 6 the feasibility of a search for GRB-driven X-ray flashes from other galaxies and in particular from Andromeda. We consider ROSAT archival data and future SAX observations of Andromeda as examples of data usable for this search.

## 2. The SSM model

The SSM is based on optically thin synchrotron emission of rapidly accelerated relativistic particles (electrons and/or  $e^\pm$ -pairs) radiating in the presence of a weak to moderate magnetic field (to avoid magnetic absorption processes) (Tavani 1995, T96a,b). A target ‘nebular’ medium, able to reprocess the relativistic energy of the flow and to trigger rapid acceleration processes, is necessary. The ultimate origin of GRB magnetized relativistic particle flows can be compact star coalescences at cosmological distances or compact star outbursts in an extended Galactic halo (for a recent review, see Fishman 1996). The target medium can be the interstellar medium, gaseous circumstellar material or self-generated gaseous environments. SSM can be applied in its generality to both the cosmological and Galactic interpretations of GRBs, even though important differences between these two models arise in the radiation processes and overall dynamics (Tavani 1996d, hereafter T96d). An MHD wind is assumed to interact in an optically-thin environment with magnetic turbulence or hydromagnetic shocks leading to rapid particle acceleration and to the formation of a prominent supra-thermal component. The SSM relevant physical quantities are the particle pre-acceleration ‘temperature’ or average Lorentz factor  $\gamma_*$ , and the local magnetic field at the acceleration site  $B_s$ . The relativistic

synchrotron critical energy of emitted photons  $E_c = h\nu_c^*$  (with  $h$  Planck's constant and  $\nu_c^*$  the critical synchrotron frequency) turns out to be proportional to the combination  $[\gamma_*^2 B_s]$ . A rapid acceleration mechanism of timescale shorter than the dynamic flow and cooling timescales modifies an otherwise quasi-Maxwellian particle energy distribution (PED). The post-acceleration PED,  $N(\gamma)$  (with  $\gamma$  the particles' Lorentz factor), turns out to be a combination of a relativistic Maxwellian<sup>1</sup> and a power law component of index  $\delta$  for energies below and above  $\sim \gamma_*$ , respectively. Depending on the efficiency of the acceleration mechanism, the PED can have different shapes (T96a,b). A *maximally efficient* acceleration mechanism is characterized by the non-thermal power-law component of the post-acceleration particle energy distribution joining the low-energy Maxwellian *at the top* of the distribution<sup>2</sup>. The SSM results in a dimensionless spectral function given by

$$\mathcal{F}(w) \equiv \int_0^{y_c} y^2 e^{-y} F'(w/y^2) dy + y_c^2 e^{-y_c} \int_{y_c}^{y_m} \left(\frac{y}{y_c}\right)^{-\delta} F'(w/y^2) dy \quad (1)$$

where we defined  $w = \nu/(\nu_c^* \sin \alpha)$ ,  $y = \gamma/\gamma_*$ ,  $y_m = \gamma_m/\gamma_*$ , with  $\nu_c^* = (3/4\pi)(q B_s/m_e c) \gamma_*^2$  the critical frequency of particles of mass  $m_e$  and charge  $q$  radiating in a local magnetic field  $B_s$ ,  $\alpha$  the average pitch angle,  $y_c$  a critical value of the dimensionless energy variable  $y$ ,  $\gamma_m$  the upper cutoff of the post-acceleration distribution function, and

$$F'(x) \equiv x \int_x^\infty K_{5/3}(x') dx' \quad (2)$$

the familiar synchrotron spectral function with  $K_{5/3}(x')$  the modified Bessel function of order 5/3. By integrating over the solid angle and emission volume, and after dividing by the square of the distance, we obtain the differential energy flux  $F_\nu^s$ , i.e.,

$$F_\nu^s \propto \mathcal{F}(\nu/\nu_c^*)[\nu_c^*, \delta, y_c] \quad (3)$$

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<sup>1</sup> We assume a three-dimensional Maxwellian distribution valid for a randomly oriented magnetic field configuration. It can be shown that a two-dimensional distribution leads to results similar to those presented here for a randomly oriented magnetic field (T96b).

<sup>2</sup> It can be shown that any other combinations of low-energy thermal and supra-thermal components will lead to synchrotron/IC spectra in contradiction with the current GRB broad-band data (T96a,b).

where we made explicit the dependence on the quantities  $\nu_c^*$ ,  $\delta$ ,  $y_c$  (we assumed the relation  $y_m \gg y_c$ , T96a,b). In the following, we use  $h\nu = E$  for the emitted photon energy.

Eq. 1 has a clear interpretation in terms of synchrotron radiation of impulsively accelerated particles by a maximally efficient mechanism. The main property of particle acceleration is reflected in the value of the critical dimensionless energy variable  $y_c$ . If  $y_c \sim 1$  (*model A*), the acceleration process is very rapid within the (comoving) dynamical timescale of the radiation front, with a drastic depletion of the quasi-Maxwellian maximum of the pre-acceleration PED near  $\gamma_*$ . In this case, the acceleration involves the majority of particles out of an initial quasi-thermal ‘reservoir’. On the other hand, an acceleration involving only a relatively small number of particles and producing a non-thermal tail of an otherwise quasi-Maxwellian PED near  $\gamma_*$  (*model B*) gives  $y_c \sim 4 - 7$ . These two possibilities are quite distinct, and we argue below that future X-ray/gamma-ray simultaneous observations of GRBs can be used to distinguish different PEDs. If  $y_c \gtrsim 10$ , the relevant PED turns out to be of a quasi-Maxwellian form, with no appreciable non-thermal component. Fig. 1 shows an example of SSM calculated photon spectra  $F_\nu/\nu$ , energy spectra  $F_\nu$  and spectral power per energy decade  $\nu F_\nu$  for the two models as a function of the dimensionless photon energy  $E/E_c$ . We have assumed  $\delta = 5$  and  $y_c = 1$  for model *A* that reproduces the broad-band spectra of GRB 910814 and 920622 (T96a,b). Model *B* of Fig. 1 is given by  $\delta = 5$  and  $y_c = 7$ . We note that the calculated spectra for the two models are not self-similar. On the contrary, the underlying quasi-thermal peak near  $\gamma_*$  of model *B* leads to a spectral curvature above  $E_c$  considerably different than for model *A*. The peak energies of the  $\nu F_\nu$  spectra are also considerably different, being  $E/E_c \simeq 1.5$  for model *A* and  $E/E_c \simeq 25$  for model *B*.

T96a,b used  $y_c = 1$ , i.e., model *A* and showed that the broad-band spectra of all bright GRBs detected simultaneously by BATSE, COMPTEL and EGRET are in agreement with the SSM calculated spectra. A purely Maxwellian spectrum is in strong disagreement with observations (T96a,b), and a model with  $y_c \sim$  a few may be marginally consistent with the data. It is important to point out, that GRO broad-band spectra of GRBs can be determined in the energy range 30 keV-100 MeV. It is then clear that extending the

simultaneous spectrum to photon energies below 30 keV provides a crucial test of the model. From Fig. 1 is also clear that the low-energy range can be strongly affected by the non trivial spectral ‘curvature’ determined by the underlying PED. The simple extrapolation  $F_\nu \sim \nu^{1/3}$  may *not* hold in the X-ray band, especially for  $E_p \sim 100$  keV (see Fig. 1) and/or hard-to-soft spectral evolution of the GRB pulse.

Typical observed values of the peak photon energy of the  $\nu F_\nu$  spectrum  $E_p$  are in the range  $100 \text{ keV} \lesssim E_p \lesssim 1 \text{ MeV}$  (Band *et al.* 1993, Ford *et al.* 1995). The peak energy  $E_p$  represents a clear feature of the broad spectrum, and Fig. 1 shows that its relation with the relativistic synchrotron energy  $E_c$  depends on the underlying model for  $N(\gamma)$ . There is also a non trivial dependence of  $E_p$  on the index  $\delta$  (T96b), and in the following we will take into account both of these effects. Even though the ultimate interpretation of  $E_p$  in terms of the physical quantity  $[\gamma_*^2 B_s]$  is subject to a model-dependent factor,  $E_p$  characterizes the observed GRB spectra in a useful way. In the following, we will show the calculated emission ratios as a function of the observable  $E_p$ .

### 3. GRB X-ray emission ratios

We calculated GRB X-ray emission ratios for a variety of assumptions regarding the post-acceleration PED. As a reference model of emission, we choose a SSM model with  $\delta = 5$  and  $y_c = 1$  (model *A*). A different choice of PED parameters would result in softness ratios differing at most by a factor of a few tens of a percent compared to those shown in all the figures except for Fig. 4. Fig. 2 shows the results of a calculation of softness energy flux ratios (SRs) for energy bands appropriate to several X-ray instruments, i.e., GINGA  $SR_{GINGA} = f(1.5\text{-}10 \text{ keV})/f(1.5\text{-}375 \text{ keV})$  (Y89), the XMOS NRL/Los Alamos experiment  $SR_{XMOS} = f(3\text{-}10 \text{ keV})/f(30\text{-}2000 \text{ keV})$  (Laros *et al.* 1984), the WATCH instrument  $SR_{WATCH} = f(6\text{-}15 \text{ keV})/f(15\text{-}100 \text{ keV})$  (Castro-Tirado 1994), *Einstein*  $SR_{Einstein} = f(0.15\text{-}3.5 \text{ keV})/f(50\text{-}300 \text{ keV})$ , ROSAT  $SR_{ROSAT} = f(0.1\text{-}2.4 \text{ keV})/f(50\text{-}300 \text{ keV})$ , the *Wide Field Cameras* (WFCs) of SAX  $SR_{WFC/BATSE} = f(2\text{-}30 \text{ keV})/f(50\text{-}300 \text{ keV})$ , and the GRB *Wide Field X-ray Monitor* (WXM) of HETE  $SR_{WXM/BATSE} = f(2\text{-}25 \text{ keV})/f(50\text{-}300 \text{ keV})$ .

The quantity  $f$  is the (arbitrarily normalized) integrated differential energy flux  $F_\nu$  for the indicated extremes of integration. Note that the calculated emission ratios here and in the following are idealized quantities that do not take into account possible spectral distortions due to detector responses. We also neglect X-ray Galactic absorption in our calculations of SRs. X-ray absorption has a negligible effect for emission above 2 keV as detected by GRB monitors<sup>3</sup>.

The calculated SRs can be used to represent the softness ratios as a function of the *average* peak energy  $E_p$  corresponding to the GRB emission under investigation. For example, the SRs can be representative of the emission near the peak of a GRB pulse, or of the total fluence. (In the latter case,  $E_p$  represents the average peak energy throughout the whole burst.) Also the time evolution of the SRs can be related with the change of  $E_p$ .

We can compare our results with the GRB detections in the X-ray band of GINGA and XMOS<sup>4</sup>. The energy fluence ratios  $SR_{XMOS}$  of bursts detected between March and July 1979 are in the range 0.0096-0.034 (Laros *et al.* 1984). From Fig. 2 we deduce a range for the average value of  $E_p$  throughout the bursts,  $200 \text{ keV} \lesssim E_p \lesssim 500 \text{ keV}$ . Yoshida *et al.* (1989) report values of  $SR_{GINGA}$  referring to the peak of the ten GRB bursts detected with good signal-to-noise during the period of March 1987 through March 1988. They report values in the range  $0.03 \lesssim SR_{GINGA} \lesssim 0.09$  (with the exception of one burst, 870319, with  $SR_{GINGA} = 0.46$  that would require an ‘unusual’  $E_p \simeq 10 \text{ keV}$ ). From Fig. 2 we therefore deduce a range of average  $E_p$  for the bursts detected by GINGA,  $90 \text{ keV} \lesssim E_p \lesssim 300 \text{ keV}$ .

Three points are worth mentioning here. The ranges of deduced  $E_p$ ’s for both the XMOS and GINGA detections are in good agreement with the expected average GRB  $E_p$ ’s

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<sup>3</sup> Obviously, SRs for *Einstein* and ROSAT may be strongly affected by Galactic absorption. Our calculations reported in Fig. 2 assume an unattenuated X-ray flux. The reported SRs are therefore upper limits to the true ratios.

<sup>4</sup> WATCH softness ratios are currently not corrected for the aspect of the detector (Castro-Tirado 1994), and a proper use of these data requires more analysis.



as determined by BATSE (Band *et al.* 1993). We deduce that the GRB emission of these bursts is in agreement with the SSM expectations, with no necessity of additional spectral components for the majority of bursts. Only the burst 870319 detected by GINGA (Y89) appears to have a SR substantially larger than those expected from SSM spectra with  $E_p \gtrsim 100$  keV. A detailed spectral analysis can determine whether this burst has either an anomalously low  $E_p$ , a prominent additional low-energy component, or the typical shape of a soft gamma-ray repeater event. A spectral analysis of the 870319 burst is strongly encouraged also in light of what discussed below.

The other important point to note here is that the 23 GRB detections by GINGA for a total exposure factor of 1.8 sr yr (Teegarden 1995) are consistent with the detection of the majority of *bright* GRBs detectable by BATSE (i.e., bursts with typical peak fluxes above  $F_t = (2.5 - 3)$  ph cm<sup>-2</sup> s<sup>-1</sup> averaged over 256 ms time bins, see Fishman *et al.* 1994, Band *et al.* 1993). This can be derived from a comparison with BATSE, that during the first 2.1 yr livetime period detected 244 GRBs of spectroscopic quality for an exposure factor of  $\sim 18$  sr yr (e.g., Teegarden 1995). The ratio of the number of spectroscopic quality bursts to exposure is approximately the same for GINGA and for the first 2.1 years of BATSE livetime. This is an important result, indicating that X-ray energy tails to GRBs are ubiquitous and with flux on the average consistent with the SSM expectations.

The third important consequence of these results is that the environment surrounding the GRB emission site is demonstrated to be optically thin to X-ray photon energies. There is no evidence of absorption processes in the X-ray energy range for the majority of GRBs (see also Preece *et al.* 1996b). There is also no evidence for synchrotron self-absorption or substantial inverse Compton distortions of the spectrum in the X-ray range. These features are of great importance in constraining theoretical models (T96d).

Fig. 3 shows the calculated hardness ratios (HRs) relevant for the BATSE energy channels 2 and 3, i.e., the energy flux  $HR_e = f(100-300 \text{ keV})/f(50-100 \text{ keV})$ , and the photon flux  $HR_p = f_p(100 - 300 \text{ keV})/f_p(50 - 100 \text{ keV})$  with  $f_p$  the integrated photon flux  $F_\nu/\nu$ . We notice that the majority of GRBs detected by BATSE have average fluence HRs (e.g., Kouveliotou *et al.* 1993, 1996) in agreement with the SSM calculated ratios. Fig. 3

shows the dependence of emission ratios on the non-thermal high-energy tail. We find that BATSE hardness ratios are not crucially dependent on the PED.

Fig. 4 shows one of the main results of this paper, i.e., the SSM calculated ratio  $SR_{SAX} = f(2-30 \text{ keV})/f(60-600 \text{ keV})$  for a variety of PEDs. Because of the relatively large energy span,  $SR_{SAX}$  depends on whether the PED is truncated near  $\gamma_*$  with  $y_c \sim 1$  or quasi-thermal with  $y_c \gtrsim 5$ . For the same  $SR_{SAX}$ , the peak energies  $E_p$  deduced from models *A* and *B* differ by a factor  $\sim 2$ . Simultaneous broad-band spectral information in the X-ray/soft  $\gamma$ -ray energy range can lead to a determination of the post-acceleration PED. We note that our calculated softness ratios for the WFCs can also be used to compare HETE’s WXM data and BATSE data. The SAX WFCs and HETE’s WXM may detect several GRBs per year, and we can expect events detected simultaneously by any two of SAX, HETE and BATSE. The broad-band spectral information of these bursts will be of great importance.

We note that a further test of the SSM is provided by a comparison of GRB ‘pulse durations’  $\tau_p$  for different energy bands. A simple realization of the SSM predicts the relation  $\tau_p \propto E^{-1/2}$  (T96a,b). This relation is in approximate agreement with auto-correlation analyses of pulse durations by BATSE (Link *et al.* 1993, Fenimore *et al.* 1995). Future data in the X-ray energy range can further constrain the energy dependence of GRB pulse durations, and accurately measure possible deviations from simple SSM predictions. Note that the GRB pulse duration can be quite different from the duration of the extra X-ray component discussed below.

#### 4. Additional X-ray components

We have shown that past and current X-ray observations of GRBs are on the average in agreement with the SSM expectations. However, a few exceptions were previously reported. Of particular relevance here, is the possible existence of *extra* X-ray components in addition to the SSM underlying spectrum. One extra component occasionally shows up as an ‘X-ray excess’ during part of the bursts (e.g., Preece *et al.* 1996a,b). The existence of X-ray

precursors and tails (with a possibly different spectrum compared to the most intense part of the bursts) was also reported for the GRBs detected by GINGA (Y89; Murakami *et al.* 1991). It is not clear if the X-ray excess detected by BATSE and the precursor/tail detected by GINGA have the same origin. An analysis of the BATSE spectroscopy detector (SD) data low-energy channel is consistent with the presence of a statistically significant excess in the 5-10 keV band in 12 out of 86 strong bursts (Preece *et al.* 1996a,b). The existence of GRBs with relatively large cumulative softness ratios was also noted in  $\sim 10\%$  of the bursts detected by WATCH (Castro-Tirado 1994). The limited spectral information of the BATSE SD and of WATCH and the statistics of the events detected by GINGA does not as yet allow a precise determination of the spectrum of this additional X-ray component. It is possible that GRBs imaged by HETE’s WXM and the WFCs on board of SAX can further constrain this low-energy component. GRBs with extra low-energy component(s) would show softness ratios substantially larger than those calculated for the SSM in Figs. 2 and 4.

A low-energy additional component of the GRB spectrum can have different physical origins including *(i)* the existence of a quasi-thermal extra component of temperature in the keV range, *(ii)* substantial spectral hard-to-soft evolution to peak energies  $E_p \lesssim 10$  keV, *(iii)* the effect of opacity surrounding the central source for Compton attenuation models (Brainerd 1994). Only future detailed (time-resolved) spectroscopy in the X-ray range can resolve this issue. We emphasize here that the presence of an extra component may be crucial to distinguish different theoretical models. Cosmological blast-wave scenarios may lead to observable quasi-thermal X-ray precursors and discrete X-ray emission episodes depending on geometry and interaction of forward and reverse shocks (T96d). Surface re-emission of irradiated compact stars in extended halo Galactic models can also produce a quasi-thermal X-ray component which might be delayed in time with respect to the main GRB pulse emission. A detailed discussion of models for these extra X-ray components in GRBs will be presented elsewhere.

Current data indicate the existence of two different X-ray spectra components, one associated with the GRB pulses (and successfully modelled by the SSM over a broad energy range), and an extra component. The latter component can occasionally modify

only part of the GRB emission (as in the case of the accumulated spectra of 3B920517 near its pulse peak from 7.6 to 8.8 s after trigger, Preece *et al.* 1996a,b), or manifest itself as a precursor/tail of relatively soft spectrum (Y89).

## 5. Attenuation and absorption of X-rays from GRBs

Two effects may suppress the observable X-ray emission of GRBs, i.e., (1) attenuation of X-rays due to propagation from source to the Earth, and (2) opacity and synchrotron self-absorption effects at the source.

In previous sections, we assumed that the effect of X-ray propagation in our Galaxy is negligible. This is justified for column densities below  $5 \cdot 10^{22} \text{ cm}^{-2}$  and photon energies well above 2 keV. However, X-ray propagation through dense regions of the Galactic disk may substantially affect the low-energy spectrum of GRBs. Fig. 5 shows a typical SSM spectrum for  $E_p = 150 \text{ keV}$  and  $\delta = 5, y_c = 1$  attenuated at low energies by photoionization of neutral gas through column densities in the range  $10^{21} - 5 \cdot 10^{23} \text{ cm}^{-2}$ .

Detecting GRBs below 2 keV may result in valuable information for distinguishing Galactic and extragalactic models of emission (see also Schaefer 1994). The existence of strong photoelectric absorption for GRBs occurring near the Galactic plane would be strongly suggestive of a remote origin in an extended halo or at cosmological distances. On the other hand, unattenuated GRB spectra down to, say, 0.1 keV would be highly problematic for cosmological models.

Neutral gas may exist near the GRB source, and the propagation of X-rays can be affected by the presence of ionized gas surrounding the source of high-energy emission. Time variable photoelectric absorption may then occur in GRB sources of large initial column densities of neutral gas. As energy from the GRB source is progressively absorbed by cold surrounding material, the absorption cutoff will be shifted to lower photon energies in a distinctive way. Fig. 5 shows that the effective column density at the source must be larger than  $10^{22} \text{ cm}^{-2}$  to affect the GRB spectrum above 2 keV. From the absence of substantial X-ray absorption in the available GINGA and XMOS data (see Sect. 3), we

deduce that typical *average* values of  $N_H$  are constrained below  $10^{22} \text{ cm}^{-2}$ . Time-resolved spectral X-ray information will be valuable in further constraining the gaseous surrounding of GRB sources. Fig. 5 can be used to predict the time evolution of the low-energy spectrum as the column density of photoionizing material evolves.

Synchrotron self-absorption may also suppress X-ray emission of GRBs. By equating the (comoving) spectral intensity  $I_{\nu'}$  with the Rayleigh-Jeans part of a blackbody spectrum, we obtain  $I_{\nu'} = 2(\nu'/c)^2 \gamma'_* m_e c^2$ . This relation is satisfied for a critical frequency  $\nu'_{abs}$  at which self-absorption sets in. Note that  $\nu'$  and  $\gamma'_*$  refer to the (comoving) reference system where most of the GRB radiation is produced. For a relativistically moving radiation front, observed and comoving quantities are related by  $\nu' = \nu/\Gamma$ ,  $\gamma'_* = \gamma_*/\Gamma$ , with  $\Gamma$  the bulk Lorentz factor of the flow. The specific radiation energy density  $u_{\nu'}$  is then  $u_{\nu'} \simeq 3.4 \cdot 10^4 \nu_{abs,1}^2 \gamma_{*,5} \Gamma^{-3} \text{ erg cm}^{-3} \text{ Hz}^{-1}$ , where  $\nu_{abs,1}$  is the observed absorption frequency in units of 10 keV, and  $\gamma_{*,5} = \gamma_*/10^5$ . The comoving average radiation energy density can be then expressed as  $\bar{u}' \simeq 8.4 \cdot 10^{22} \nu_{abs,1}^3 \gamma_{*,5} \Gamma^{-3} \text{ erg cm}^{-3}$ . A synchrotron self-absorption critical frequency  $\nu_{abs}$  in the X-ray range would therefore indicate extreme conditions of radiation. Relativistic beaming by a moving radiation front would somewhat alleviate the requirement on the radiation energy density. The distinctive roll-over and asymptotic form of the energy spectrum  $F_{\nu} \sim \nu^{5/2}$  at frequencies below  $\nu_{abs}$  is distinguishable from photoionization effects at X-ray energies. We note that  $\nu_{abs}$  may evolve in time towards smaller values as the GRB pulse progresses, and time-resolved X-ray spectra might be used to study the evolution of the burst energy density at the radiating site.

## 6. Search for X-ray flashes in Andromeda and other galaxies

X-ray flashes associated with GRBs from other galaxies might be detectable by X-ray instruments. If GRBs originate in a Galactic extended halo, it is plausible to expect the detection of X-ray flashes related to GRBs in the halo of nearby galaxies, since typically X-ray detectors are more sensitive than those employed at higher energies (e.g., Hamilton, Gotthelf & Helfand 1996). Indeed, the detection or lack of detection of X-ray flashes in

nearby galaxies such as Andromeda may provide a crucial test to establish the nature of GRBs (see also, Li, Fenimore & Liang 1996).

We show here that the calculated and previously observed X-ray flux of GRBs can be used to strengthen the conclusions from these searches. As an example, we consider a search for GRB-driven X-ray flashes in Andromeda (M31) to be carried out with ROSAT archival data. We assume a fractional area of the halo including the Andromeda galaxy  $\eta = \eta_{-1} 10^{-1}$  for a  $1^\circ \times 1^\circ$  field of view, and a (cumulative) livetime  $\tau_l = \tau_6 10^6$  sec. We can then estimate the ROSAT exposure of the Andromeda halo in the (unconventional) units of ‘halo x time’ as  $3 \cdot 10^{-3} \tau_6 \eta_{-1}$  halo yr. The ratio of this exposure with the GINGA exposure of the Galactic halo (re-expressed in the proper units as  $\sim 0.14$  halo yr) is  $\sim 2 \cdot 10^{-2} \tau_6 \eta_{-1}$ . We deduce that the number of events detectable by the PSPC would be below unity if the ROSAT detections were limited to the same fraction of the bright GRB population accessible to GINGA. However, this may not be the case. From Fig. 1 we deduce that the fractional flux expected in the ROSAT band for a burst detected by BATSE in the 50-300 keV range (without an X-ray excess) is  $\xi_{ROSAT} = 10^{-2} \xi_{-2}$  for  $E_p \sim 200$  keV (i.e., at the average value of the  $E_p$  distribution from BATSE data, Band *et al.* 1993). Typical peak luminosities in the BATSE energy band are  $10^{-6} - 10^{-7}$  erg cm $^{-2}$  s $^{-1}$ . Displacing this population of bursts detected by BATSE by a factor in distance of  $\sim 4 - 5$  (representing the approximate distance of the Galactic halo to Andromeda’s), we can estimate the peak luminosities in the ROSAT band in the range  $5 \cdot 10^{-10} - 5 \cdot 10^{-11}$  erg cm $^{-2}$  s $^{-1}$ . For a typical absorption in the halo of Andromeda ( $N_H \simeq 10^{21}$  cm $^{-2}$ , e.g., Trinchieri *et al.* 1988) and a photon spectral index less than unity, we deduce PSPC countrates in the range 22.5-2.2 cts s $^{-1}$ . We therefore conclude that, depending on the burst duration and intensity, ROSAT can detect GRBs in Andromeda of intensity a factor of  $\sim 10$  lower than the bright bursts detectable by BATSE and GINGA. Unless the (logN-logS) intrinsic fluence distribution of GRBs from Andromeda is drastically quenched for small fluences, the number of GRB-driven X-ray flashes may be up to a few (times  $\eta_{-1} \tau_6 \xi_{-2}$ ) in the current ROSAT PSPC data. The timing properties of these transient events can make them distinguishable against the background. By considering realistic values of  $\eta_{-1} \tau_6 \xi_{-2}$  in the range 0.1–0.5 (taking into account limitations in the exposure and moderate X-ray absorption), we estimate the number of X-ray flashes

expected in the ROSAT database of Andromeda to be of order unity. We also notice that ROSAT and similar instruments such as *Einstein* are not expected in this model to detect GRB-related flashes of galaxies at distances larger than 2-3 Mpc  $[\tau_l/(10^5 \text{ s})]^{1/2}$ .

We can also consider a search for GRB-driven X-ray flashes in Andromeda by the WFCs on board of SAX. The typical WFC  $5\sigma$  detection above a background of  $\sim 20 \text{ cts s}^{-1}$  (Piro *et al.* 1995) gives  $\sim 40 \text{ cts s}^{-1}$ . This countrate, interpreted as a peak flux for an integration time of order of a few seconds, corresponds to an energy flux of  $\sim 0.2$  Crab, i.e.,  $\sim 5 \cdot 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 2-30 keV band. Typical peak fluxes for bright GRBs detected by BATSE ( $F \gtrsim F_t$ ) can be translated at the Andromeda halo distance, giving energy fluxes  $\gtrsim (2.5 - 5) \cdot 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 50-300 keV band. From Fig. 2 we deduce that the calculated SSM fraction of the peak flux in the WFC vs. BATSE energy ranges is  $\xi_{WFC} \sim 0.2 - 0.15$  for average peak energies in the range of 200-300 keV. For bright bursts with values of  $E_p$  at their peaks in the range 200-300 keV (which are about half of the total number of bright bursts detected by BATSE, see Ford *et al.* 1995), we deduce an SSM flux estimate of  $(0.5 - 1) \cdot 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 2-30 keV energy band. These bursts might be detectable by the WFCs<sup>5</sup>. We can estimate the necessary livetime/exposure<sup>6</sup> for WFC observations of Andromeda as a function of a required number of X-ray flashes,  $N_f$ . If the Andromeda halo has a population of bright GRBs similar to that one accessible to GINGA in our Galaxy, we deduce a livetime  $\tau_{WFC} \sim 30 - 40 \text{ days}$  ( $N_f/10$ ). The hypothesis of an extended galactic halo origin for the GRBs can therefore be tested by long WFC observations of Andromeda. Other nearby spiral galaxies are outside the distance range accessible to the study proposed here.

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<sup>5</sup> Note that bright bursts with relatively large values of  $E_p$  may not be detectable by the WFCs at the Andromeda distance. The softness ratio  $\xi_{WFC}$  is below 0.1 for  $E_p \gtrsim 500 \text{ keV}$ , see Fig. 2.

<sup>6</sup> The large field of view of the WFCs ( $20^\circ \times 20^\circ$ ) ensures that the Andromeda halo can be monitored by single pointings. Therefore, in this case  $\eta = 1$  and the exposure is equal to the livetime.

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### Figure Captions

FIG. 1 - Calculated (unattenuated) SSM spectra for models *A* and *B* with  $\delta = 5$ . (*Solid curves:*) model *A* for  $y_c = 1$ ; (*dashed curves:*) model *B* for  $y_c = 7$ .

FIG. 2 - Calculated SSM softness ratios for energy ranges of different X-ray instruments. Model *A* with  $\delta = 5$  and  $y_c = 1$  is assumed with no X-ray attenuation. See text for the definition of energy bands.

FIG. 3 - Calculated SSM energy and photon hardness ratios relevant for the BATSE energy range. (*Solid curves:*) Maxwellian PED; (*short-dashed curves:*) non-thermal PED with  $y_c = 1$  and  $\delta = 5$ ; (*long-dashed curves:*) non-thermal PED with  $y_c = 1$  and  $\delta = 4$ ; (*dotted curves:*) non-thermal PED with  $y_c = 1$  and  $\delta = 3$ .

FIG. 4 - Calculated (unattenuated) SSM energy softness ratios relevant for the SAX WFCs and lateral shields for different assumed PEDs. (*Solid curve:*) Maxwellian PED; (*dotted-short-dashed curve:*) non-thermal PED with  $y_c = 7$  and  $\delta = 5$ ; (*long-short-dashed curve:*) non-thermal PED with  $y_c = 5$  and  $\delta = 4$ ; (*short-dashed curve:*) non-thermal PED with  $y_c = 1$  and  $\delta = 5$ ; (*long-dashed curve:*) non-thermal PED with  $y_c = 1$  and  $\delta = 4$ ; (*dotted curve:*) non-thermal PED with  $y_c = 1$  and  $\delta = 3$ . Calculated ratios for models *A* and *B* lead to clearly distinct values of the peak energy  $E_p$ .

FIG. 5 - Photoabsorbed SSM photon spectrum in arbitrary units (model *A* with  $y_c = 1, \delta = 5, E_p = 150$  keV) for different equivalent column densities  $N_H$  (solar abundance). (*Dotted curve:*) unattenuated spectrum; (*solid curve:*) photoabsorbed spectrum for  $N_H = 10^{21} \text{ cm}^{-2}$ ; (*long-short-dashed curve:*)  $N_H = 5 \cdot 10^{21} \text{ cm}^{-2}$ ; (*dotted-long-dashed curve:*)  $N_H = 10^{22} \text{ cm}^{-2}$ ; (*dotted-short-dashed curve:*)  $N_H = 5 \cdot 10^{22} \text{ cm}^{-2}$ ; (*long-dashed curve:*)  $N_H = 10^{23} \text{ cm}^{-2}$ ; (*short-dashed curve:*)  $N_H = 5 \cdot 10^{23} \text{ cm}^{-2}$ .









