Theory of Gamma-Ray Burst Emission in Light of BSAX Results

M. Tavani \textsuperscript{a,\textit{b}}

\textsuperscript{a} IFCTR/CNR, via Bassini 15, I-20133 Milano (Italy).
\textsuperscript{b} Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027 (USA).

We briefly discuss the theoretical implications of recent detections of gamma-ray bursts (GRBs) by BSAX. Relativistic shock wave theories of fireball expansion are challenged by the wealth of X-ray, optical and radio data obtained after the discovery of the first X-ray GRB afterglow. BSAX data contribute to address several issues concerning the initial and afterglow GRB emission. The observations also raise many questions that are still unsolved. The synchrotron shock model is in very good agreement with time-resolved broad-band spectra (2–500 keV) for the majority of GRBs detected by BSAX.

1. A Year of Surprise

The discovery of X-ray afterglows by BSAX revolutionized the field of GRB research \cite{8,14,35}. The discovery caught us by surprise. Certainly, there was no theoretical prediction of hard \cite{4,51} high-energy emission lasting hours-days after the main events. ‘Pre-BSAX models’ of GRB shock waves predicted a much faster decay of the hard component produced by the initial impulsive particle acceleration (e.g., \cite{25}). Before the BSAX discovery, the only hope to detect GRB counterparts was believed to be searching for rapid UV/optical transients lasting a few minutes/hours or possibly delayed radio flares (e.g., \cite{31}).

The ingenuity of the BSAX team was remarkable in ignoring theoretical models and carrying out the fastest ever slews of an X-ray satellite to GRB error boxes. BSAX discovery shattered old beliefs, and opened a new way of confronting difficult problems of GRB physics. A more complete picture of the GRB phenomenon is now emerging with all its complexities and puzzles. All theoretical models are challenged by the wealth of X-ray, optical and radio data, and many problems remain unsolved at the moment. We briefly discuss here some of the open issues.

BSAX showed for the first time that a substantial fraction of GRB energy is dissipated in the X-ray range at late times (hours, days, sometimes weeks) after the main events. ‘Are classical GRBs the tip of the iceberg of more complex radiation processes lasting much longer than expected from the cooling timescales of initial pulses?’ The ‘delayed’ gamma-ray emission discovered by EGRET in the case of GRB 940217 \cite{19} clearly shows how GRB ‘durations’ determined by BATSE in the 50–300 keV range can be misleading. The delayed gamma-ray emission of GRB 940217 can now naturally be interpreted as a manifestation of GRB afterglows. Particles associated with this type of bursts can remain accelerated for a timescale $\sim 10^2$ - $10^3$ times longer than the decay timescales of initial GRB pulses. The fluence of the delayed gamma-ray emission of GRB 940217 is larger than 10% of that detected for the main event \cite{19}. Also in the case of X-ray afterglows detected by BSAX, at least a fraction larger than 10% of the total fluence is emitted at late times (e.g., \cite{6,8}).

The total energy inferred from the X-ray afterglow \cite{6} and possible optical counterpart \cite{6} of GRB 970508 ($\geq 10^{52}$ ergs) exceeds the most optimistic estimates of coalescing neutron star models (e.g., \cite{30}). If GRB sources are at extragalactic distances, do they imply a new kind of explosive
phenomenon? (see also the speculations of ref. [32] to be compared with those of ref. [34]).

Renormalizing the logN–logP distribution of GRBs (see Fig. 1) in terms of redshift for an assumed luminosity function can be done for GRB 970508 associated with the (lower limit) optical transient redshift \( z = 0.83 \) [26]. Unless GRB 970508 is anomalous, it can be shown that the standard candle assumption cannot satisfactorily describe the GRB brightness distribution, contrary to the conclusions of previous studies (e.g., [44]). Cosmological models of GRBs have to be formulated now without the appeal of a natural energy scale provided by the neutron star coalescence model. What is the origin of the spread in luminosity (and spectral characteristics as shown in ref. [44]) of GRB sources?

BSAX discoveries opened the way for rapid follow-up observations in the optical and radio bands. At present, four out of eight GRBs detected by BSAX (GRB 970228, 970402, 970508, 971214) unambiguously show the existence of fading X-ray sources within the WFC error boxes (10 – 30 arcmin\(^2\)) pointed \( \sim 8 \) hours after the events. Of the remaining four GRBs, two error boxes could not be rapidly pointed (GRB 960720 and 980109), and the others pointed within \( \sim 14 – 16 \) hours show faint sources with ambiguous associations (GRB 970111 and 971227). Another GRB error box pointed by ASCA within 1 day after the event (GRB 970828) also shows an X-ray fading afterglow source [27,5]. Usually the X-ray flux decay is well represented by a power-law of the type \( t^{-\alpha} \). Why are the time exponents \( \alpha \)'s of X-ray afterglows different from burst to burst? Is there any correlation between the afterglow strength and the initial GRB peak intensity or spectrum?

At present, three optical transients were identified within the WFC error boxes of GRB 970228 [4], GRB 970508 [3] and GRB 971214 [17]. All are within the error boxes of the fading X-ray sources, reinforcing their associations with their respective GRBs. However, they all show different characteristics. The delayed (\( \sim 2 \) days) optical transient (OT) associated with GRB 970508 resulted in the spectral identification of absorption lines of an object at \( z \simeq 0.83 \) (either the host or a foreground galaxy [27]). After the decay, the optical lightcurve follows a power-law decay of index \( \sim 1.17 \pm 0.04 \) for several weeks (e.g., [34]). The nature of the OT associated with GRB 970228 is currently controversial, with a nebulosity near a fading pointlike OT [16,18]. The OT was still detectable by HST \( \sim 6 \) months after the event near \( V \simeq 28 \) [16]. Its inferred optical lightcurve shows clear deviations from a power-law decay of index \( \sim 1.14 \pm 0.05 \) [16]. The OT associated with GRB 971214 shows an initial power-law decay of index \( \sim 1.4 \pm 0.2 \) [7], and a possible flattening near \( R = 25.6 \) about 10 days after the event [22]. What is the nature of the faint nebulosities associated with GRB 970228 and GRB 971214? If these are distant star-forming galaxies, why would GRBs be preferentially hosted near the cores of these galaxies rather than farther away as coalescing neutron star models predict? If the comoving GRB formation rate follows that of star forming galaxies (strongly peaked near \( z \simeq 1 \) [23]), why are only the bright, harder and longer GRBs showing the strongest deviation from the Euclidean brightness distribution [7]? Significant luminosity and spectral cosmological evolution of GRBs at \( z \gtrsim 1 \) may be required [14].

About half of the GRBs promptly studied by optical searches do not show any OT below \( R > 22 – 23 \) (GRB 970111, 970402, 970828, 970828, 971227, 980109). Is the lack of OTs in more than half of GRBs due to absorption within the host? Is the lack of detectable absorption in many of the X-ray afterglow spectra obtained by SAX consistent with optical absorption [taking into account redshifting by \( (1+z)^3 \) of the X-ray cutoff energy]?

GRB 970508, the event associated with an extragalactic OT, is ‘anomalous’ in many ways when compared with other GRBs. (i) It is the only GRB with a non-monotonic X-ray afterglow decay \( \sim 1 – 3 \) days after the event [37]. Four BSAX TOO observations were necessary to finally observe its decay in the 2–10 keV band (but apparently not in the softer LECS band [27]). (ii) Its associated OT was detected to rise \( \sim 2 \) days after the event after a stable plateau state [3]; contrary to the other two GRBs showing mono-
Figure 1. GRBs detected by BSAX marked on the cumulative brightness distribution of the 4th BATSE catalogue [29]. Peak intensities in the BSAX-GRBM detector have been rescaled to fit BATSE’s energy range (50-300 keV) assuming a power-law photon index of 2. BSAX WFCs are clearly capable of detecting faint GRBs near the detection threshold for BATSE. Three GRBs associated with optical transients (OT) are marked with their respective peak magnitudes (GRB 970228 [46], GRB 970508 [3], GRB 971214 [17]). No OT was discovered in other GRB error boxes. The only GRB associated with a (possibly scintillating) radio source is GRB 970508 [11] of low gamma-ray flux [37]. Radio searches in other GRB error boxes were rapidly performed with null results [3].
tonically decreasing OTs (GRB 970228 [46], and GRB 971214 [17]). (iii) GRB 970508 is also the only GRB so far associated with a (scintillating?) radio source [11]. Are the peculiar properties of GRB 970508 caused by the ‘environment’ surrounding the GRB source, or can they be attributed to a background AGN? Why is only the very weak GRB 970508 associated with an apparently persistent [12] radio source?

If delayed radio emission is common in bright GRBs produced by relativistic fireballs (e.g., [31]), more radio detections would have been expected (see Fig. 1).

Finding satisfactory explanations to all these questions will be challenging for any theory of GRBs. The issues facing cosmological models [20, 43, 47–49] in the ‘post–BSAX era’ of GRB research include: an energy crisis, burst number density evolution vs. star forming galaxies, luminosity and spectral evolution, absorption and reprocessing properties of GRB environments in distant galaxies, diversity of X-ray and optical decays, persistent optical emission ∼6 months after GRB 970228, and lack of radio emission for the majority of GRBs.

Other models should be considered, and a superposition of GRB populations of different origins may still be viable. More detections of optical/radio transients in GRB error boxes are definitely needed.

2. Contributions by BSAX

BSAX observations contribute to address important aspects of the GRB emission mechanism for both the prompt impulsive emission and the delayed afterglows. We indicate here ten important contributions by BSAX that can be used for detailed theoretical modelling.

(1) Extending the GRB spectrum to X-ray energies: time resolved spectroscopy. BSAX data complement and improve those obtained by GINGA [50, 40]. Combining WFC and GRBM data for sufficiently intense GRBs can provide a unique database for studying time-resolved spectroscopy from ∼2 keV to hundreds of keV. No systematic low-energy ‘suppression’ or spectral ‘up-turns’ is detected by BSAX, clearly confirming that possible deviations from the phenomenological Band’s model [1] affect a minority of GRBs.

(2) Discovery of substantial spectral re-hardening (e.g., GRB 970228) for late GRB pulses. Usually hard-to-soft spectral evolution dominate across individual GRB pulses [28] or among different pulses of complex GRBs [33]. The broad-band detection by BSAX of the complex GRB 970228 [14] clearly shows how a second train of pulses separated from the first part of the GRB by several tens of seconds can be much harder than expected from simple extrapolation. Particle re-energization clearly occurs tens of seconds after the main event, giving support to the idea that the second train of pulses in GRB 970228 may be related to its strong X-ray afterglow [8].

(3) Confirming the energy dependence of GRB lightcurves. Many initial GRB pulses detected by BSAX show a characteristic apparent ‘time delay’ between the hard (50-600 keV) and soft (2-30 keV) lightcurves. This phenomenon has also been clearly observed in different energy ranges by CGRO instruments (e.g., [28]). Rapid spectral evolution with the ‘sweeping’ of a fixed energy band by the peak energy $E_p$ of the $\nu F_\nu$ spectrum can satisfactorily explain the observations.

(4) Pulse width vs. photon energy relation: $\Delta \tau \propto E^{-1/2}$. BSAX clearly confirms the pulse broadening as a function of decreasing photon energy detected also in the BATSE range (e.g., [28]). This feature of GRB pulses strongly support synchrotron models of emission [41].

(5) Discovery of long-duration X-ray afterglows (XRA) occasionally lasting ∼days/weeks after the events (as in the case of GRB 970228 [8]). Lower limits to the X-ray afterglow fluences can be deduced in the range of several tens of a percent of the main pulse fluences.

(6) Discovery of ‘average’ XRA power-law decays: $F_x \sim t^{-\alpha}$, with $\alpha = 1.1 - 1.6$. Interpreted as manifestations of persistently accelerated particles, XRAs can be used to derive constraints on the initial and maximum energies of radiating leptons in relativistic shock waves [43]. Only forward shocks agree with BSAX observations [43, 45], predicting an X-ray flux decay of the
type \( f_\gamma \propto \xi_\gamma(t) t^{-3/2} \) with \( \xi_\gamma(t) \) an X-ray ‘window’ function depending on spectral evolution. The requirements on the initial (\( \gamma_m \)) and maximum (\( \gamma_m^\ast \)) energies of particles accelerated by an impulsive relativistic shock are stringent \( [4] \):

\[
\gamma_m \gamma_m^\ast \sim 10^{15} n_o^{-1/2} \Gamma_0^{-3/2} \lambda_B^{-1/2} (t/8 \text{ hr})^{3/2} \tag{1}
\]

where \( n_o \) is the average number density of the surrounding medium, \( \Gamma_0 \) the initial value of the bulk Lorentz factor of the shock wave in units of \( 10^2 \), \( \lambda_B \) a parameter set to unity for equipartition between kinetic and magnetic field energy densities, and \( t \) the time after the burst in the observer frame. Fluctuations are occasionally detected in BSAX X-ray afterglows possibly indicating re-acceleration episodes (see also the GRB 970828 afterglow detected by ASCA \( [23] \)).

(7) Discovery of strong violations of power-law XRA decays: the case of GRB 970508 \( [57] \).

(8) First observation of a non-thermal XRA spectrum (GRB 970228) of photon index near 2 \( [74] \). This important discovery is also supported by a similar spectral determination of the GRB 970828 afterglow by ASCA \( [3] \). It can be shown that the combination of flux decay and spectral properties of GRB afterglows is inconsistent with simple cooling models of neutron star surfaces \( [34] \).

(9) Lack of prominent X-ray ‘precursors’. WFC data can be used to test for the first time the possible existence of precursor X-ray emission as predicted in several fireball models. No evidence for fireball thinning is found, implying values of the bulk Lorentz factor of the expanding shell \( \Gamma \gtrsim 2 \) a few.

(10) Delayed GRB emission allows optical identification. Probably the most important consequence of the observations originating from the BSAX detections.

3. The Synchrotron Shock Emission Model

Among the many possible spectral models of GRB emission (Compton attenuation due to Klein-Nishina scattering effects \( [5] \), absorption effects by thick material near compact objects \( [22] \), or processes leading to electron/positron creation and beaming \( [4] \)), the shock synchrotron model (SSM) is of special relevance to relativistic fireball models \( [4,22] \). BSAX results confirm SSM predictions to \( \sim \) keV energies for the majority of detected GRB pulses (exceptions will be discussed below). The SSM is based on optically-thin synchrotron emission of relativistic particles (electrons and/or \( e^\pm \)-pairs) radiating in the presence of a weak to moderate magnetic field (to avoid magnetic absorption processes) \( [4,12] \). A model that successfully describes broad-band GRB spectra is based on a particle energy distribution consisting of a relativistic Maxwellian below a critical energy. This reflects the physical conditions of a thermalized electromagnetic/particle outflow produced by an initial impulsive burst. Depending on the characteristics of external media and their radiative environments, a 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 of power-law index \( \delta \). Depending on the efficiency of the acceleration mechanism, the particle energy distribution can have different shapes \( [12] \). The SSM results in the dimensionless spectral function of refs. \( [11,12] \). Fig. 2 shows SSM calculations of GRB spectra that reproduce with good accuracy the broad-band spectra obtained by CGRO. BSAX spectral data allow to extend the energy range of these fits to \( \sim \) keV energies with good agreement between theory and observations. We note that the phenomenological spectral model by Band \( [1] \) is in excellent agreement with SSM spectra, that therefore provide a natural theoretical foundation for it.

It can be shown that BSAX and CGRO spectral data imply a maximally efficient acceleration mechanism \( [1,12] \) not dissimilar from what calculated \( [5] \) and observed (e.g., \( [3] \)) in synchrotron nebulae. The SSM spectral shape turns out to be a universal 2-parameter function in the energy range \( \sim 1 \text{ keV} - 1 \text{ GeV} \) the critical energy \( \varepsilon_c \) (proportional to the local magnetic field strength \( B \), and to \( \gamma_m^2 \)), and the index \( \delta \). In the absence of a supra-thermal component, the low-energy (\( E \ll \varepsilon_c \)) emission is dictated by synchrotron emissivity of energy index 1/3. For intermediate
Figure 2. Calculated SSM $\nu F_\nu$ spectra reproducing the burst-averaged spectra of the GRBs simultaneously detected by BATSE, COMPTEL and EGRET on board of CGRO (adapted from ref. [41]). Also time-resolved BSAX spectral data are in agreement with these SSM calculations assuming optically thin radiation environments. BSAX data are consistent with SSM spectra of initial peak energies in the range $10 \text{ keV} \lesssim E_p \lesssim 500 \text{ keV}$ and subsequent hard-to-soft spectral evolution. An interesting exception is indicated by the initial part of the GRB 960720 pulse showing an apparent absorption below $E_p \simeq 100 \text{ keV}$ compared to the SSM prediction. Most likely, a modification of optically thin SSM by relativistic plasma effects is implied for this type of bursts [45].
photon energies \( E \lesssim \varepsilon_c \) the spectrum steepens, and SSM predicts a very distinctive ‘curvature’ of the continuum for specific combinations of the relativistic Maxwellian and power-law components \([1],[2]\). The observed ‘peak’ photon energy \( E_p \) is proportional to the relativistic synchrotron energy \( \varepsilon_c \) (modulo possible factors due to Doppler blueshift \( \sim \Gamma \), cosmological redshift \( \sim (1 + z)^{-1} \), and overall IC upscattering, if applicable). No substantial modification of GRB spectral shapes by inverse Compton (IC) processes is evident in BSAX and CGRO data. This indicates that IC cooling, if it occurs at all, ‘gently’ shifts the overall spectrum dictated by synchrotron emission. This is a crucial constraint for many cosmological models characterized by an overproduction of IC emission compared to pure synchrotron (e.g., [24]). SSM physical parameters can be derived by by the combined set of CGRO and BSAX spectral data \([3]\).

\[
10^3 \lesssim \gamma_* \lesssim 10^6 \quad 1 \text{ G} \lesssim B_s \lesssim 10^3 \text{G} \quad (2)
\]

modulo redshift and IC upscattering factors. These values are quite natural for optically thin synchrotron nebulae powered by MHD outflows.

Interesting deviations from the average low-energy spectrum are observed in a few cases. An apparent suppression of low-energy photons during the initial part of some GRB pulses is detected in a small fraction \( (\lesssim 15\%) \) of events by BATSE \([7]\), and GINGA \([11]\). However, difficulties of the BATSE spectral analysis at low energies and intensities, and uncertainties on the incidence angle of GRBs detected by GINGA make these measurements somewhat uncertain. BSAX data can resolve the issue. Among the GRBs detected by the WFCs, only GRB 960720 \([22]\) (during the first second of the main pulse lasting \( \sim 10 \text{ sec} \) in the GRBM energy band) shows a clear sign of low-energy suppression. This time-dependent suppression suggests a modification from the idealized optically thin conditions assumed in the simplest version of the SSM. Low-energy SSM emission below \( \sim 50 \text{ keV} \) can be temporarily suppressed by relativistic plasma effects \([22]\). The fact that low-energy suppression occurs at the beginning of GRB pulses is a clear indication that the radiative environment relaxes from a complex to a thinner medium as expected in plasma acceleration models \([5]\).

More surprises may enrich our study of GRBs in the near future. We need more optical/radio identifications of reliable GRB counterparts to settle the issue of the GRB origin. A systematic time-resolved spectral analysis is necessary for both BSAX and BATSE data to test emission models. Joint BSAX and BATSE spectral analysis will be of great importance for GRBs detected by both instruments.

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