GAMMA-RAY BURSTS: THE FOUR CRISSES (*)

M. Tavani 1,2

(1) Istituto Fisica Cosmica, CNR, via Bassini 15, Milano I-20133 (Italy)
(2) Columbia Astrophysics Lab., Columbia University, New York, NY 10027 (USA)

ABSTRACT We discuss some open problems concerning the origin and the emission mechanism of gamma-ray bursts (GRBs) in light of recent developments. If GRBs originate at extragalactic distances, we are facing four crises: (1) an energy crisis, models have to account for more than $10^{53}$ ergs of energy emitted in the gamma-ray band; (2) a spectral crisis, emission models have to account for the surprising ‘smoothness’ of GRB broad-band spectra, with no indication of the predicted spectral ‘distortions’ caused by inverse Compton scattering in large radiation energy density media, and no evidence for beaming; (3) an afterglow crisis, relativistic shock models have to explain the complexity of the afterglow behavior, the longevity of optical transients detectable up to six months after the burst, the erratic behavior of the radio emission, the lack of evidence for substantial beaming as indicated by recent searches for GRB afterglows in the X-ray band; (4) a population crisis, from data clearly indicating that only hard and long GRBs show a strong deviation from an Euclidean brightness distribution, just the opposite of what expected from extragalactic models without substantial cosmological evolution. All previously proposed cosmological models are challenged: in particular, the neutron star-neutron star coalescence model most likely will not survive the resolution of the problems raised by points (1) and (4).

1. INTRODUCTION

Recent observations suggest that gamma-ray bursts (GRBs) might originate at extragalactic distances (for a review, and references concerning observations, see Hurley 1998). However, a satisfactory resolution of the question regarding the ultimate source of the GRB phenomenon still escapes us. As usually happens in rapidly evolving fields, observational puzzles outnumber theoretical explanations. Observations provide a very complex scenario. From the handful of optical transients (OTs) detected within the error boxes of X-ray afterglow sources, GRBs appear to originate at large distances ($z > 1 - 2$). Is this emerging picture proved? Does the extragalactic origin apply to all GRBs? In this paper we briefly discuss four problematic issues requiring drastic resolutions within the framework of extragalactic GRB models. The page limit does not allow a discussion of the qualitative successes of the relativistic fireball model, or a treatment of alternative models. We will assume, for the sake of the argument, that all proposed associations of OTs and extragalactic hosts with GRBs are correct.

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2. THE FOUR CRISES

(1) The energy crisis

The implied enormous energies for isotropic emission in the hard X-ray/soft
gamma-ray band (> 10^{53} ergs as deduced directly for GRB 971214 or indirectly for
GRB 970228 by the absence of spectroscopic or photometric redshift of the OT’s
host, implying 1 ≲ z ≲ 2) are problematic for any model. The neutron star-neutron
star (NS-NS) models proposed a few years ago were characterized by a few percent
of the energy (∼ 10% of the total mass-energy) available for high-energy emission,
i.e., 10^{51} ergs (e.g., Paczynski 1990, Meszaros & Rees 1993). Clearly NS-NS models
require substantial beaming to explain new GRB-OT associations, or a very efficient
mechanism of energy conversion for which we do not have any other indication of
its existence. NS-NS models also suffer from the relative closeness of OT’s to their
host galaxies, contradicting calculations of the NS-NS coalescing binary evolution.

We are left with three main alternatives: (1) hypernovae (a concept introduced
after the detection of GRB 970508, see Paczynski 1998); (2) a special class of failed
supernovae (e.g., MacFadyen & Woosley 1998); and (3) relatively massive black
holes with their rotational and gravitational energy transformed by very efficient
electromagnetic/MHD effects (e.g., Meszaros, Rees & Wijers 1998) or quantum ef-
fects (e.g., Preparata et al. 1998) into relativistic particle outflows. Even before
addressing the theoretical details of these models, one crucial aspect is clear: all
models of this type require relativistic beaming to explain GRB light curves. However,
there is no evidence today that the GRB prompt emission is beamed. A
recent analysis of GRB lightcurves simulated by relativistically beamed emitting
fronts fails to reconcile data with theoretical expectations (Fenimore et al. 1998).

(2) The spectral crisis

Broad-band GRB spectra are remarkably smooth. This property is in contrast
with lightcurves, that are often very complex. The ‘smoothness’ of GRB spectra
applies to both time-averaged spectra (Tavani 1996a,b) and also to time-resolved
spectra, as indicated in BATSE data (e.g., Band 1996), and in BSAX data covering
the ∼3−300 keV energy range (e.g., Piro et al. 1998, Frontera et al. 1998, 1999).
Efficient particle acceleration and synchrotron emission can naturally reproduce
the majority of available time-resolved spectra (Tavani 1996b, 1997). What is now
called the Shock Synchrotron Model (SSM) qualitatively agrees with expectations
from a particular class of relativistic fireball models (e.g., Meszaros et al. 1994,
hereafter MRP94). (Low-energy suppression applies to a minority of time-resolved
spectra, possibly indicating a violation of optically thin conditions during the initial
phase of some GRB pulses, see Tavani 1998b; for a different approach, Liang 1997).

However, the agreement of data with an optically thin SSM with no spectral
distortions is surprising. Strong deviations from the simplest SSM spectral shape are
expected if reverse and forward shock contributions to the prompt emission operate
simultaneously or at different times. Strong modifications by inverse Compton
scattering are expected in the majority of relativistic shock front for cosmological
GRB models (e.g., MRP94, Pilla & Loeb 1998). None are observed. ‘Piston models’
(e.g., MRP94) might explain the absence of multicomponent spectra, even though it is not clear why mixing of the reverse and forward shock fronts would apply to all GRBs. In any case, the absence of IC distortions strongly constrains extragalactic models, and no satisfactory explanation has yet been proposed.

(3) The afterglow crisis

The remarkable discovery of detectable X-ray afterglows lasting hours/days/weeks clearly demonstrates that the GRB phenomenon can dissipate a very large fraction of the total energy at very late times (Costa et al., 1997, 1998). This is in contrast with pre-afterglow models of GRB fireball dissipation. Decelerating relativistic shock fronts can generate radio/optical/X-ray emission only for very efficient particle acceleration acting during the initial impulsive phase and most likely even at later times. It is not clear whether the broad-band afterglow emission can be understood in terms of decelerating relativistic fronts with simple energized particle injections (e.g., Sari, Piran & Narayan 1998). Clearly, the efficient and probably prolonged particle acceleration phases of GRB afterglows require a more detailed theoretical analysis. In addition, no evidence exists for an enhanced GRB rate expected in models of afterglow X-ray emission dominated by strong beaming effects. No GRB afterglows more than expected were found on timescales of hours/days in the ROSAT All Sky Survey database (Greiner 1998). It is also interesting that beaming does not affect the rate of GRB prompt X-ray emission as deduced by the null results of a search in X-ray all-sky survey archival data (Grindlay 1999).

(4) The population crisis

We know relatively little about the short GRBs with duration \( \tau_b < 2.5 \) s. They are usually quite hard, and may be thought as more ‘elementary’ than the usually multi-peaked bursts of longer duration. It is interesting that the brightness distribution (logN-logP) for this subclass of bursts shows little deviation from an Euclidean three-dimensional distribution. They can be classified as Short/Hard (S/H) bursts, typically with a BATSE’s hardness ratio \( H_{32} > 3 \). No counterpart for these bursts has yet been detected, and in principle they can be anywhere (see also Hurley 1998).

Long duration events (\( \tau_b > 2.5 \) s) constitute the majority of detected GRBs, and if derived from a source population at extragalactic distances (e.g., star forming galaxies) with no substantial cosmological evolution of burst properties (spectrum, intensity), their brightness distribution is expected to be strongly non-Euclidean especially for the Long/Soft (L/S) subclass (i.e., for long GRBs with hardness ratio in the ideal range to be detected by BATSE, \( H_{32} \lesssim 3 \)).

This expectation is in direct contradiction with the data (Tavani 1998a, hereafter T98a). It is surprising for extragalactic models with no evolution that only Long/Hard (L/H) bursts (with \( H_{32} > 3 \)) have a strongly non-Euclidean brightness distribution. Remarkably, the brightness distribution of L/S bursts is very similar to that for S/H bursts. Fig. 1 shows the brightness distributions of these subclasses as derived from the average properties of GRBs from the 4-th BATSE Catalogue.

This ‘population problem’ requires a drastic cure. Two possibilities arise: (i) source evolution at large redshifts has to produce GRBs on the average much harder
(on the borderline for being detected efficiently by BATSE) and more intense than those at smaller redshifts; or (ii) BATSE’s selection effects have to play a major role in producing an apparent non-Euclidean and inhomogeneous distribution only for L/H bursts (these bursts typically show emission outside the ideal energy range for BATSE’s triggers, 50–300 keV, see T98a). The fact that the brightness distributions of spectral (hard/soft) subclasses derived from the individual properties of GRB pulses (Pendleton et al., 1997) are similar to those derived from the average properties (T98a) favors the latter explanation. More work is needed to clarify this important issue.

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FIGURE 1. BATSE’s brightness distributions ($\log N$-$\log P$, with $N$ the cumulative number of bursts above a given peak photon countrate $P$ in the energy range 50-300 keV and for the 64 ms time resolution) for different GRB sub-classes (from Tavani 1998a). Distributions for the three main GRB sub-classes are shown:

(S/H) GRBs with $T_{90} < 2.5$ sec, and $H_{32} > 3$ (short/hard bursts);
(L/H) GRBs with $T_{90} > 2.5$ sec, and $H_{32} > 3$ (long/hard bursts);
(L/S) GRBs with $T_{90} > 2.5$ sec, and $H_{32} < 3$ (long/soft bursts).