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Relativistic Outflows in Gamma Ray Bursts

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Abstract. Despite that gamma-ray bursts is a phenomenon quite different from accreting compact objects, it could be that their hard x-ray emission is associated with a very similar mechanism of energy dissipation. In both cases, we could deal with reconnection of a turbulent magnetic field with intensive e^+e^- pair production and quasi-thermal Comptonization.

1. Introduction

The approximate consensus on gamma ray bursts (GRBs) can be reduced to a few brief statements:

– GRBs are cataclysmic events with an energy release $\sim 10^{51}$erg in γ-rays (assuming isotropic emission) at cosmological distances.

– The primary event is a coalescence of two compact objects of stellar origin (neutron stars and black holes, Blinnikov et al. 1984; Paczyński 1992) or an exotic explosion of a single stellar object (hypernova, Paczyński 1998)

– All we see are effects associated with an expanding blast wave (fireball), or propagating jet, or multiple colliding shocks of dimensions and time scales of a few order of magnitude larger than the scales of the primary event (which is invisible in itself at the present level of sensitivity, see Mészáros & Rees 1993).

There exist other points of view, of course, e.g., GRBs as sporadic microblazars (Shaviv & Dar 1995a; for criticism of fireball models, see Dar 1998). I will use the fireball paradigm, keeping in mind a jet geometry as an alternative. The principal problems arising in the inhomogeneous fireball and the jet scenarios as well as the possible underlying physical processes are similar.

There are two classes of GRBs (which could be different phenomena or different modes of the same phenomenon) – short ($\lesssim 1$ s) and long ($\gtrsim 1$ s). The discussion below concerns the long GRBs. Due to the large intensity of many bursts we have very rich hard X-ray/soft γ-ray GRB data: excellent light curves and good spectra. However the data are so diverse and sometimes puzzling, that usually new good data complicate the problem rather than clarify it. I will start with the time variability data and try to review possible conclusions inferred from temporal properties. Then I will review the spectral properties and discuss possible regimes of emission.

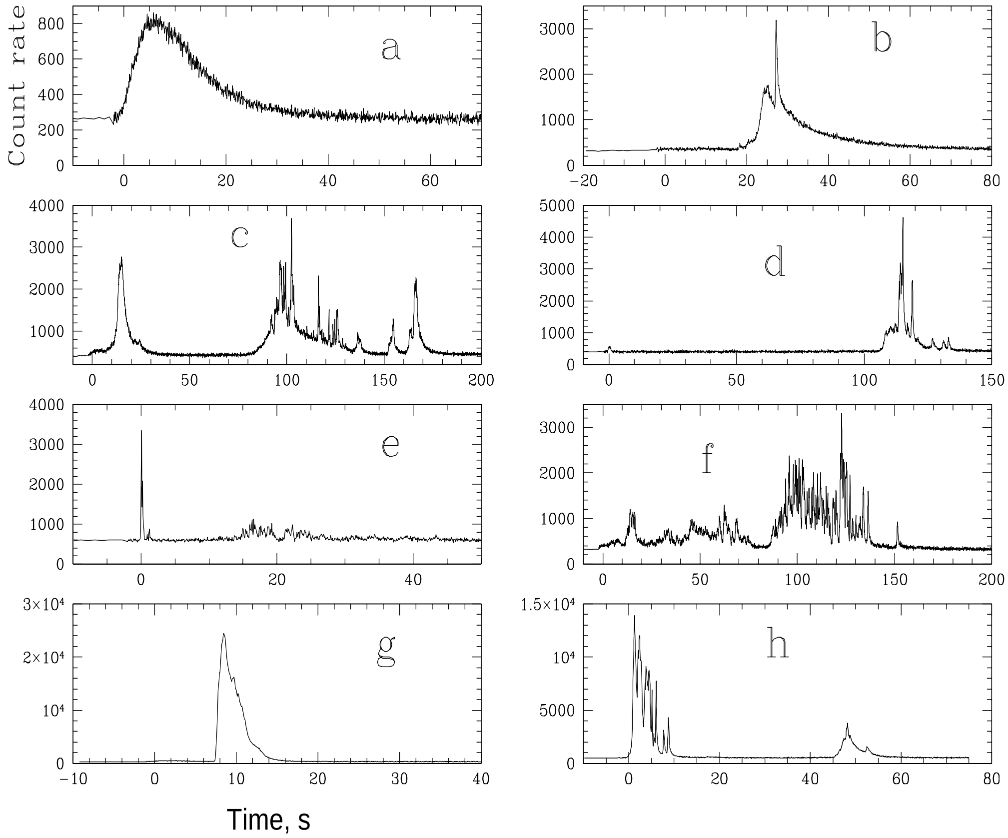

Figure 1. Examples of light curves of strong gamma-ray bursts: a) a GRB consisting of a single canonical pulse; b) two overlapping pulses of different durations; c) an event showing a wide range of time scales; d) an event with a weak short precursor; e) a GRB looking like combination of a typical short and a typical long GRB, there are several events of this kind in the BATSE sample; f) one of most complex events; g) the strongest burst of the "long" class; h) two episodes separated by a very quiet interval.

2. Time Variability, Phenomenology

GRB temporal properties which are worth to emphasize are the following:

2.1. **Bimodality**. The duration distribution of GRBs extending over 5 orders of magnitude has two humps (Meegan et al. 1998) which are believed to correspond to different classes of GRBs: short and long GRBs, separated by a minimum around 2 s. These could also just be different modes of the same phenomenon (sometimes a precursor looking like a short burst is followed by a long burst, Fig. 1e). Our discussion concerns mainly long bursts which constitute 70 - 75 % of GRBs

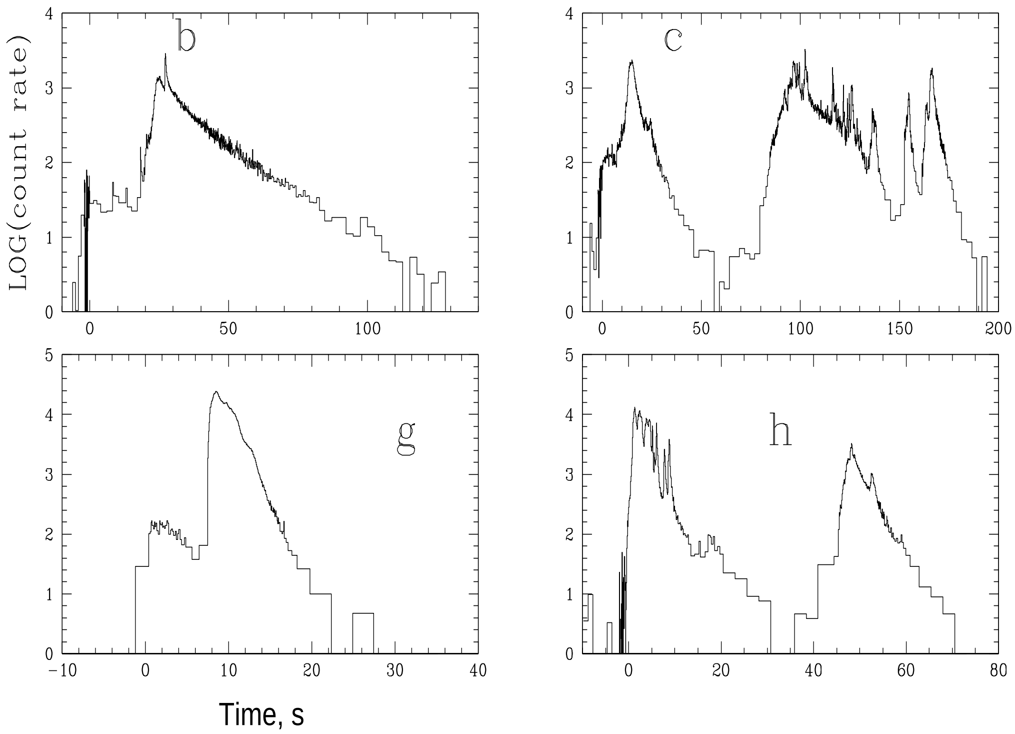

Figure 2. Some of the examples from Fig. 1 with subtracted background plotted in logarithmic scale. Labels correspond to those in Fig. 1. Note the large dynamical range of the light curves: near-exponential tails can be traced over almost 4 orders of magnitude of intensity (g), the intensity can drop below 10^{-3} of the peak value and then regain the same level (c, h). Event (g) consists of two peaks which are morphologically similar and differ in amplitude by a factor of 200. This tells us something about intrinsic luminosity function: if the emission of pulses is a stochastic process, then the weak pulse in event (g) could be emitted without the strong one and the event would be 200 times weaker (but still detectable). Tails of pulses are almost never perfect exponentials. Nevertheless they are better described as exponentials than as power laws.

2.2. **Diversity**. Some events consist of a single smooth pulse of almost standard shape (Fig. 1a), others are very complex and chaotic (Fig. 1f), and some are a combination of smooth pulses and chaotic intervals (Fig. 1c). No distinct morphological classes are found. At first sight, GRB light curves obey no rules.

2.3. **Large amplitude of variations**. There are strong events with emission episodes separated by quiet intervals. The upper limit for emission between episodes is below 10^{-3} of the peak flux in some events (see Figs. 1h, 2h). In other terms, the emission can turn off to a very low level and then turn on again.

2.4. **Composite structure**. Any event is the sum of elementary pulses which are additive and can overlap. This statement is difficult to prove. It is, however, a stable impression. This is more or less obvious for events consisting of a few pulses (Fig. 1b) and seems be a reasonable generalization for chaotic events. The most erratic events could consist of $\sim$ 1000 pulses (Stern & Svensson 1996). For attempts to decompose bursts into single pulses, see Norris et al. (1996)

2.5. **Absence of a starting mark**. There is no typical feature in the light curves that could be associated with the primary event. A burst can begin in very different ways - a slow smooth rise (Fig. 1a,b,f), a sharp abrupt rise (Fig. 1h), a weak precursor separated by tens of seconds from the main event (Fig. 1d), etc.

2.6. **Weak and slow time evolution**. The direct time evolution of complex bursts from their beginning to the end is slow and weak (Fig. 1c,f). There are only slow statistical trends: hard-to-soft evolution is more frequent than soft-to-hard (Ford et al. 1995) and the highest peak of the burst has a statistical tendency to appear at the beginning. A direct time dependence should exist, but it is not easy to extract and its typical characteristic scale exceeds 100 s.

Summarizing 2.5 and 2.6 we can state that the primary event leaves no mark and we cannot define the "zero time" for the event.

These are phenomenological facts which one can derive from just looking at many time profiles or plotting the simplest distributions. In the next section, I will consider a more quantitative description of the time variability.

3. Time Variability: Wide Range of Time-scales and Self-Similarity

Stern (1996) found that the average peak aligned profile of all BATSE GRBs has a stretched exponential (SE) shape:

$$I = I_0 \exp\left[-(t/t_0)^{1/3}\right], \qquad (1)$$

where t is time since the highest peak of the event, and t_0 is a time constant $\sim$ 0.5 s. This dependence extends over 3 orders of magnitude in time ($0.2 - 200$ s) and over 2.5 orders in the amplitude of the average signal (Fig. 3). It is worth to note that the similar distribution for solar flares is not such a good SE. If one tries to describe the average time profile of solar flares with a SE one obtains an index close to 1/2 instead of 1/3 (Stern 1996). Stretched exponentials are quite common in complex dynamical systems with a wide spectrum of variations. An example which will be discussed below is turbulence where some distributions have an SE shape (Ching 1991; Jensen, Paladin, & Vulpiani 1992). We can speculate that SEs are associated with near-critical systems where the criticality is not complete. In the case of exact criticality, the characteristic scale (e.g. the time constant) disappear and all distributions should convert into a power law. The SE does contain the time constant t_0. It does not mean that we have found a characteristic time scale. An SE can be associated with a truncated power law spectrum. Then t_0 is some function of $t_{\min}$ and $t_{\max}$ at which the system changes its behavior.

Indeed, the average power density spectrum (PDS) of long bursts is a truncated power law, $P(f) \propto f^{-1.67}$ (Beloborodov, Stern & Svensson 1999), extending between 0.02 and 2 Hz (Fig. 4). The amusing fact is that the average PDS

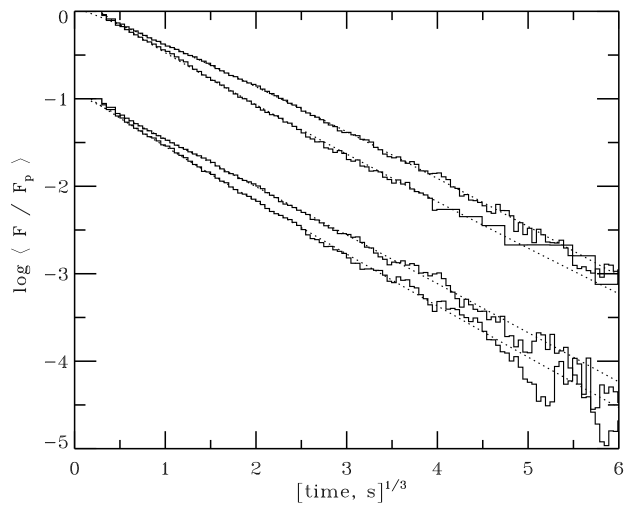

Figure 3. Stretched exponential slopes (rising and decaying) of the average time profile of GRBs (from Stern, Poutanen & Svensson 1999). Upper set of curves: the full useful BATSE 4 sample, 1310 GRBs. Lower set of curves (shifted down): the 953 brightest GRBs. Rising slopes are steeper. Dotted curves represent stretched exponential fits.

has exactly the same slope ($-5/3$) as the Kolmogorov spectrum describing the energy distribution in developed turbulence. This will be discussed below.

The low frequency turnover is associated with the well known turnover in the duration distribution of GRBs (~ 30 s) which in turn is associated with some global properties of the phenomenon. The high frequency turnover is something new. It should be associated with some nonlinearity in the physical processes appearing at a certain scale of the emitting systems. Maybe this is related to the compactness parameter of local events associated with the emission of separate pulses.

What can we conclude from all these facts?

- We probably deal with a complex dynamical system which generates a wide spectrum of features exhibiting some scaling invariance (self-similarity) over at least 2 orders of magnitude.
- Regular extended distributions indicate that all bursts, despite their diversity, can be considered as different random realizations of the same stochastic process.
- The underlying stochastic process is close to a near-critical regime. This is what we need in order to observe a huge diversity of GRBs. Otherwise we would have to assume very different conditions in different bursts. Near-criticality provides large fluctuations under stable conditions.

These conclusions are speculative, of course, and can hardly be formulated quantitatively. Nevertheless, a toy pulse avalanche model of Stern & Svensson

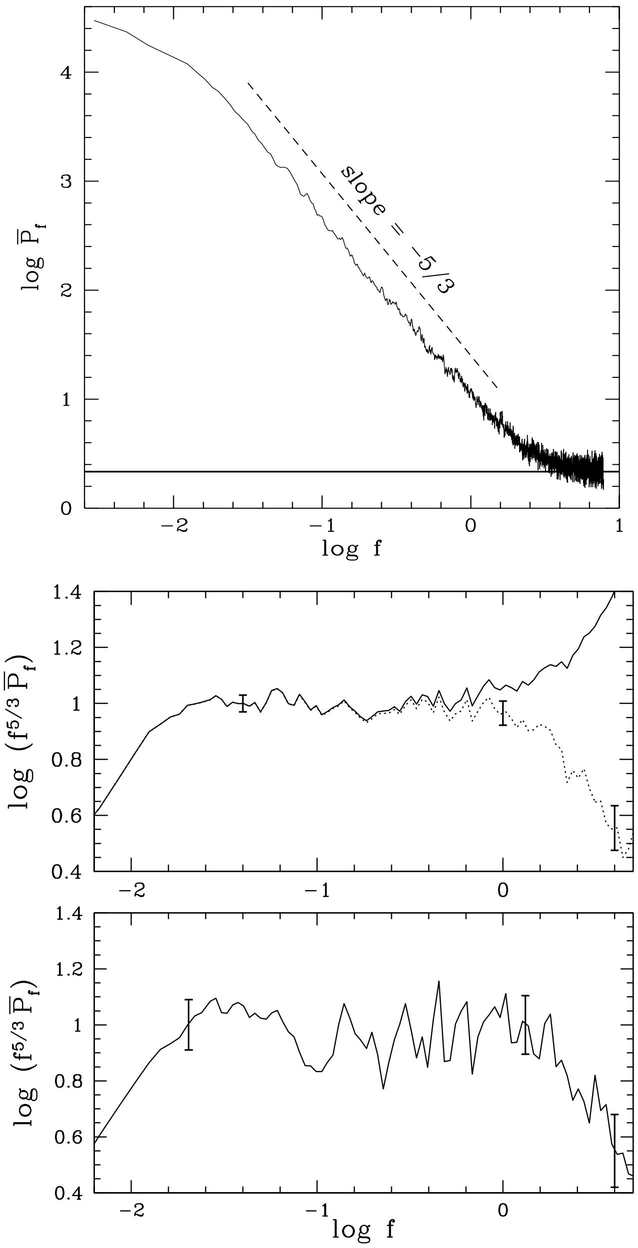

Figure 4. Average Fourier power density spectrum for 214 long ($T_{90} > 20$ s) strong bursts (from Beloborodov, Stern & Svensson 1999). Upper panel: the original PDS, the solid horizontal line shows the average Poisson level. Middle panel: the PDS multiplied by $f^{5/3}$. Dotted curve shows the spectrum after subtraction of the Poisson level. Bottom panel: the average PDS for the 27 strongest events in the sample.

(1996) constructed on the basis of these assumptions gives a successful quantitative statistical description of GRBs (including the stretched exponential average profile and the power-law average PDS). The model in a near critical regime reproduces the diversity of GRBs for the same set of parameters. The success of the model does not mean that the pulse avalanche model is valid and is the only possibility. It rather means that the approach based the above conclusions is reasonable.

4. Underlying Scenario: A Recurrent Central Engine versus a Turbulent or Inhomogeneous Fireball

What physics can be behind the stochastic process discussed in the previous section?

The best studied scenario of GRB emission is based on a relativistic expanding fireball (Cavallo & Rees 1978) energized by the merging of two compact objects. If the baryon loading of the fireball is small then it must be ultrarelativistic (Pacyński 1990). In an early stage, the fireball cannot emit efficiently just because the radiation is trapped due to the very large optical depth and almost all energy goes into kinetic energy (see Mészáros & Rees 1993). It agrees with fact 2.5 - we do not see any marker of the primary event. And later, when the fireball becomes optically thin and interacts with the interstellar medium, it emits a GRB through shock particle acceleration.

This scenario satisfies the energy requirements and can reproduce a proper time scale of tens of seconds at Lorentz factors $\sim 100 - 300$. What is missing in this scenario in its straightforward version is the complex stochastic time behavior with the properties summarized above.

Fenimore, Madras, & Nayakshin (1996) and Fenimore, Ramires, & Summers (1998) found an evident controversy in the simplest model of the single expanding shell. If the expanding relativistic homogeneous shell emits an instantaneous flash, the observer will see an extended pulse with a characteristic width $\sim t - t_0$, where t is the observation time of the beginning of the pulse and t_0 is the observation time of the primary event (if it were observed) producing the expanding shell. Therefore, if we associate a pulse in a GRB with a flash of a single relativistic shell, we should see nothing earlier than $t - \Delta t$ where Δt is the characteristic time scale of the pulse. This is apparently not the case in many complex GRBs.

Another argument against a single explosion is the low filling factor (i.e., the ratio of the area of emitting regions to the total fireball surface) derived from the time variability (Fenimore et al. 1998). The low filling factor leads to a low efficiency (Piran & Sari 1997).

These problems gave support to "recurrent central engine" models which have become very popular (e.g., Rees & Mésźaros 1994; Sari & Piran 1997). The recurrent central engine is usually described as a long-living (up to hundreds of seconds) accreting system where an accretion disc is formed by a disrupted neutron star. The system emits relativistic shocks that collide producing pulses of gamma ray emission (Kobayashi, Piran, & Sari 1997; Daigne & Mochkovich 1998).

How can we then reproduce a wide power-law PDS from the central engine? Probably there is no way to do this with a straightforward internal shock model. Light curves simulated with internal shocks have nothing common with real bursts. They have an intrinsic time constant and a very different Fourier PDS with a power law asymptotic with the wrong slope: $P(f)$ = const instead of $P(f) = f^{-5/3}$.

In principle, an accreting system can provide a power law PDS, e.g., the Cyg X-1 PDS is a power law $P(f) = f^{-1}$ over 1.5 decades (from 0.03 Hz to 1 Hz, see Belloni & Hasinger 1990). However, we cannot see the time profile produced by the central engine itself as the history of accretion will be reprocessed by internal shocks. The Kolmogorov PDS can hardly be obtained straightforwardly with internal shocks because too much power has to be transferred to low frequencies. Maybe one can invent some rule for the ejection of internal shocks to reproduce the Kolmogorov slope. However, this would be something farfetched.

The long-living central engine helps to solve some problems such as a very slow (if existing) evolution of temporal and spectral properties in complex bursts. Nevertheless, we need something else, more complicated than shock collisions, to produce the self-similar behavior over 2 decades of time scales. As was emphasized in the previous section, we need a complex dynamical process for this. I would suggest that we should search for such a process in the shock evolution rather than in collisions of internal shocks.

We can suggest at least two suitable dynamical processes: MHD turbulence, which is very natural in an relativistic outflow and dynamical instabilities, most probably the Rayleigh - Taylor instability. Both can generate a wide range of irregularities with a high energy density contrast. Reconnection of the magnetic field generated by a turbulent dynamo is certainly a very efficient way to dissipate the energy into gamma rays.

Some arguments in favor of this scenario can be borrowed from solar flares. Their time behavior resembles GRBs (while it still differs from GRBs at a quantitative level – solar flares have a different average time profile and a different average PDS) and we do know that solar flares results from reconnection of a magnetic field with a complex structure. Lu and Hamilton (1991) described power law distributions of flare energy release with a cellular automata model which is also a kind of a near-critical pulse avalanche.

Summarizing the issue:

The time variability of GRBs can hardly appear straightforwardly as a result of internal shock collisions or as a consequence of variations of the external medium. The time behavior should be associated with a dynamical process that makes the outflow strongly inhomogeneous in a wide range of scales giving rise to a kind of fractal pattern.

The inhomogeneous structure of the outflow removes the main objections against a single explosion scenario. An argument in favor of the recurrent central engine is the absence of evident evolution of long events (Fenimore 1999). However, some evolution probably exists (e.g., Ford et al. 1995) and this argument can hardly be used as a proof.

5. Lorentz Factor, Compactness and Emission Regime

The cosmological origin of GRBs unavoidably implies a relativistic motion of the emitting region towards the observer. Let us consider an emission episode with a luminosity, $L = 10^{50}$ erg/s, and a characteristic variability time scale, 1 s. The size of the emitting region should not be greater than 1 light second, i.e., $r \sim 3 \cdot 10^9$cm. Then, assuming no relativistic motion we obtain:

A compactness parameter:

$$\ell = \frac{L\sigma_T}{m_e c^3 r} \sim 10^{12}$$

An equilibrium (blackbody) temperature $T = (L/4\pi r^2 \sigma)^{1/4} \sim 30$ keV.

We can hardly see anything except the 30 keV Planck spectrum using this assumption and such a system cannot be stable - it should explode. Now let us describe the emission region as a blob, quasi-spherical in the comoving frame, moving towards the observer with a Lorentz factor Γ. Then the comoving luminosity is $L_c = L\Gamma^{-4}$ (Γ^{-2} from angular collimation, Γ^{-1} from time transformation and Γ^{-1} from blueshift), where L is the apparent luminosity (assuming isotropy).

For the size of the emission region we take $r_c = r\Gamma$. Then the comoving compactness is:

$$\ell_c = \ell\Gamma^{-5} = 10^{12} \cdot \Gamma^{-5} \tag{2}$$

If we want to deal with simple linear physics describing the gamma ray emission, we should take $\Gamma > 100$. Then we have no problem with intense pair production and can apply the optically thin synchrotron-self Compton models (see, e.g., Panaitescu & Mészáros 1998). This is the most popular approach and the constraint $\Gamma > 100$ is generally accepted.

For other comoving values we have:

The energy density at the emitting surface:

$$\epsilon_c \sim 3 \cdot 10^{19}\Gamma^{-6} \quad \mathrm{erg/cm^3}. \tag{3}$$

The equipartition magnetic field:

$$H_c \sim 3 \cdot 10^{10}\Gamma^{-3} \quad \mathrm{G} \tag{4}$$

The equilibrium temperature:

$$T_c \sim 30 \cdot \Gamma^{-3/2} \quad \mathrm{keV}. \tag{5}$$

And the temperature, blueshifted to the observer frame:

$$T \sim 30 \cdot \Gamma^{-1/2} \quad \mathrm{keV}. \tag{6}$$

The global size of the relativistic fireball (or the distance from the source, having in mind a jet geometry), for a characteristic emission time of 300 s:

$$R \sim 10^{13}\Gamma^2 \quad \mathrm{cm}. \tag{7}$$

One can obtain a large variety of physical conditions depending on the Lorentz factor. On the other hand, there are arguments for a small dispersion of the Lorentz factor in different GRBs (e.g., a sharp break in the average PDS, Beloborodov, Stern & Svensson 1999). What is the typical Lorentz factor? This is one of the most important issues in the whole GRB problem.

At a huge Lorentz factor, $\Gamma \sim 1000$, the blast wave passes a distance of order of a parsec during the emission phase. This value was assumed in the model of Shaviv & Dar (1995b) describing GRB emission as upscattering of the star light by a $\Gamma \sim 1000$ blast wave crossing a globular star cluster. The model gives a wrong description of the GRB time variability (e.g., fact 2.3 can not be explained). It seems that we do not need such a Lorentz factor for any other purposes and taking into account some other problems (e.g., the requirement of a good vacuum, $n < 10^{-5}\mathrm{cm}^{-3}$ for long events), we will not consider this possibility seriously.

The main choice is between large ($\Gamma \sim 100-300$) and moderate ($\Gamma \sim 10-50$) Lorentz factors. This choice will define the emission regime: in the first case this should be optically thin synchrotron (synchrotron - self Compton), in the second case, intensive pair production should take place and we have a much more complicated nonlinear, optically thick emitting system.

6. $\Gamma \sim 100-300$ versus $\Gamma \sim 10-50$ or Optically Thin versus Optically Thick Emission

A large Lorentz factor ($\Gamma \sim 300$) is attractive because it can explain the GRB emission as a result of the interaction of the blast wave with the interstellar medium. Indeed, the kinetic energy of the interstellar gas swept up by the fireball with a Lorentz factor Γ at the observer time t is

$$E_{KE} = 6 \cdot 10^{49} t_{100}^3 \Gamma_{100}^7 \cdot n \quad \mathrm{erg}, \tag{8}$$

where n is the gas density in cm^{-3}, $t_{100} = t/100$ s, and $\Gamma_{100} = \Gamma/100$. Accepting the value $t = 100$ s for the emission phase (for a recurrent central engine model one can afford a slightly smaller t; for a single explosion model one must take $t > 100$ s in some cases) and $n = 0.1\ \mathrm{cm}^{-3}$ we obtain $E_{KE} \sim 10^{52}$ erg for $\Gamma = 300$. Under such conditions we should see a strong energy dissipation from the interaction between the fireball and the interstellar medium within the first 100 s. If $n = 10^{-4}\ \mathrm{cm}^{-3}$ (a GRB in a galactic halo) then one can slightly adjust T and Γ to obtain a considerable deceleration of the fireball in a reasonable time.

The interaction between the fireball and the external medium solves the free energy problem. The free energy source for the gamma ray emission is just the bulk kinetic energy of the fireball. The most popular scheme of the emission is shock particle acceleration and synchrotron - self Compton radiation (e.g., Tavani 1996; Panaitescu & Mészáros 1998; Dermer 1998) One can see from Eq. (2) that pair production is negligible at such high Γ and the electron scattering optical depth is small. Therefore we deal with optically thin linear emission. The involved physics is well studied and easy to work with. However we have a number of very serious problems with this simple linear physics.

The first difficult question is **"what causes the specific time variability of GRBs?"**. Is it inhomogeneities of the external medium? How can one then explain the stretched exponential average time profile and the power law PDS? With a fractal structure of the interstellar medium? Hhow can we then explain the huge amplitude of variations (Fig. 2)? We certainly need some essentially nonlinear system to produce rapid variations by 3 orders of magnitude.

A process which can produce both a large dynamical range of variations and a wide range of time scales is magnetic reconnection (we note that it works in a similar way in solar flares). An equipartition magnetic field with a complex geometry can be generated by a turbulent dynamo. Then such a field can gain additional energy with compression in the deceleration stage and reconnect. This could be a solution of the problem of time variability for $\Gamma \sim 100 - 300$ (we are unfortunately not able to solve this problem at a quantitative level).

The next problem arises from the **GRB spectra.** In both variants of energy release at $\Gamma \sim 100 - 300$, shock acceleration and magnetic reconnection, the gamma-ray emission is blueshifted optically thin synchrotron radiation.

Real GRB spectra are well approximated by the Band expression (Band et al. 1993) consisting of two asymptotic power laws:

$$dN/dE \propto E^{\alpha}$$

at small E,

$$dN/dE \propto E^{\beta}$$

at large E and

$$dN/dE \propto E^{\alpha} e^{-E/E_p}$$

in the intermediate range. E_p parameterizes the break energy. At large negative β, this expression resembles the hard X-ray spectra of AGNs, especially if one subtracts the reflection hump (see Zdziarski et al. 1997). E_p is associated with the pair temperature in that case. In AGNs, we have α close to -2 (-1.9 is the most typical value, and $E_p \sim 60 - 150$ keV). The high energy spectrum, $E \gg E_p$, in AGNs cannot be reconstructed because of poor photon statistics.

In GRBs the soft part is considerably harder: α varies between -2 and $+1$ (Band et al. 1993). There are some fits of spectra with $\alpha \sim +1$ but they have large errors, a short fitting interval, and a low E_p (Crider et al. 1997). The largest α that one can trust is near 0 (Preece 1998, private communication). E_p is also larger than that for AGNs and variable within a single burst. The highest values of E_p is above the BATSE range (~ 1.5 MeV), the lowest is below the BATSE range (~ 30 keV) and for the main fraction of spectra, 100 keV $< E_p <$ 500 keV (Band et al. 1993). The typical hard energy slope is $-2.8 < \beta < -1.7$ (clustering around $\beta \sim -2.1$, Preece et al. 1996), sometimes much steeper, consistent with a pure exponential cutoff ($\beta \sim -\infty$).

Summarizing the GRB spectral phenomenology:

- The GRB low energy (hard X-ray) spectra are considerably harder then the AGN spectra and have a break at a higher energy.

- The GRB spectra are much more diverse than the AGN spectra, nevertheless they have a typical shape: a harder low energy power law, an exponential break, and a softer high energy power law.

- The spectra evolve during a single pulse. A pulse starts with a maximum E_p, then E_p decreases, sometimes by factor of a few (Ford et al. 1995).

How do optically thin synchrotron models fit this spectral pattern? The first problem appears with the low energy spectra. A synchrotron model cannot give a spectrum with $\alpha > -2/3$, while there are considerably harder spectra, $\alpha = 0$, at least. This issue is studied by Preece et al. (1998). The second problem is the spectral break, sharp enough to be fitted with an exponential (Band et al. 1993). It implies a very sharp electron energy distribution, which remains sharp during rapid evolution (note that the synchrotron photon energy is proportional to the square of the electron Lorentz factor).

From my point of view these problems are fatal for the synchrotron shock models. We should search for a less linear and less trivial physics to explain GRB emission (especially if we want to explain the nontrivial time variability at the same time).

I started the discussion with a comparison between GRB and AGN spectra and this is more motivated than it could seem at first sight. There is a number of arguments that in the case of GRBs as well as in the case of AGNs that we deal with an equilibrium e^+e^- pair plasma. It is surprising that while there exist a large number of works on synchrotron shock models, we know of very few attempts to describe GRB spectra with a Comptonizing pair plasma. I can only mention the works of Ch. Thompson (see Thompson 1998 and references therein) and Ghisellini & Celotti (1999). Liang (1997) and Liang et al. (1997) studied optically thick thermal Comptonization in application to GRBs taking the temperature and the optical depth as external parameters.

It is a well known fact that the pair plasma is a good thermostat and is able to produce spectra with a stable break (which also can be sharp) in the X-ray range (Svensson 1984). The break results from quasi-thermal Comptonization. Its position is defined by the pair equilibrium and depends on the compactness parameter and on the type of the energy supply: pure thermal (direct heating of Maxwellian electrons), nonthermal (heating of the relativistic tail of electron energy distribution), or hybrid (both).

In the pure thermal case, the pair temperature is self-adjusted in a way to support pair production at the tail of the photon energy distribution. The resulting temperature decreases logarithmically with increasing compactness, at $\ell \sim 1000$ the pair temperature is ~ 40 keV and the peak in νF_ν distribution appears at ~ 80 keV. This is the energy in the comoving frame, and it implies a too small Lorentz factor as the average observable E_p is 300 – 400 keV.

A smaller pair temperature can be achieved in nonthermal or hybrid model. To demonstrate that it is in principle possible to reproduce GRB spectra with optically thick pair plasma, I made a series of simulations with a large particle nonlinear Monte-Carlo code (Stern et al. 1995) for high compactnesses ($\ell \sim 1000 - 2000$). Figure 5 demonstrates the result of one attempt that can be considered as more or less successful. The break position at 20 – 30 keV is consistent with a Lorentz factor 10 – 20 which implies a higher compactness (see eq. 2) which in turn would give cooler pairs. The simulation at $\ell \gg 1000$ is technically difficult. The impression is that consistency with data can be achieved at $\ell = 10^4$ and $\Gamma \sim 20 - 30$.

The recipe how to obtain a proper spectral shape can be formulated as follows:

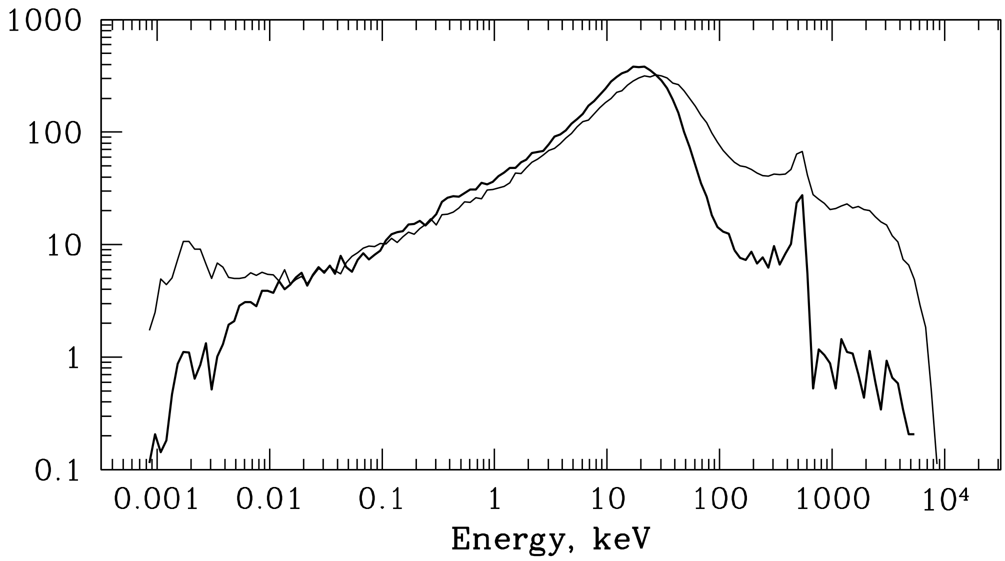

Figure 5. Examples of simulated spectra of optically thick pair plasma. The nonlinear large particle Monte-Carlo technique of Stern et al. (1995) was used (2^{17} large particles). The active region is a sphere with uniform energy injection,while the temperature and the pair density depend on radius (10 discrete shells): both are obtained in the simulation as a result of the pair and energy balance. Energy is injected by instant acceleration of pairs to 10 MeV. The synchrotron emission is strongly self-absorbed (the peak near 0.001 keV is the harder edge of the partially self-absorbed synchrotron spectrum), the energy of the accelerated pairs goes to photon Comptonization, or heats thermal electrons through synchrotron emission - self-absorption. The compactness is 1000, the magnetic field 10^6G. The pair optical depth is ~ 10, and the temperature varies from 4 keV in the center to 10 keV near the surface. The two spectra correspond to different states of the system. The thin line shows the steady-state spectrum. The thick line shows the decaying state. The spectrum is integrated over time from $2r/c$ to $4r/c$ after the energy injection was turned off. The pair depth dropped in the second case and we see radiation escaping from the center where the temperature is lower.

The main condition to obtain a hard spectrum below E_p is photon starvation, i.e., only a small number of soft photons enters the Compton upscattering process (see Zdziarski, Coppi, & Lamb 1990). The main source of soft photons is synchrotron radiation of the nonthermal pair component. To get rid of it one should restrict the nonthermal tail to the energy range for which the synchrotron radiation is reabsorbed by thermal pairs. In the presented example, this condition is fulfilled and the resulting low energy spectral slopes, $\alpha = -1.1$ for the steady-state spectrum and $\alpha = -0.95$ for the decaying state, are typical for GRBs. To obtain a harder spectrum one should take a larger magnetic field and energy density to have a higher reabsorption energy. A rising pair optical depth and energy density will eventually lead to a Planck spectrum with the temperature estimated by Eq. (6).

An optically thick pair plasma provides another advantage: a nonlinearity which can give rapid variations with a large amplitude. A large pair optical depth can be generated during a few r/c and can annihilate on the same time scales, i.e., when the emitting system turns off, it does not just cool down – it disappears.

The only objection against a moderate Lorentz factor and a large compactness is associated with the GeV photon emission detected in some bursts. At a high compactness, high energy photons should be absorbed through photon-photon pair production. This constraint can be easily avoided by assuming that the hundred keV – MeV emission and the GeV emission originate from different processes in different places, e.g., the latter could result from shock acceleration, the former from magnetic reconnections behind the shock.

Summarizing the issue:

A large Lorentz factor ($\Gamma \sim 100 - 300$) naturally enables the conversion of the fireball kinetic energy into radiation through interaction with external matter. It implies a simple, linear mechanism of gamma ray emission which does not seem to satisfy the data.

At a moderate Lorentz factor ($\Gamma \sim 10 - 30$), more interesting physics appear: a nonlinear system of an optically thick pair plasma and radiation at a high compactness. This regime is much more difficult to study. Nevertheless, this case can hopefully provide a welth on nonlinear phenomena that could explain many puzzling properties of GRBs.

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