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The Diversity of Gamma Ray Burtsts and Can we learn anything new from GRB 221009 A?

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The brightest gamma-ray burst GRB 231009A has renewed interest in the phenomenon of GRBs, which in many ways still remains a mystery. Reports of "forbidden" multi-TeV photons, causing a lot of theoretical work, do not seem to be confirmed, however, the record-breaking event remains very interesting and may clarify some questions. In particular, the event demonstrated an interesting interplay between the precursor, prompt emission, and afterglow. The temporal variability of GRBs and their emission spectra discussed in the report imply that we are observing a very complex and diverse phenomenon, involving many different mechanisms such as multiple jets, radiation dominated internal shocks, MHD turbulence reconnections, and e^+e^- pair loading of external medium.

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1. Introduction

The apparently brightest gamma-ray burst ever observed, GRB 221009A, has been detected by many space observatories including *Fermi* [1, 2] in 0.1 MeV - 100 GeV range and on Earth by LHAASO array in the range of hundreds GeV to several TeV [3]. The strongest impact of this event is due to claims of two photons 18 GeV (LHAASO) and 250 TeV (Carpet 2) which cannot come from z = 0.15 because of the absorption on the extragalactic background light. A new physics has been suggested to explain these photons, see e.g. Ref. [4]. Study of GRB 221009A spectra can be used also to put constraints on the strength of the extragalactic magnetic field [5].

Can we, using the rich *Fermi* data, find hints of some subtle, interesting effects just because of the exceptional brightness of this event? There exists a consensus on the general scenario of GRBs. It includes:

(i) A collapsar, presumably a WR star, with a dense ($\sim 10^{13}$ g cm^{-3}) neutronized accretion disk [6] .

(ii) A relativistic jet launched by the accretion disk burns a channel in the progenitor star [7].

(iii) The jet beyond the star emits the so called ”prompt GRB” due to a kind of its internal instability (e.g. via internal shocks [8]).

(iv) The jet propagating in the external medium produces an external shock which we observe as a gradually fading afterglow.

Before discussing the case of GRB 221009A, we will provide a brief phenomenological overview of the observations and their possible implications.

2. GRB phenomenology: spectra

Photon specra of prompt GRBs emission do not look like speccra of any other astrophysical sources. Fig. 1 demonstrates best fit parametrisation with Band function for the nine brightest GRBs from the Fermi GBM Burst Catalog. [1]. The Band function is the simplest parameterization that describes most of the spectra of prompt gamma-ray bursts. It consists of two power laws - low energy and high energy asymptotes smoothly connected by an exponential. Most of the spectra are comparatively ’narrow’, i.e. the main fraction of the energy fluence comes within one order of magnitude energy range. Moreover, these curves show time-integrated spectra, while time-resolved spectra are even more narrow.

The spectral slope in the soft energy range (below 100 keV) is typically $\alpha \sim -1$ (in units of dN/dE, note that in Fig.1 we traditionally show the spectral energy distribution E^2 dN/dE), which is harder than the synchrotron fast cooling spectrum, that would be expected from the shock accelerated electrons. Moreover, some prompt GRB spectra at their low energy wing are harder than the synchrotron spectra of non-cooling (or slow-cooling) electrons; this rules out synchrotron radiation as the main source of the prompt GRB emission. A realistic alternative is the thermal comptonization of seed synchrotron or thermal photons. The conditions for such a process can be a relativistic radiation-mediated shock [9]. When it propagates even in an optically thin medium, it boosts seed photons above $m_e c^2$ due to multiple scattering at both sides of the shock. Then, these photons generate optically thick e$^+$e$^-$ plasma with a temperature of a few tens keV, which produces

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[1] The catalog can be found here https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

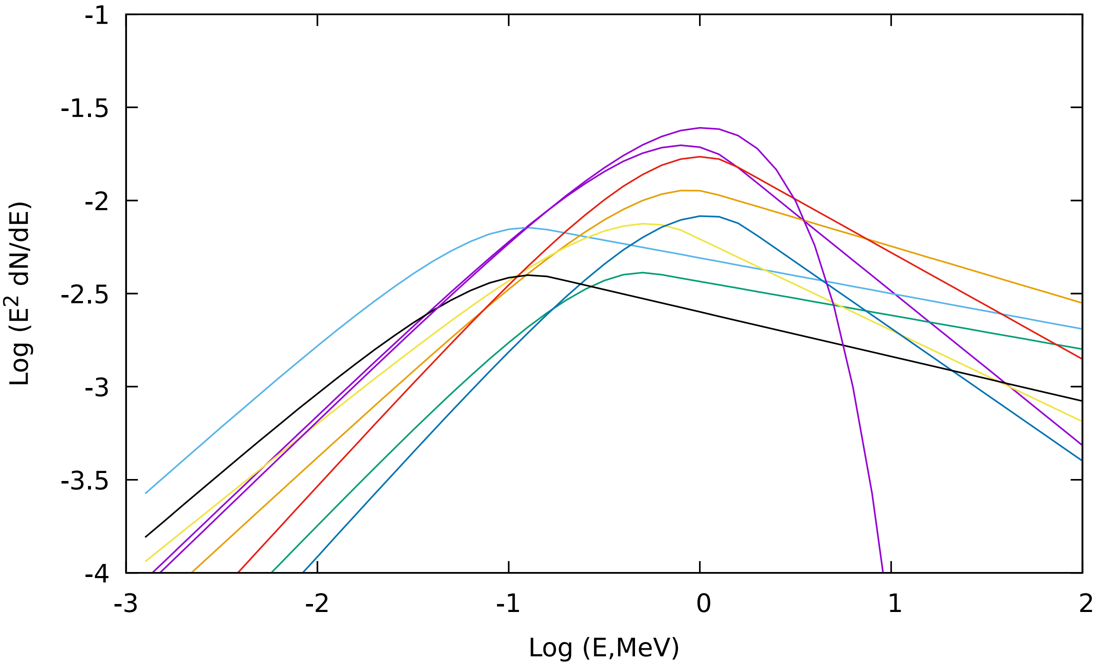

Figure 1: Spectra of 9 brightest GRBs from *Fermi* burst catalog approximated by the Band function.

a thermal comptonization maximum that is blue-shifted to the hundred keV - MeV range. In the scenario of radiation mediated shock with intensive pair production the narrow spectral maximum and hard x-ray part of the spectrum are direct consequences of thermal comptonization.

The spectrum of GRB afterglow, on the contrary, extends to at least 10 orders of magnitude as a power law with $\alpha \sim -2$ (flat spectral energy distribution) or slightly harder (Fig. 2). This is a typical spectrum of electromagnetic cascade in optically thin medium where the slope is within limits $\alpha = -1.5$ (slow cooling spectrum) and $\alpha = -2$ (saturated electromagnetic cascade, [11]).

3. GRB phenomenology: time variability

Light curves of the prompt GRB emission are strikingly diverse (Fig. 3). The simplest GRB consists of one pulse, so called "Fast Rise, Exponential Decay", FRED. Some light curves consist of several FREDs, often overlapping. Some looks like a pile of many tens or even hundreds of overlapping pulses of different duration. Some light curves of emission episodes have an arbitrary shape which can not be decomposed on usual FREDs. In some events the prompt emission may "turn-off" dropping down to the level below 10^{-3} of preceding emission, then "turn on" again.

The important feature of prompt emission is the absence of any characteristic time scale. Fourier power density spectra of very "rich" brush-like light curves are almost power law extending by 3 orders of magnitude, see Fig. 4. There are no specific frequencies between limiting mHz and a few Hz.

Another interesting and puzzling feature is the precursor - a short relatively weak pulse of the prompt emission that precedes the main emission episode. It may be separated from the main event by more than a hundred second quiescent interval, as in the case for GRB 221009A.

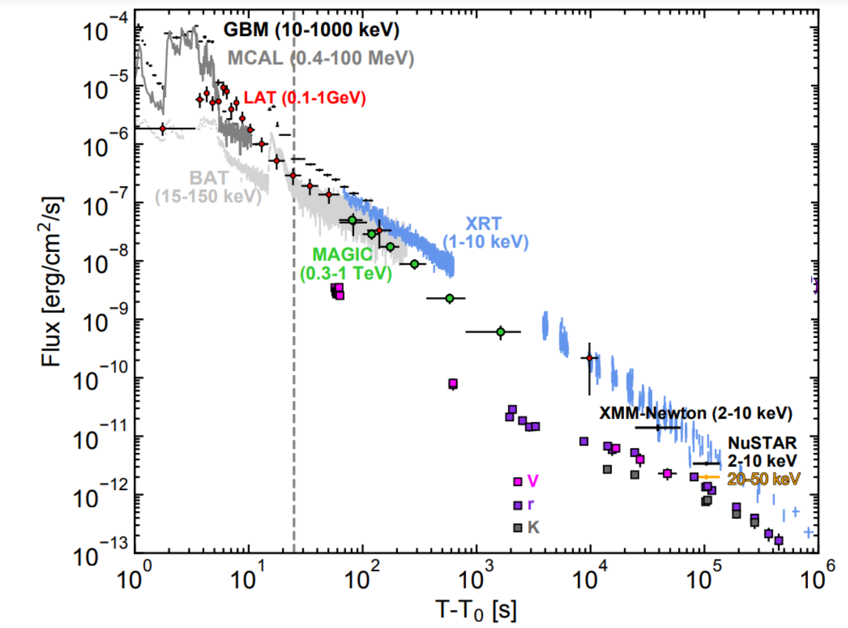

Figure 2: Afterglow of GRB 190114C in diddерent energy ranges covering more than 12 orders of magnitude, from Ref. [10].

4. Qualitative interpretation: prompt emission versus afterglow

The temporal variability of the prompt emission is probably associated with the unsteady operation of the ”central engine” (accretion disk), and instabilities within the jet. The most popular explanation for the discrete pulses of gamma-ray bursts is the internal shock wave mechanism [8]: the variable Lorentz factor of the jet causes internal shock waves that emit more or less standard pulses of soft gamma radiation. More recent studies with 3D MHD simulations demonstrate another possible scenario of the jet energy dissipation - kink instability [14]. It is likely that internal shocks and kink instability are not enough to explain all the diversity of GRB light curves. Light curves such as those in Fig. 4 indicate a more developed instability such as relativistic turbulence. Like a radiation-dominated shock, relativistic turbulence, even without magnetic reconnection, can cause the same effect: intense pair production and thermal Comptonization. In both cases we are dealing with large Lorentz factor gradients, and there is no significant difference between a head-on shock and a shear layer. MHD turbulence has been considered as a source of gamma radiation for various astrophysical phenomena in [15, 16] and, in particular, in [17] for gamma ray bursts.

To summarize, in the case of the prompt emission we are dealing with a complex interplay of various phenomena: the central engine (which can completely turn-off and then turn-on again, see Fig. 3 c,h), internal shocks and various jet instabilities including relativistic MHD turbulence. It seems that the only way to clarify the problem of prompt GRB emission is through intensive MHD simulations, complemented with nonlinear treatment of interacting photons and e^+e^- pairs [18], including their feedback on the MHD part. Unfortunately, the second part of this toolkit is still quite poorly developed.

In the case of the afterglow the radiation mechanism is much simpler - just classical shock

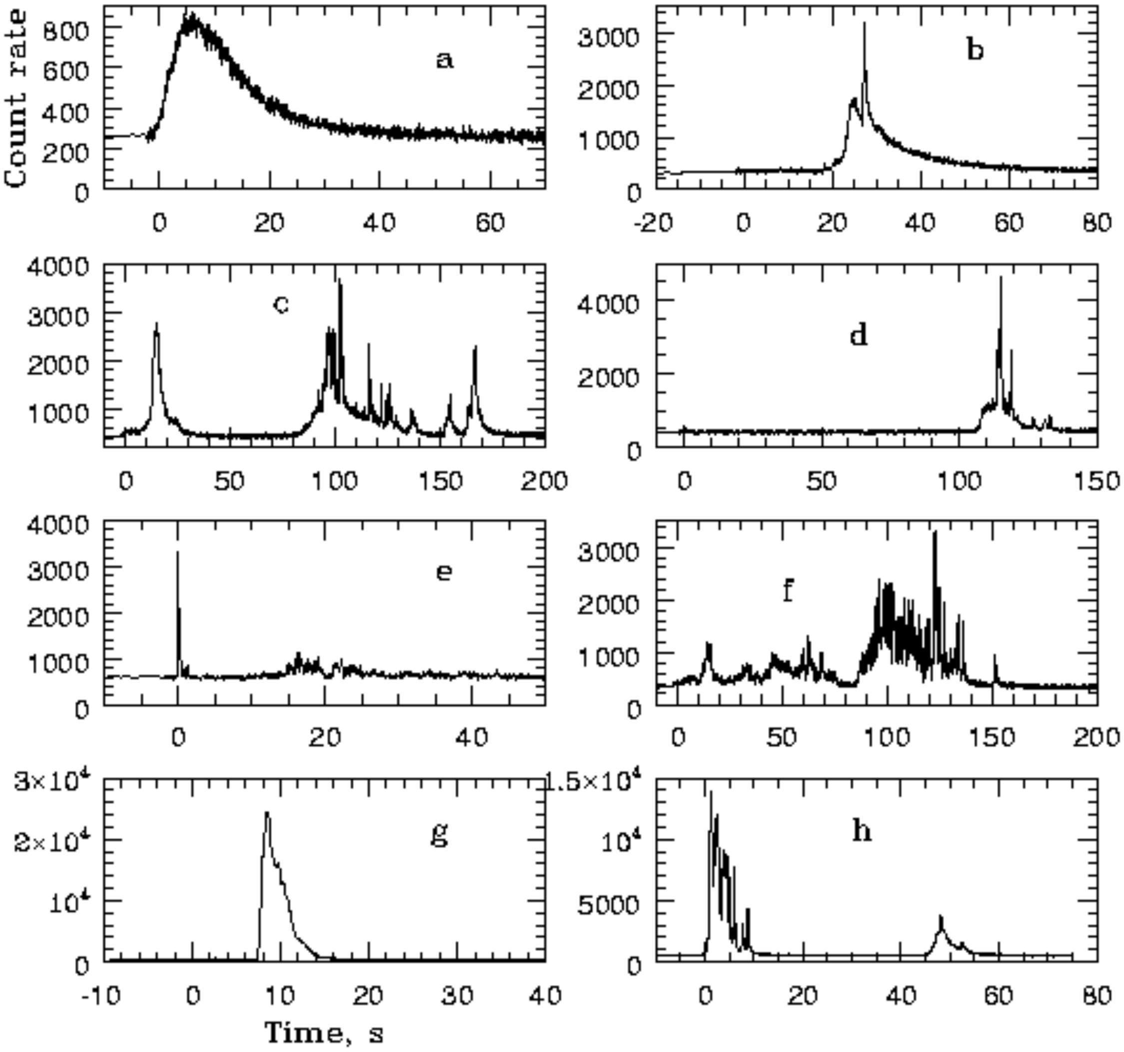

Figure 3: Examples of GRB light curves, from Ref. [12].

acceleration in optically thin medium with photon-pair cascade. Nevertheless, the dynamics of shock is still non-trivial, since it is influenced by pair loading [19] and pre-acceleration of the external medium [20]. However, this is unlikely to change the general conclusions about the spectral and temporal properties of the GRB afterglow.

5. Two afterglows of GRB221009A

The light curves of GRB 221009A in different energy ranges are shown in Fig. 5. Unfortunately Gamma Burst Monitor (hereafter GBM) was oversaturated at the peak of the event. The Large Area Telescope (hereafter LAT), which records high energy photons, was also oversaturated in the same time intervals of a total duration ~30 s. Another problem is the large viewing angle: for bursts occurring ~75° off-axis of LAT the efficiency of photon detection drops below 10%. When corrected for the angular dependent efficiency and using next visibility windows for the burst location, the

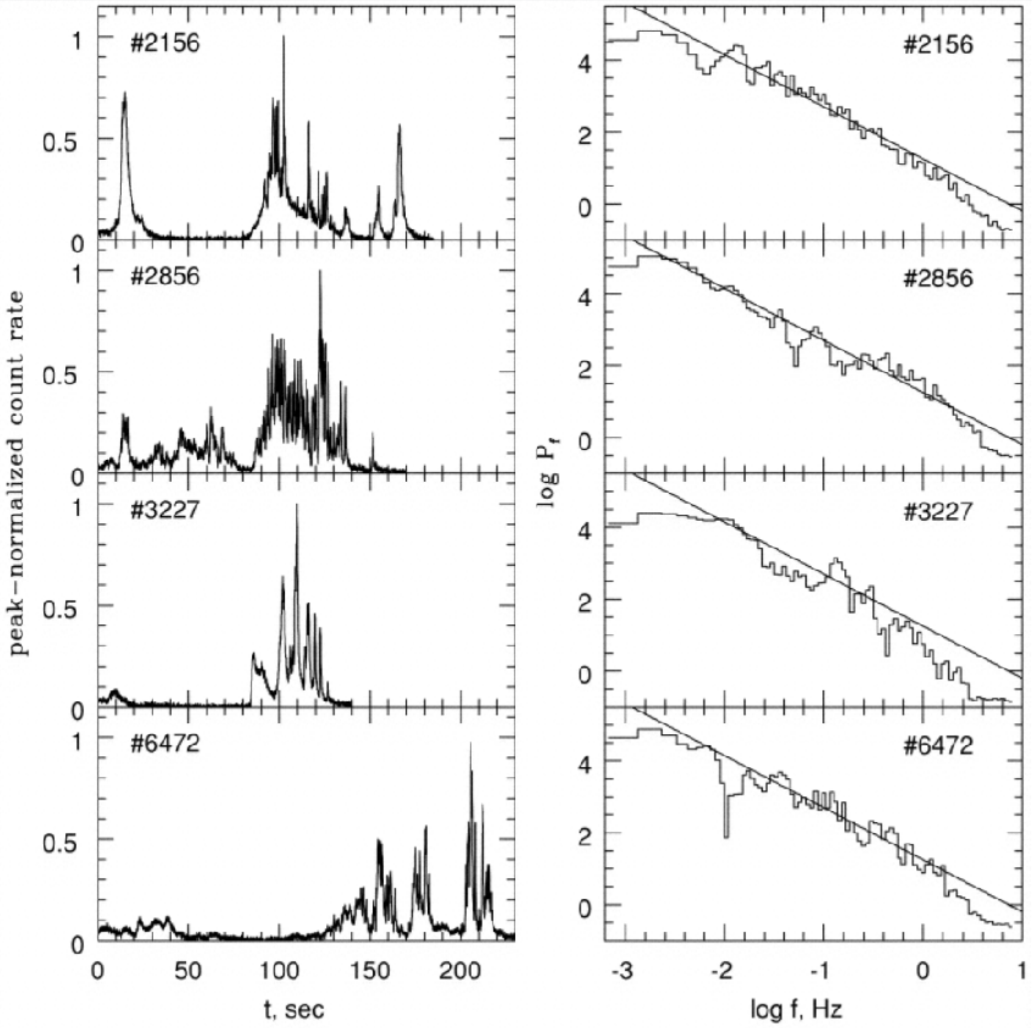

Figure 4: Power density spectra of some GRBs with the most complex variability, from Ref. [13].

LAT data demonstrate a typical afterglow in the range above 100 MeV. The light curve of the afterglow is consistent with a power law which can be traced up to 2 days [21]. Such an afterglow is a common feature for many GRBs, the prompt emission of GRB 221009A demonstrates nothing unusual.

We also notice that the afterglow overlaps with prompt emission in time. As can be seen in Figs. 5a and 6a, the emission in the time interval 300 - 400 s looks like a typical afterglow: a wide hard energy spectrum with a smoothly decaying light curve. Then, after 400 s, typical prompt GRB activity appears, peaking at 500 s. This is quite natural - the external shock can be formed soon after the jet breakthrough, while the central engine continues to energize the jet (see also [2]. Probably GRB 221009A is not unique in this respect as well.

However, the emission at the early stage of the burst seems more interesting. Fermi LAT detected 6 photons in the range 20 - 230 MeV in the time interval 7 - 50 seconds after the trigger, see Fig. 5b and Ref. [21]. The expected number of background photons in this time interval from this direction is 0.65, implying a significance level of 0.5×10^{-4} [21]. The precursor pulse (looking

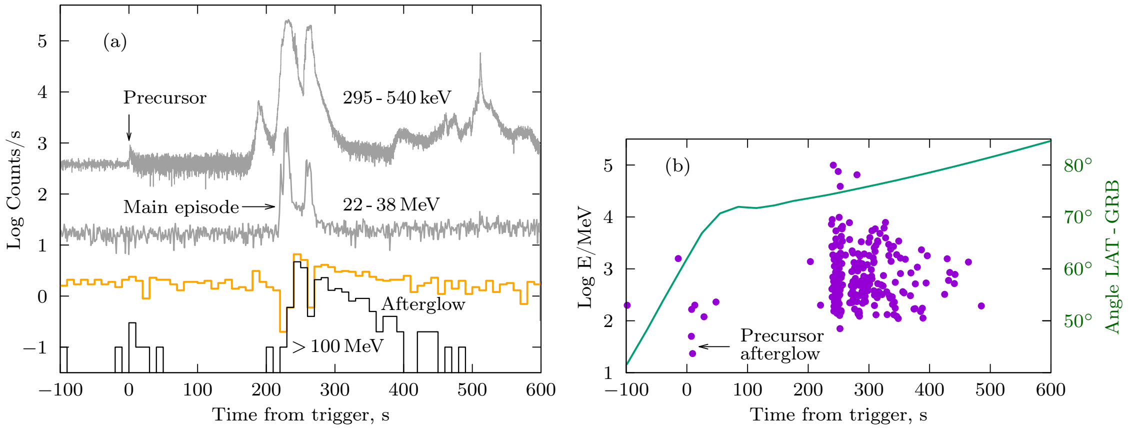

Figure 5: Time evolution of GRB 221009A in raw data. Prompt phase and early afterglow. (a) Count rates in various energy ranges on a logarithmic scale, upper curve GBM NaI 295 - 540 keV, middle curve GBM BGO 22 - 38 MeV, lower blue curve LAT, 8° circle around the location of GRB 221009A, yellow curve - all LAT photons. Dips at 210 and 260 s result from detector saturation. (b) Individual LAT photons in the 8° circle around the position of GRB 221009A (left logarithmic energy scale) and the angle between the LAT axis and the burst direction (right scale). Note the emission in the 10-200 MeV range 50 s after the precursor. (From [21]).

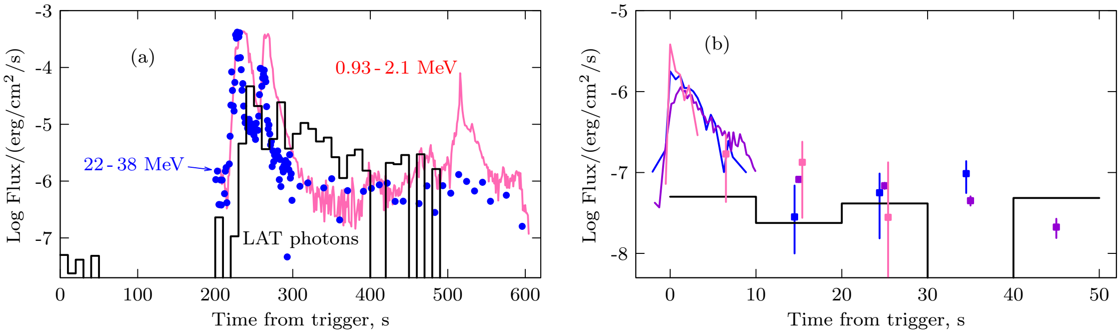

Figure 6: (a) Prompt GRB and early afrerglow in different energy ranges. Histogram: energy flux of LAT photons normalized to angular-dependent effective area calibrated with Vela-X source. Pink line: energy flux in 0.93 - 2.1 MeV range from Gamma-Burst Monitor BGO detectors. Blue circles: the same in 22 - 38 MeV energy band. (b) Lower left corner of (a) with additional data. Magenta: sum of 5 brightest NaI detectors, in 0.1 - 0.3 MeV band assuming 400 cm^2 effective area. Blue: BGO detectors in 0.38 - 0.93 MeV band assuming 200 cm^2 effective area. Pink: BGO, 0.93 - 2.1 MeV band. Black: distribution of the energy flux represented by 6 LAT photons from 20 to 230 MeV.

like a typical "simple" GRB), which triggered GBM, died out at ~10 s. However, the emission in sub-MeV region still continued up to 50 s, or even longer as claimed by [2]. Note that the energy flux in the energy ranges 0.93–2.1 MeV and 20–230 MeV is comparable, i.e. the spectrum is consistent with a flat one $\alpha = -2$ typical for GRB afterglow and unusual for the prompt emission. A smooth time profile of the emission after the precursor also supports its interpretation as an external shock. This would mean that the precursor is associated with its own independent jet with its own afterglow/external shock.

This precursor jet was two orders of magnitude weaker than the main one and declined before the main emission started. This case of a GRB with two afterglows supports a scenario of a specific central engine action that produces a precursor, as in the fallback model [22], and disfavours models that consider both the precursor and main event as an output of a single jet as it is assumed in the photospheric precursor model [23].

It seems that GRB 221009A rises new questions rather than clarifies previous puzzles. Does the channel drilled by precursor in the star body affects the main episode? Does its external shock affects the main afterglow? To summarize, GRB 221009A supports the view that GRBs are a very complex and even intricate phenomenon that cannot be described by any simple model. Its understanding requires heavy realistic simulations of 3D MHD with particle acceleration and interactions.

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