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Cosmic rays and gamma-ray bursts

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Contents

Abstract. The nature of cosmic gamma-ray bursts (GRBs), still unsettled 30 years after their discovery, is the most intriguing current astrophysical problem. In a recent *Physics-Uspekhi* review [1], a theory relating their origin to the Solar system periphery, as well as galactic and metagalactic hypotheses are discussed. For the latter two, the total GRB energy release proves to be large enough to enable cosmic rays (CRs) to be simultaneously produced by the same source. In this paper a fourth possibility, the present author's 'interstellar' hypothesis [3], which also permits the simultaneous production of CRs and GRBs in cosmic plasma pinches is discussed.

1. Introduction and estimates of basic GRB and CR parameters

The aim of the present paper is to consider the possibility of creation of cosmic gamma-ray bursts (GRB) and cosmic rays (CR) in plasma pinches. The observed features of GRB are described in review [1], and of CR – in Ref. [2], so we shall use these data in describing the properties most interesting for our purposes here.

The main puzzle of GRB is that no astronomical objects (stars, nebulosities, galaxies) have been observed at the location of a GRB in the sky either before or after the GRB. So the distances R to the GRB and hence their nature and energy release E are unknown.

The maximum energy flux from a GRB at Earth is $S_{\max} = 10^{-3}$ erg cm^{-2} and four variants of GRB location are considered:

(1) at the Solar system periphery ($R > 100$ AU $= 1.5 \times 10^{15}$ cm);

(2) inside the galactic disk ($R < 100$ pc $= 3 \times 10^{20}$ cm);

(3) in a spherical halo around the Galaxy ($R > 100$ kpc $= 3 \times 10^{23}$ cm);

(4) at metagalactic distances ($R > 1000$ Mpc $= 3 \times 10^{27}$ cm).

Assuming GRB emission isotropy, the maximum energy released in one GRB is $E_{\max} = 4\pi R^2 S$ and should be 2×10^{28} ergs, 10^{39} ergs, 10^{45} ergs, and 10^{53} ergs for each of these distances, respectively.

Some authors connect the first variant with the possibility of comet encounters (or their magnetic envelopes) within the Oort cloud (see Ref. [1] and references therein). Then the observed isotropic distribution of GRBs over the sky seems to be difficult to explain. The last figure is already comparable with the rest-mass energy of the Sun $E_{\odot} = Mc^2 = 2 \times 10^{54}$ ergs, and since a typical GRB lasts for a few seconds, such a rapid 'burning' of a Solar-like mass appears to be a rather exotic phenomenon. Therefore we shall not consider the first and fourth variants and will focus on the second and third ones.

Note that GRBs are observed, on average, once a day, so the figures above correspond approximately to the total power of all the *observed* GRBs per day, considering all GRBs identical. For our purposes, it is useful to compare this power with that of CR. Their energy density is 1 eV cm^{-3}, so taking our Galaxy radius of 10 kpc and the galactic volume $V_{\text{Gal}} = 10^{68}$ cm^3 the total energy in CR is 10^{56} ergs. However, they leave our Galaxy by diffusion in 10^8 years, so to fuel them persistently a power of the order $W_{\text{CR}} = 10^{45}$ erg day^{-1} is required, which is clearly close to the power of GRB in the third variant. Judging by these figures, one may even suppose CRs and GRBs to be generated by the same sources, so we shall consider this possibility later.

In review [1], the second, third, and fourth variants are mainly discussed in relation to neutron stars (cooled down and thus unobservable). Essentially, the only alternative to this is to assume that GRBs are generated by electric discharges which can be called 'cosmic lightning'. No 'electrodes' with superhigh charge, of course, exist in space, but looped currents can occur. In our papers (see Refs [4 – 8] and references therein) we discuss the possibility of particle acceleration in strong but short-lived electric fields emerging during episodic current disruptions in cosmic plasma pinches.

The presence of cosmic magnetic fields is caused by the corresponding currents, and then by equations $\operatorname{div} \mathbf{B} = 0$, $\operatorname{div} \mathbf{j} = 0$ both the fields and currents must be looped. The

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simplest and at the same time most general such configuration is a 'magnetic torus' surrounded by pressured plasma, as shown in Fig. 1. One may assume that such configurations should occasionally emerge due to cosmic magnetic field line reconnection. One may also assume that tori with the same magnetic field line orientation could be combined into a bigger torus, as shown schematically in Fig. 2a.

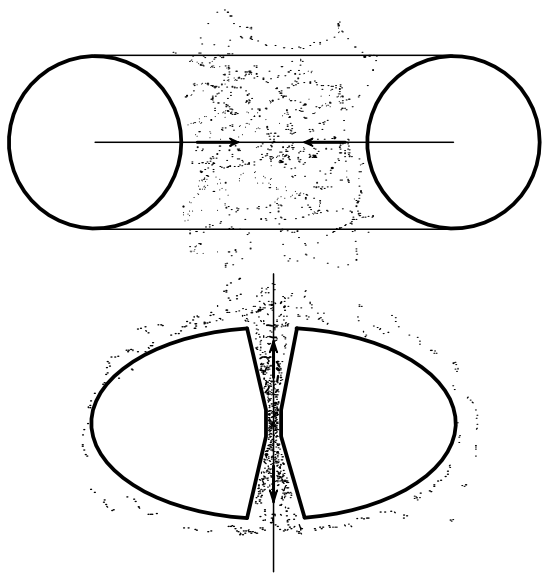

Figure 1. Contraction of a magnetic torus with the formation of a central pinch in the presence of external pressure.

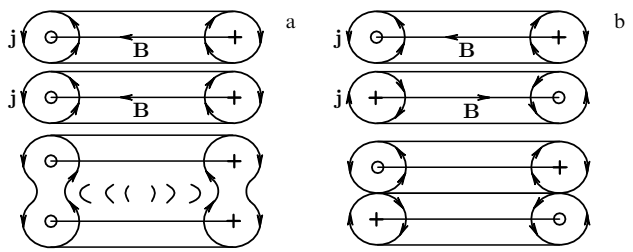

Figure 2. Merging of two tori with the same orientation of magnetic field (a) and annihilation of tori with opposite magnetic fields (b).

If present, the external plasma pressure can balance the magnetic field pressure at the periphery of the torus, whereas close to the axis the field will compress the plasma by gradually expelling it from the 'doughnut hole', which leads to the formation at the axis of a plasma pinch with longitudinal current. Due to a 'sausage' instability, first considered in our paper [9], the neck on the pinch will grow until a complete break of the current occurs, and two particle acceleration mechanisms should be consecutively realized: the mechanism of hydrodynamical pressing-out, and then the mechanism of electrodynamic acceleration in the induced electric field. This is the hypothetical picture of GRB origin we propose.

It is important to note that, firstly, in the first mechanism of the pressing-out of quasi-neutral plasma from the pinch neck the velocity of electrons and ions must be the same, so the energy of the proton component in the accelerated beams must be $M/m = 1836$ higher than the energy of the electrons. Assuming that GRBs are due to bremsstrahlung radiation of electron beams, whereas ion beams (unobserved directly) are identified with CR, the CR power must be about 2000 times higher than the GRB power, which increases the probability of CR fueling by this mechanism.

Secondly, narrow-collimated electron beams of ultra-relativistic energies (we recall that photons with energies 20 – 30 GeV have been observed in GRBs, see Ref. [10]) must generate narrow-collimated beams of bremsstrahlung radiation, part of which must shine off the detectors on Earth. In this case the actual total power of GRBs could be a few orders of magnitude higher than the power of the observed GRBs. The CR fueling power will correspondingly increase due to our proposed pinch mechanism. Now we pass to describing in more detail this mechanism of CR generation.

2. Two possible pinch-mechanisms of cosmic ray generation

It has been shown in papers [7, 8] that a simple analytical formula describing the observed spectrum of galactic CR with all its tiny features can be derived in the framework of the pinch-hypothesis. This spectrum is not yet definitely determined and is differently observed by different installations. Examples are shown in Fig. 3 (Ref. [11]). Experimental data from Ref. [12] (rombs) which are apparently the most reliable in the high energy region are also shown. The thin solid line corresponds to the theoretical formula (9), which will be briefly derived below.

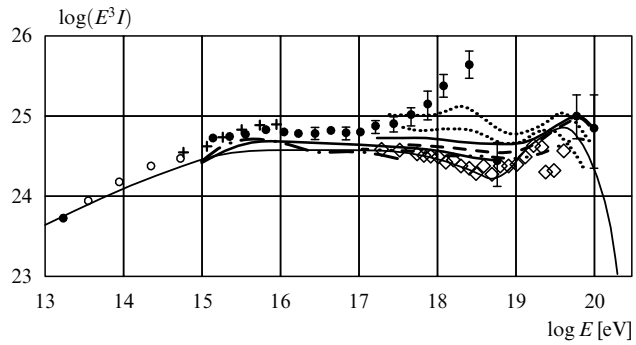

Figure 3. The spectrum of galactic KR from Ref. [11] (multiplied by factor E^3). Data from Ref. [12] are shown by the diamonds, the thin solid line shows our approximation (9).

As is seen from Fig. 3, to describe the experimental spectrum eight parameters are required as a minimum, which must reflect the following features of the spectrum: (1) the general normalization, (2) the slope of the initial part, (3) the location of the first break, (4) the slope after it, (5) the location of the second break, (6) the slope after it, (7) the location of the last minimum, and (8) the last slope. When constructing the an approximate formula we tried to use the minimum number of parameters and here apparently six parameters are sufficient.

Theory of relativistic pinches (see Refs [4 – 8]) predicts that during one pinch break two groups of accelerated particles with different energetic spectra should emerge:

$$I_1 = A_1 E^{-\nu}, \qquad \nu = 1 + \sqrt{3} = 2.732\,,$$
$$I_2 = \frac{A_2}{E}\exp\left(-\frac{E}{E_i}\right). \tag{1}$$

Here $A_1, A_2, E_i = qJ_i/c$ are constants. The first spectrum appears at the stage of pressing-out plasma from the neck until the complete break (as from a pipette; for brevity we refer to these particles as pipette particles), and the second spectrum appears at the subsequent induction stage after the current J_i break (the induction particles).

For pipette particles, the theoretical power-law index $\nu = 2.732$ is in very good agreement with experiments at least at energies $10^{10} \leqslant E \leqslant 10^{13}$ eV; in Fig. 2, however, the region of higher energies with some spectral features is shown. Here for simplicity we neglect pipette particles and will consider induction particles only.

Assuming a lot of pinches are broken down from time to time in the Galaxy, we can construct the sum written in the form

$$I_0 = \frac{S}{E} + \frac{b}{E}\exp\left(-\frac{E}{E_{\rm met}}\right),\ S = S(E) = \sum_i c_i \exp\left(-\frac{E}{E_i}\right), \tag{2}$$

where $b,\ E_{\rm met} = qJ_{\rm met}/c,\ c_i,\ E_i = qJ_i/c$ is a set of constants. The sum S can be rewritten as an 'integral over currents' by introducing the variable of integration with the dimension of energy $I = E_i = qJ_i/c$ (essentially, these are currents) and setting

$$S = \int_0^\infty C(I)\exp\left(-\frac{E}{I}\right)\,{\rm d}I, \tag{3}$$

where $C(I)$ is the current distribution function. We are ignorant about the precise statistics of broken currents in the Galaxy, but we can consider a simple model allowing this integral calculation. In papers [7, 8] this function is assumed to have the form

$$C(I) = \frac{c_0}{I^\mu}\exp\left(-\frac{I}{4E_{\rm Gal}}\right), \tag{4}$$

where $c_0, \mu, E_{\rm Gal}$ are constants, and then the last term in the spectrum (2) reads

$$\frac{S(E)}{E} = \frac{c_0}{E}\int_0^\infty \frac{1}{I^\mu}\exp\left(-\frac{I}{4E_{\rm Gal}} - \frac{E}{I}\right){\rm d}I = A_0\,\frac{K_{\mu-1}(x)}{x^{\mu+1}}, \tag{5}$$

where $A_0 = 4c_0(2E_{\rm Gal})^{-\mu}$, $x = \sqrt{E/E_{\rm Gal}}$, and $K_{\mu-1}(x)$ is the modified Bessel function. At any x, for this function we recommend the use of the following approximation

$$K_{\mu-1}(x) \simeq \Gamma(\mu-1)\cdot 2^{\mu-2}\frac{\exp(-x)}{x^{\mu-1}}\,\xi_\mu(x),$$
$$\xi_\mu(x) = (1+\beta_\mu x)^s, \quad \beta_\mu = \frac{1}{2}\left[\frac{\sqrt{\pi}}{\Gamma(\mu-1)}\right]^{1/s}, \tag{6}$$

where $s = \mu - 3/2$. This approximation is precise for $K_{3/2}$, and, for example, for K_1, K_2 differs from the table $K_{1,2}$ by no more than 3% for any x.

To compare the theoretical spectrum (2) with experimental ones, one should take into account that the spectra in Fig. 2 are shown multiplied by a factor E^3 (to partially rectify the plots). With this factor taken into account, it is convenient to recast equation (2) into the form

$$E^3 I_0 = c_{\rm Gal}E^{3-\mu}\exp(-x)\xi_\mu(x) + c_{\rm met}E^2\exp\left(-\frac{E}{E_{\rm met}}\right), \tag{7}$$

where a new notation for the constants is used. Here only five parameters remain, so by fitting them one can find a good spectral approximation. However, an analysis of the different variants performed in Refs [7, 8] has shown that it is useful to take into consideration the diffusion drift of CR particles from the Galaxy.

The diffusion of particles with energy E is described by the diffusion equation $\mathrm{div}(D\nabla n) = Q_0(E)$, where $n = n(\mathbf{r}, E) = I/c$ is the density of particles, and the r.h.s. describes sources of 'primary generated' particles. If we consider the diffusion coefficient to depend on the energy as $D(E) = D_0\Phi(E)$, the last factor can be moved into the r.h.s. and the observable spectrum must have the form $I \sim I_0(E)/\Phi(E)$. For this factor, the following expression was obtained in papers [7, 8]

$$\Phi(E) = \sqrt{1 + \frac{E}{E_1}}, \tag{8}$$

where E_1 is a new variable to fit.

The final spectrum without pipette particles but accounting for the diffusion (and the additional factor E^3) can be conveniently written as

$$E^3 I(E) = \frac{A\epsilon_{13}^{3-\mu}}{\sqrt{1+\epsilon_\alpha}}\left(\frac{1+\sqrt{\epsilon_\beta}}{\exp(\sqrt{\epsilon_\beta})} + \frac{\epsilon_\delta^{\mu-1}}{\exp\epsilon_\gamma}\right), \tag{9}$$

where special notations for the normalized energies $\epsilon_\alpha = 10^{-\alpha}E$ [eV] and the like are introduced for brevity. Factor A is a parameter relating the entire spectrum to the characteristic energy $E = 10^{13}$ eV at which $\epsilon_{13} = 1$ and $E^3 I = A$.

This dependence with the best-fit parameters $A = 4\times 10^{23}$; $\mu = 2.55$; $\alpha = 15.2$; $\beta = 17.9$; $\gamma = 19.4$; $\delta = 18.9$ we obtained is shown by the thin solid line in Fig. 2. As we see, it allows one to describe the main features on the spectrum: the first break (at energy $E \simeq 3\times 10^{15}$ eV), the second dip (at $E \simeq 3\times 10^{18}$ eV), and the subsequent 'metagalactic' hump (at $E \simeq 3\times 10^{19}$ eV). Let us discuss these results in more detail.

3. The analysis of parameters of the pinch-model for cosmic ray generation

On the one hand, equation (9) can be considered as a convenient purely mathematical approximation which is valid for the entire spectrum. Introducing one more induction term, one could account for the second increase seen in the plot at the energy where other observations (data from Ref. [12]) point to the second dip.

On the other hand, equation (9) based on the pinch hypothesis of cosmic ray generation may have, as we believe, a deeper physical meaning, since the parameters of the model can be reasonably related to the characteristics of our Galaxy and its surroundings. Here one may select several main characteristics: the mean distance between stars, the disk thickness, its diameter, and the mean distance between galaxies. In addition, one should take into account the degree

of plasma activity in the Galaxy and its surroundings, which apparently determines the total CR intensity and thus the spectrum normalization.

In our model (in which the quantity $E_{\alpha,\beta,\gamma}$ plays an important role), the three characteristic energies in equation (9) $E_* = eJ_*/c$ correspond to three currents $J_{\alpha,\beta,\gamma} = cE_{\alpha,\beta,\gamma}/e$ (see Table 1).

Table 1. Characteristic parameters of the model.

Parameters	Powers		
	$\alpha = 15.2$	$\beta = 17.9$	$\gamma = 19.4$
Particle energy $E_{\alpha,\beta,\gamma}$, eV	1.6×10^{15}	7.9×10^{17}	2.5×10^{19}
Filament current $J_{\alpha,\beta,\gamma}$, A	5.3×10^{13}	2.6×10^{16}	8.4×10^{17}
Magnetic field B, G	6×10^{-5}	6×10^{-5}	6×10^{-6}
Filament radius $r_{\alpha,\beta,\gamma}$, ly	$\simeq 0.2$	$\simeq 100$	$\simeq 30000$
Larmor radius $\rho_{\alpha,\beta,\gamma}$, ly	$\simeq 0.2$	$\simeq 100$	$\simeq 30000$

Now we take into account that the current J (in amperes) streaming along a cylinder with radius r generates on its surface a magnetic field $B = J/5r$, so that $r = J/5B$. The magnetic field of our Galaxy is, on average, 6×10^{-5} G, and the first two currents $J_{\alpha,\beta}$ would generate such a field at the current canal radii $r_{\alpha,\beta}$ listed in the table. The first radius in our model can be ascribed to current filaments of the interstellar plasma (is it these that generate gamma-ray bursts?), and the second radius is about 10 times smaller than the thickness of the galactic (Milky Way) disk with its gas-dust 'arms'. Finally, the metagalactic magnetic field is approximately 10 times lower than the galactic one and the third current J_γ would generate such a field at the current canal radius r_γ also listed in the table.

Such estimates of the current filament sizes — interstellar, galactic, and metagalactic — seem to be reasonable and at the same time coincide with the Larmor radii for the particles with the corresponding three energies in the galactic and metagalactic magnetic fields. This three-stage hierarchical relation between energies, currents, their sizes, magnetic fields, and particle Larmor radii makes the pinch model for CR generation sufficiently self-consistent. Now let us see whether one can relate this model to gamma-ray bursts as well.

4. A possible relation of the model to gamma-ray burst generation

As already mentioned, the hypothesis of GRB generation in pinches was proposed in Ref. [3], where GRBs were considered to originate in interstellar plasma pinches at distances of at least a few parsecs. Such remote distances require a sufficiently high energy of the burst. However, the few second duration of GRBs suggests a comparatively small size of the electron jet (if this is the real nature of GRBs) and an acceleration region of the order of the diameter of the Sun. Due to these difficulties, this assumption has been criticised in Ref. [13], where pinch-sources of GRBs have been suggested to be nearer, at the Solar System periphery (at distances of the order 100 AU). One may suppose, however, that the magnetic energy is first stored in a big torus, as shown schematically in Fig. 1. Then its inner region contracts to the center for a long time, with such a contraction being possible only provided that at the outer remote surface the field pressure is balanced by the pressure of the external interstellar plasma. Only at the final stage is some fraction of the magnetic energy rapidly transmitted to the electron and ion beams. We now consider this issue in more detail.

The mean distance between stars is about several parsecs. Assuming isotropy, with the distance $R_{\min} = 1$ pc $= 3 \times 10^{18}$ cm to the GRB and the maximum flux observed $S = 10^{-3}$ erg cm^{-2} we find the energy of one GRB to be $E = 10^{35}$ ergs. With the initial interstellar magnetic field $B = 10^{-4}$ G such an energy is contained within the volume of a sphere of radius $R_0 = 4 \times 10^{14}$ cm $\simeq 30$ AU, which is about the distance to Pluto, i.e. the size of the Solar System.

However it is reasonable to assume that the field loops are initially of interstellar distance size and much more energy is contained inside each loop. For example, a sphere of 1 kpc in radius contains initially the magnetic energy $E = 4.5 \times 10^{46}$ ergs. Assuming one loop to collapse in the Galaxy per day we obtain the power $W = 4.5 \times 10^{46}$ erg day^{-1}, which is 50 times as high as the previously discussed power necessary for persistent CR fueling, and much more than the power necessary to fuel GRBs. For our model this would mean that only 2% of the potential power of the magnetic loops is released in pinches.

Now we consider the problem of the observed GRB durations and its connection with the assumed pinch sizes. Fig. 4 taken from paper [14] (see also Ref. [1]) shows the GRB duration distributions t_{50} and t_{90}, during which either 50% or 90% of the total registered energy is released.

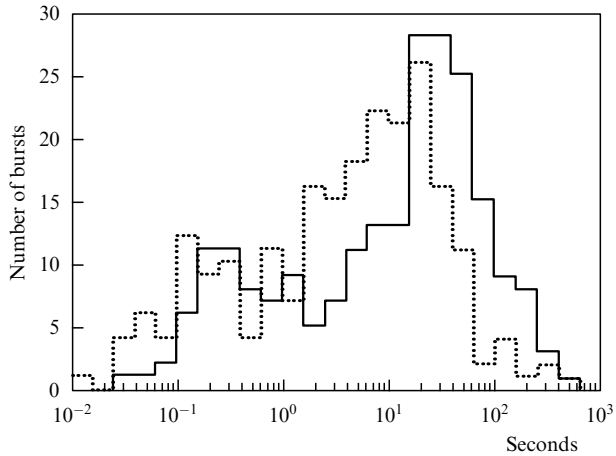

Figure 4. The distribution of GRB durations t_{50} (the dashed line) and t_{90} (the solid line).

Two maxima are clearly seen on the plot apparently implying that two types of GRB occur — short ($t \leqslant 1.5$ s) and long ($t \geqslant 1.5$ s). Qualitatively, this is in accordance with our model, in which the possibility for the formation of even three types of pinches — interstellar, disk-galactic, and halo-galactic (or metagalactic) — is envisaged. Probably, a GRB with a duration of 90 min and a maximum photon energy of 18 GeV described in Ref. [10] should be related to the third type (see Fig. 5). Clearly, such quanta cannot have a 'temperature' origin in thermonuclear reactions on the surface of neutron stars, whereas the bremsstrahlung radiation of ultrarelativistic electrons seems to be capable of producing such quanta.

For laboratory pinches, the problem of the duration of a gamma-ray burst (which is observed!) was studied in Refs.

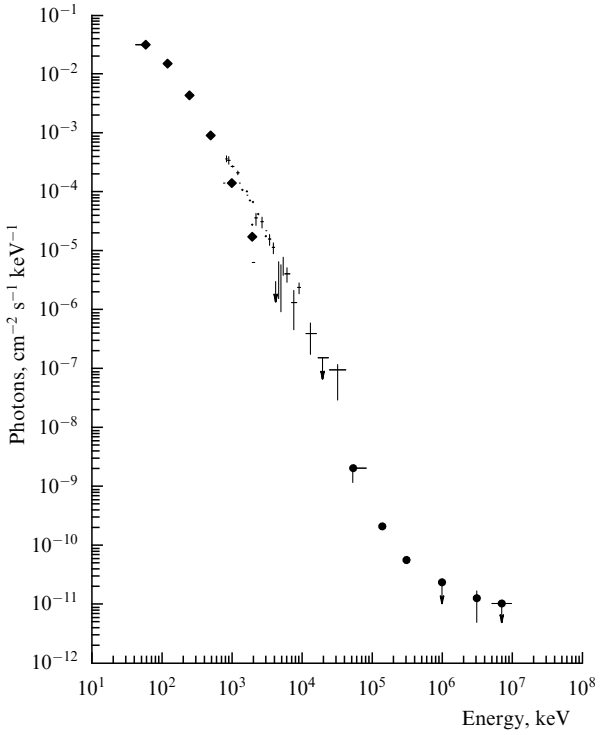

Figure 5. GRB spectrum from paper [10].

[15, 16], and we repeat briefly these calculations. An important role here is played not by the pinch itself, but its near surroundings, where the density of the periphery plasma n_e^0 is comparatively low, and this plasma contains the magnetic field $B_0 = 2J_0/cr$ of the main pinch trapped during the contraction process. Assuming cylindric symmetry, the waves in this plasma are described by the equation for the vector potential $A = A_z(r,t)$ and the electron current:

$$\Box A = \nabla^2 A - \frac{A''_{tt}}{c^2} = -\frac{4\pi}{c} j, \quad j = -en_e^0 v_z^e, \quad v_z^e = \frac{cE_r}{B_0}. \quad (10)$$

To the first approximation heavy protons may be considered at rest and only light electrons to undergo the electric drift, so the radial component of the field is found from the equations

$$\operatorname{div} \mathbf{E}_r = -4\pi e n_e^1, \quad (n_e^1)'_t = -\operatorname{div}(n_e^0 \mathbf{v}_r),$$

$$v_r = -\frac{c}{B_0} E_z = \frac{A'_t}{B_0}. \quad (11)$$

Hence we obtain $E_r = (4\pi e n_e^0/B_0)A$ and considering $B_0 = 2J/cr$ we write down a very important equation (10) in the form

$$\frac{(rA'_r)'_r}{r} - \frac{A''_{tt}}{c^2} = \left(\frac{4\pi e n_e^0}{B_0}\right)^2 A = \frac{4r^2}{R_0^4} A, \quad (12)$$

where we introduced the 'screening' length $R_0 = \sqrt{J_0/\pi n_e^0 c|e|}$ characterizing the depth of penetration of slow waves with frequencies $\omega_{Bi} \ll \omega \ll \omega_{Be}$ generated by pinch oscillations in the magnetized plasma at the periphery.

Equation (12) describes the field accelerating ions of the periphery plasma near the pinch. In particular, from this equation the second 'induction spectrum' of formula (1) is obtained. To estimate the acceleration time, we mention its oscillatory solution:

$$A(r,t) = a \sin\frac{t}{T_0} \exp\left(-\frac{r^2}{R_0^2}\right), \quad T_0 = \frac{R_0}{2c}, \quad (13)$$

where T_0 is the period of oscillations. Expressing the current in amperes, we arrive at useful expressions for the characteristic time of the neck break and for the screening length:

$$T_0 = 1.3 \times 10^{-7} \sqrt{\frac{J[\mathrm{A}]}{n_e}}, \quad R_0 = 8.14 \times 10^3 \sqrt{\frac{J[\mathrm{A}]}{n_e}}. \quad (14)$$

Now we try to apply them to GRBs. The density n_e is unknown, and we accept $n_e = 1$ cm^{-3} for a estimate. Substituting here the filament currents from Table 1, we find three time scales, three screening lengths, and three numbers N of particles, where

$$N = \frac{J_0}{c|e|} \sqrt{\frac{J_0}{\pi n_e^0 c|e|}}.$$

The values found are listed in Table 2.

Table 2. Assumed parameters estimates.

Parameters	Filament current, A		
	$J_\alpha = 5.3 \times 10^{13}$	$J_\beta = 2.6 \times 10^{16}$	$J_\gamma = 8.4 \times 10^{17}$
GRB duration $T_{\alpha,\beta,\gamma}$, s	1	22	124
Screening radius $R_{0\alpha,\beta,\gamma}$, cm	5.9×10^{10}	1.3×10^{12}	7.5×10^{12}
Number of particles $N_{\alpha,\beta,\gamma}$	6.6×10^{32}	7.1×10^{36}	1.3×10^{39}
Weight of protons $M_{\alpha,\beta,\gamma}$, t	$\simeq 10^3$	$\simeq 1.1 \times 10^7$	$\simeq 2 \times 10^9$
Energy of protons $Q^{(p)}_{\alpha,\beta,\gamma}$, ergs	6×10^{34}	2.8×10^{41}	1.3×10^{45}
Energy of electrons $Q^{(e)}_{\alpha,\beta,\gamma}$, ergs	3.3×10^{31}	1.5×10^{38}	7×10^{41}

These estimates fall within the observed GRB durations range 10^{-2} s, since the currents, according to the assumed distribution function (4), can be smaller than the values used above. In addition, the density can differ from the accepted value $n_e = 1$ cm^{-3}. We recall that in the solar wind near Earth $n_e = 10$ cm^{-3}, in the interstellar medium $n_e = 1$ cm^{-3}, but near the contracting pinches the figures may be different, and the density outside galaxies is unknown.

The total number of particles being accelerated can be evaluated from the equation

$$N = \pi R_0^2 L_z n = \frac{L_z J_0}{c|e|} \simeq 2.1 \times 10^8 L[\mathrm{cm}] J[\mathrm{A}],$$

where L_z is the neck length. Assuming it to be equal to R_0, we obtain estimates N listed in Table 2, where the total energies of the proton and electron beams in one GRB are also presented (see Section 5). These figures, however, correspond only to induction (apparently the most energetic) particles and do not take into account the particles accelerated by the first 'pressing out' mechanism.

To conclude this Section, we point out one nontrivial effect, which can reduce the GRB duration. Namely, if a

sufficiently long electron beam enters the plasma, its bunching is possible due to instabilities leading to its length contraction(see Refs [17, 18]). However, we will not consider it here.

5. A possible interpretation of the main features of GRBs

We wish to show that the pinch-model explains qualitatively the main features of GRBs (which are also listed in Ref. [1]).

(1) The key fact is that at the sites in the sky where GRB have occurred, no astronomical objects have been identified as yet, and in this respect GRB are similar to our proposed short 'cosmic lightning' in the interstellar plasma.

(2) The isotropy of GRBs in the sky will be provided assuming they occur in interstellar space. The sensitivity of devices is not yet sufficient to discover weak GRBs at remote distances exceeding the galactic disk semi-thickness, which is $R_{\max} = 500$ pc near the Sun. The registered GRB radiation fluxes fall within the range $10^{-7} - 10^{-3}$ erg cm^{-2}, and the four-order difference would imply the closest GRBs occur at interstellar distances of $R_{\min} \simeq 5$ pc.

(3) The duration of GRBs lies within the range $10^{-2} - 10^{3}$ s, with two distinct groups being distinguished – the short and the long ones (Fig. 4), which by our model can be related to two pinch types — interstellar and disk-galactic (Table 1).

(4) The observed registration rate (1 per day) might be explained by plasma activity of ordinary Solar-like stars, whose number is about 5×10^{7} within a sphere of $R_{\max} = 500$ pc in radius. This would mean that one star somehow generates one GRB per 10^{5} years. As is known (see Ref. [19]), the plasma solar wind carries out energy at a rate of $10^{27} - 10^{29}$ erg s^{-1}, which yields a total energy of $E \sim 10^{40}$ ergs for 10^{5} years; a small fraction of this energy would be sufficient to generate one GRB. The solar wind carries away torn-off magnetic field loops, and the additional compression of plasma with increasing field may occur at the expense of the kinetic energy of streams during the encounter with the headwind from a neighboring star. Near the Earth the wind velocity is about 500 km s^{-1} and keeping it constant the wind plasma may fly away 30 pc in 10^{5} years thus reaching nearby stars provided no interstellar gas and magnetic field resistance is met.

(5) As a rule, each GRB consists of an irregular sequence of several microbursts, and this feature is difficult to interpret within the framework of both the cometary and neutron star hypothesis. In contrast, in our 'electron-beam' model one may suggest several variants of such an interpretation.

First, it is natural to suppose that several necks are developed along the cylindrical pinch simultaneously, which are broken non-simultaneously.

Another possibility is the encounter of two clouds with 'frozen' magnetic fields with oppositely oriented or, at least, not coincident directions. Then a neutral current layer should emerge near the boundary (in fact, a plane pinch), which should be broken due to tearing-instability into a 'picket fence' of a few cylindrical pinches that break non-simultaneously. Both pictures are clearly seen on shots of laboratory pinches — both cylindrical and planar — and the cosmic analogy seems natural here.

In addition, the initial beam may break into separate bunches or filaments. An oscillatory regime of acceleration like solution (13) is also possible. All this can appear as a sequence of microbursts in one GRB.

(6) Now we briefly demonstrate energetic GRB spectra. In Fig. 5 the spectrum is shown (from Ref. [10]) for an unusually long (90 min) GRB with a maximum energy of quanta of 18 GeV. The authors of Ref. [10] point out themselves that in the energy range 40 keV – 3 MeV the spectrum is fitted by the formula

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} = 0.02\left(\frac{100}{E}\right)^{1,2} \exp\left(-\frac{E}{900}\right) \tag{15}$$

with the dimension photons cm^{-2} s^{-1} keV^{-1} and energy in keV. Interestingly, this formula is similar to our 'induction' spectrum (1), which describes ions (protons) and not gamma-ray quanta, however one may expect a similarity between both spectra. Therefore one may estimate the energy of one GRB from the following considerations.

(7) To estimate the energy of bursts and the distances to them we consider the proton spectrum in the form

$$\frac{\mathrm{d}N_\mathrm{p}}{\mathrm{d}E} = \frac{C_1}{E}\exp\left(-\frac{E}{E_1}\right),$$

where $E_1 = eJ_1/c$.

The number of protons N_p and their total energy Q can be evaluated by the formulas

$$N_\mathrm{p} = C_1 \ln\left(\frac{E_1}{E_{\min}}\right), \quad Q^{(\mathrm{p})} = C_1 E_1 = N_\mathrm{p}\langle E\rangle,$$
$$\langle E\rangle = \frac{E_1}{\ln(E_1/E_{\min})}. \tag{16}$$

Since $E_{\min}$ is under a slowly varying logarithm, we conventionally accept $E_{\min} = 10$ keV, and then for pinches of type α, β, γ from Table 1 we find the mean energy of one proton:

$$\langle E_\alpha\rangle = 5.7 \times 10^{13}\ \mathrm{eV}, \quad \langle E_\beta\rangle = 2.5 \times 10^{16}\,\mathrm{eV},$$
$$\langle E_\gamma\rangle = 7 \times 10^{17}\,\mathrm{eV}.$$

Substituting the corresponding number

$$N_\mathrm{p} = \frac{J_0}{c|e|}\sqrt{\frac{J_0}{\pi n_\mathrm{e}^0 c|e|}}$$

of protons from Table 2, we obtain three total energies of proton beams $Q^{(\mathrm{p})}$, which are listed in Table 2. Further, it is reasonable to assume the electron beams contain an energy $M_\mathrm{p}/m_\mathrm{e} = 1836$ times smaller, which yields $Q^{(\mathrm{e})}$ also shown in Table 2.

For isotropic emission these figures must correspond to the energy fluxes observed in the range $10^{-7} \leqslant S = Q/4\pi R^2 \leqslant 10^{-3}$ erg cm^{-2}, so the source distances are determined from $R = (Q/4\pi S)^{1/2}$. For the cases under consideration this yields distances $R_\alpha = 1.7 \times (10^{-2} - 1)$ pc, $R_\beta = 3.6 \times (10 - 10^{3})$ pc, $R_\gamma = 2.5 \times (10^{3} - 10^{5})$ pc, and we believe these estimates are likely.

(8) Gamma-ray bursts are observed neither in the optical, nor in the radio diapason, and this is naturally expected in our model with high-energy electron beams in a plasma, which are incapable of generating optical quanta with energies of the order 1 eV. A possible, in principle, super-longwave radio emission (with a Solar radius wavelength) cannot be detected by current devices.

(9) In many papers (see Ref. [1]), the correlation of the signal intensity (the number of photons) with the energy of

photons has been noted. In our model this could be explained by a narrow collimation of GRB emission. As mentioned above, a narrow-collimated beam of ultrarelativistic electrons radiates in a narrow beam during braking, with the opening angle of emission gradually increasing with braking. Only at the final stage, when the energy decreases to weakly relativistic values, the radiation becomes nearly isotropic, so after the braking has stopped the emission diagram is formed as shown qualitatively in Fig. 6. This emission diagram can be approximated by the simplest formula for an ellipsoid with two parameters

$$\frac{\mathrm{d}I}{\mathrm{d}\Omega}\left[\frac{\mathrm{erg}}{\mathrm{sr}}\right] = s(\vartheta) = \frac{2s_{\min}}{1+\xi-(1-\xi)\cos\vartheta},$$

$$\xi = \frac{s_{\min}}{s_{\max}} < 1, \tag{17}$$

so for the upward direction we have $\vartheta = 0$, $\mathrm{d}I/\mathrm{d}\Omega = s_{\max}$ and for the downward direction $\vartheta = \pi$, $\mathrm{d}I/\mathrm{d}\Omega = s_{\min}$. Near the maximum $\cos\vartheta \simeq 1 - \vartheta^2/2$, and here we have $s \simeq s_{\max}[1+\delta_*^2]^{-1}$, where $\delta_* = \vartheta/\langle\vartheta\rangle$, $\langle\vartheta\rangle = 2[\xi/(1-\xi)]^{1/2}$.

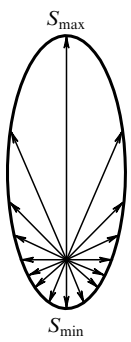

Figure 6. Anisotropic candle emission.

We recall that the angular and spectral distributions of the bremsstrahlung radiation of ultrarelativistic electrons is described by the formula (see Ref. [20])

$$\mathrm{d}I = h\omega\,\mathrm{d}\sigma, \quad \mathrm{d}\sigma \simeq r_{\mathrm{e}}^2 \Lambda \frac{\mathrm{d}\omega}{\omega}\frac{\delta\,\mathrm{d}\delta}{(1+\delta^2)^2},$$

$$\delta = \gamma\vartheta, \quad \gamma = \frac{E_{\mathrm{e}}}{mc^2}, \quad \Lambda = 16\alpha\ln\frac{2E_{\mathrm{e}}^2}{mc^2 h\omega}, \quad \alpha = \frac{1}{137}, \tag{18}$$

so in both cases denominators with a similar angular dependence enter the expressions. Since the emitted photon energy $h\omega$ is a certain fraction of the electron energy E_{e}, the intensity radiated in a given direction is connected with the photon energy.

Note also that the narrow-collimated radiation beam can easily past our devices, so only at the end of the braking process when the energy of electrons decreases to weakly relativistic values, the radiation becomes nearly isotropic and can be registered by detectors.

6. Conclusions

To conclude, we note that pinch breakings, in principle, can occur in the plasma near old neutron stars, although no GRB have been observed from radiopulsars. This may require a revision of the numerical values of parameters discussed above within the framework of the same qualitative picture, so one should wait for new discoveries in the enigmatic problem of GRB origin.

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