Concerning the possible generation of cosmic rays and gamma bursts in plasma pinches

B. A. Trubnikov and V. P. Vlasov
Institute of Nuclear Fusion, "Kurchatov Institute" Russian Research Center

S. K. Zhdanov
Moscow Engineering Physics Institute, Moscow, Russia

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The hypothesis is considered that the cosmic gamma bursts are generated by bremsstrahlung of electrons accelerated in lightning-like discharges arising in "peripheral plasma shells" of stars. Such shells could be formed between stars as a result of a long-term accumulation of plasma "wind" (similar to the "solar wind") in those places where it collides with the wind from neighboring stars. The possibility that ions are generated and accelerated as cosmic rays in the same discharges is also considered. © *1995 American Institute of Physics.*

INTRODUCTION

1. Approximately once in 24 hours, satellite-borne devices register brief, intense bursts of cosmic gamma radiation, but the distances to their sources and their nature remain unknown. From a number of features in their energy spectra it was previously supposed that they arise on old neutron stars which are not directly observable. However, present observations on satellites ("Granat" of Russia and "GRO" of the USA) do not confirm the presence of the aforementioned features,[1–3] and so some authors consider other possibilities for gamma-burst (GB) generation, not connected with neutron stars.

For example in our papers[4,5] it is assumed that the GBs arise in discharges of the "cosmic lightning" type within interstellar plasma clouds. This hypothesis is criticized in Ref. 6, where it is supposed that the discharges occur within the Solar system at distances of the order 100 a.u. Note also Ref. 7, where the possibility of that the GBs are generated in comet collisions is considered.

Previously in a number of papers (see, for example[8–10]), we considered the possibility that galactic cosmic rays (GCRs) are accelerated in current-carrying electrical discharges of hypothetical "cosmic lightning." As a result of an instability, their cylindrical channels should develop narrow necks from which quasi-neutral plasmoids should be extruded along the axis. In this situation the velocities of the electrons and ions should be equal, so the energy of a proton should be $m_p/m_e \sim 2000$ times greater than the energy of an electron.

In this study the question under discussion is whether the observed GBs are a direct manifestation of such "cosmic lightning" events, and whether GCRs (as a proton component) and GBs (as an electron component giving the bremsstrahlung) arise in them simultaneously.

2. The power of galactic cosmic rays and gamma bursts. It is known that the GCR energy density is equal 1 $\mathrm{eV \cdot cm^{-3}}$, so that at the volume of the Milky Way Galaxy, 10^{68} $\mathrm{cm^3}$, their total energy is equal, $\sim 10^{56}$ erg. However, over approximately 100 million years they diffuse out of the Galaxy, so for their sustenance a source power $W_{GCR}=2\cdot 10^{40}$ erg/s is necessary. For the "pinch mechanism" the power in the electron component from all the GCR sources would be 2000 times smaller, $W_e=10^{37}$ erg/s (we are attempting to associate the number of such sources in the Galaxy with the number of gamma-burst sources).

Approximately one GB, $\sim 1-10$ s long, is registered every 24 hours, with an energy flux density ranging from a minimum of 10^{-6} to a maximum of 10^{-3} $\mathrm{erg \cdot cm^{-2} \cdot s^{-1}}$. However, the distances R to them are unknown. It is natural to assume that the weak GBs correspond to large distances R_{max} and the strong ones to short distances R_{min}, and then we have the ratio $R_{max}/R_{min}=\sqrt{1000}=31.6$. With an average GB duration of 3 s we have an estimate of the total energy of one GB:

$$E_1[\mathrm{erg}]=4\cdot 10^{-2}R^2_{\mathrm{min,ss}}=4\cdot 10^{-5}R^2_{\mathrm{max,ss}}. \tag{1}$$

We now assume that the GBs are related not with neutron stars but with ordinary stars. Since 1 GB is observed every 24 hours, relation (1) corresponds, on average, to a steady-state source power $W=5\cdot 10^{-10}\,R^2_{\mathrm{max,ss}}$ erg/s in a sphere of radius R_{max} and volume $V=(4/3)\pi R^3_{max}$. In the neighborhood of the Sun the density of stellar matter is $\rho=0.05\,M_\odot\,\mathrm{ps}^{-3}$ (1 ps$=3\cdot 10^{18}$ cm), so the number of stars in the aforementioned sphere is $N=\rho V/M_\odot=7.4\cdot 10^{-57}\,R^3_{\mathrm{max,ss}}$.

Hence, we have a steady-state source power of GBs per star $W_{\mathrm{1star}}\approx 0.7\cdot 10^{47}\,R^{-1}_{\mathrm{max,ss}}$ erg/s. And since the Galaxy has 10^{11} stars, we must to ascribe to them a total GB source power $W_\gamma=0.7\cdot 10^{58}\,R^{-1}_{\mathrm{max,ss}}$ erg/s. Then, if we assume that $W_\gamma=W_e$, we find $R_{max}\approx 220$ ps, a distance which is apparently shorter than the width of the galactic disk.

Then the energy of one typical GB would be $E_1\approx 2\cdot 10^{37}$ erg.

It is remarkable that the same estimate of energy per GB was obtained previously from the hypothesis that neutron stars are the sources of the GBs. In our model the distance to nearby sources of GBs comes out as $R_{min}\approx 7$ ps, which is approximately equal to the average distance between stars. The number of stars in a sphere of radius R_{max} is $N\approx 2$ million, which ensures the observed isotropy in the directional distribution of GB sources.

The estimates obtained look quite reasonable and permit us to assume that GCRs and GBs are being generated simultaneously in the "cosmic lightning" events which occur from time to time in clouds of magnetized cosmic plasma, the properties of which are discussed below.

3. The assumed characteristics of plasma clouds. In interstellar space there are large molecular clouds, where new stars can often emerge. However, we are interested in smaller plasma clouds which are not directly observable. It can be assumed that they arise in those places where the plasma "stellar winds" emitted by adjacent stars collide. In the neighborhood of the Sun we have:

number density of stars $n=L^{-3}=0.05\ \mathrm{ps}^{-3}$, average distance between them $L=2.7$ ps$=8\cdot 10^{18}$cm,

and their relative velocity $v=20$ km/s.

If L is assumed to be the radius of a plasma shell, the cross section for shell collisions will be $\sigma=\pi L^2$, the number of collisions of one shell with another per unit time is $\nu=n\sigma v=\pi v/L\approx 8\cdot 10^{-13}$ $s^{-1}\approx 7\cdot 10^{-8}$ per 24 hours. Multiplying this value by $N=2\cdot 10^6$, the number of stars in a sphere of radius R_{max}, we obtain 0.14 [GBs/24h], which is rather close to the observed frequency of "one GB per day." This agreement which could be improved by a small change of factors, is in our opinion a rather remarkable fact also.

The duration of a GB ($\sim$3 s) indicates that the length at which the neck of a pinch breaks off should be of the order of $\lambda\sim 10^{11}$ cm. It corresponds to the diameter of the Sun, and, as was noted in Ref. 6, the most important question for the hypothesis under consideration is: how can an energy E_1 giving one GB be concentrated in an area with such dimensions?

4. Can "stellar wind" generate the gamma bursts? In Ref. 6 it is assumed that GBs occur at distances of the order of $R_{min}\sim 100$ a.u.$=1.5\cdot 10^{15}$ cm, and then $E_1\sim 10^{29}$ erg. However, if $R_{min}=7$ ps$=2\cdot 10^{19}$ cm, then $E_1=1.6\cdot 10^{37}$ erg.

Evidently, to account for the latter value we must assume that the total pinch length l, with "roots of lightning" feeding it, can considerably exceed the length of the narrowest part, the neck, gradually pinched by forces of magnetic pressure. Most probably, the currents are closed, and plasma clouds often have toroidal configurations. It would be of interest to note that similar structures (but with huge dimensions, $\sim$50 ps!) are observed close to the center of our Galaxy. However, we are interested in smaller "solar wind" structures.

In the neighborhood of Earth the solar wind has a velocity $v=400$ km/s, a density of particles (basically protons p) $n=50$ cm^{-3}, and carries with it a "frozen" magnetic field. If these characteristics are the same within a whole sphere surrounding the Sun, the total mass flow rate carried by the wind will be $dM/dt=4\pi R^2 m_p nv=10^{13}$ g/s$=10$ million tons/s. At the average distance between the stars $L=2.7$ ps and at their relative velocity $v=20$ km/s, the "time of slipping" of two neighboring stars is $T=L/v=4\cdot 10^{12}$ s$=130$ thousand years. During this period the solar wind carries away a total mass $\delta M=3.6\cdot 10^{25}$ g (for comparison the mass of the Earth is $6\cdot 10^{27}$ g). In contrast, at the velocity of the wind $v=400$ km/s the time of its passage to a distance $L/2=1.3$ ps$=4\cdot 10^{18}$ cm would be $t_{L/2}=10^{11}$ s$\approx$3000 years.

If we mentally surround the Sun by a cube with 6 faces, on one face we shall have a mass $\delta M/6=6\cdot 10^{24}$ g, moving with a velocity of 400 km/s, and, hence, having a total kinetic energy $K\approx 5\cdot 10^{39}$ erg. This energy, in principle, is sufficient for generation of 300 GBs with an energy of $1.6\cdot 10^{37}$ erg each.

If these very approximate estimates are increased by only 20 times, the energy $E\sim 10^{41}$ erg in each discharge could supply not only the electron component of the GBs but could also sustain the proton component of the GCRs. Below we discuss the possible ways of discharge formation.

5. The preliminary contraction of a pinch and its rapid break. It can be assumed that

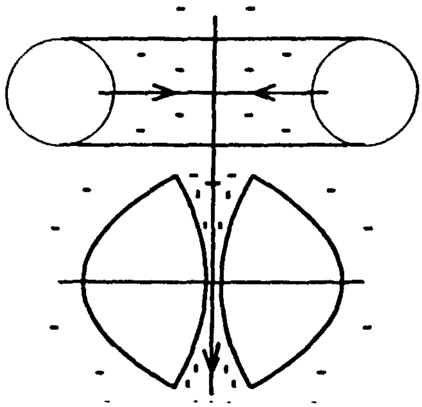

FIG. 1. Evolution of a magnetic torus and the formation of a pinch with a neck.

in the collision of plasma winds from adjacent stars the kinetic energy of the winds is converted, upon stopping, into the potential energy of a magnetic field. The average magnetic field of the Galaxy (it is in a dynamic balance with the GCRs) is known to be $\langle B\rangle = 10^{-5}-10^{-4}$ G, and we assume, as a first step, that the magnetic field induced by the stopped (and accumulated for a long time) plasma stellar wind has approximately such a value and is not chaotic, but initially forms separate closed toroids with the minimum radius $r_{\min}$ and with the maximum radius $r_{\max}$. At the maximum radius the internal field $B_\varphi \sim r^{-1}$ is assumed to be equal to the external field $\langle B\rangle$, so the condition of equality between the pressure outside and inside the toroid is fulfilled here.

Therefore, the toroid itself does not expand here, but it can expand towards the z axis due to the plowing and extension of a plasma from the center up and down along the z axis, as is illustrated schematically in Fig. 1. At the initial average internal field $B_\varphi \sim 10^{-4}$ G, and at our adopted value of the energy of one GB ($E = 1.6 \cdot 10^{37}$ erg), the volume of a toroid should be $V = 4 \cdot 10^{46}$ cm^3. Then, its initial dimensions should be of the order of $r_{\max} \sim 10^{15}-10^{16}$ cm$\sim 10^{-2}-10^{-3}$ ps. Approximately the same length, $l \sim 10^{15}$ cm, should also be ascribed to the central pinch under formation. However, to explain the duration of a GB ($\sim$3 s) we must assume that the length of its most narrow part—the neck—is smaller (see Fig. 1). Before the final break the length of the neck can be $\lambda \sim 10^{12}$ cm at a neck diameter of the order of $D \sim 10^{11}$ cm. So the initial radius of the central pinch decreases by 4 orders of magnitude, and, in turn the magnetic field on its boundary increases similarly, reaching before breakoff a value of the order of $B_{\max} \sim 1$ G at a current $J \sim 5 \cdot 10^{11}$ A. During the process of plowing, the plasma density increases by 8 orders of magnitude in the central pinch. If, for instance, it was initially $n \sim 10$ cm^{-3}, then at the instant of the current breakoff we would have $n \sim 10^9-10^{10}$ cm^{-3} in an area with a volume of the order of $V = (\pi/4)\lambda D^2 \sim 10^{34}$ cm^3. We note that the possibility of such GB generation in the annihilation of a closed magnetic field loop was mentioned previously in a qualitative manner in the review,[11] in reference to the magnetosphere of a neutron star. A similar way of pinch formation was also proposed in Ref. 12, in reference to the solar flares.

The situation created by the collision of two plasma winds carrying oppositely-directed "frozen" magnetic fields, could be a second possible approach. In this situation a so-called "neutral current layer" (flat pinch) arises in the plane of collision.

For a rather long time it can be in equilibrium, but upon exceeding some critical parameters it loses stability and, due to reconnection of magnetic force lines, breaks into some cylindrical pinches. Such a picture has been observed in experiments[13] with flat pinches. However, in application to cosmic GBs for such configurations of the currents, it is difficult to evaluate the possible lengths of the pinches, in contrast to the above-discussed approach with the magnetic toroid.

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