On generation of ultra-high-energy cosmic rays in gamma-ray bursts

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Abstract. Solution of the problem of proton acceleration in Gamma-Ray Bursts is suggested. The acceleration occurs in the relativistic shocks via the surfatron mechanism (surfing). It is shown that the proton acceleration up to $10^{14} - 10^{17}$ eV is possible in the case of a spherical shock (fireball); the flat shock accelerates up to $10^{16} - 10^{20}$ eV.

1. Introduction
Cosmological gamma-ray bursts (GRB), i.e., hard X-ray flares within the ~30 keV to ~1 GeV energy range with a complex temporal structure and non-thermal spectrum, are the most puzzling phenomenon in present-day high-energy astrophysics. To explain the observed GRB properties, one should consider the radiating region that expands at an ultrarelativistic velocity. Currently, the relativistic fireball model where a GRB and its afterglow emerge at the radiation of the particles accelerated in relativistic shocks explains most successfully all the aspects of the phenomena. The shock motion velocity $U$ is close to the speed of light, $c$, and the corresponding Lorentz factor is $\Gamma \approx (1 - U^2/c^2)^{-1/2} > 1$. Shocks are formed at the interaction of the ultrarelativistic flux various parts, and at the interaction between the flying-apart shell and the surrounding interstellar medium. At present, conventional is the judgment that shocks generated in space are the most probable sources of high energy particles accelerated, as a rule, close to shock wave fronts.

On the other hand, as noted in [1], high-amplitude plasma (Langmuir) waves may be generated in gamma-ray bursts besides shocks. In the presence of plasma waves, particle acceleration is possible within the “plasma wakefield accelerator” model where particle acceleration to higher energies during a gamma-ray burst [1]. Thus, particle acceleration in gamma-ray bursts may be implemented both in shocks and in non-linear Langmuir waves moving at relativistic velocities.

2. Surfatron acceleration mechanism (surfing) and its characteristics
There arises the question of the mechanism for particle acceleration. Unfortunately, the possibility to apply the widely known Krymski (diffusive) mechanism [2] to explain particle acceleration by relativistic shock waves seems rather doubtful [3]. Therefore, we should apply alternative methods for particle acceleration. Among them, there is the conversion acceleration mechanism [3]. Another possible mechanism is the surfatron acceleration (acceleration by surfing) of particles trapped in large amplitude waves propagating in space plasma [4–8].

Surfing occurs in weakly magnetized plasma. In this mechanism, particles are trapped and accelerated in a steep-forefront potential wave. Moving positive potential jump is capable of accelerating ions, and the negative jump is capable of accelerating electrons. We will consider the
acceleration mechanism offered in the general case for a one-dimensional non-linear potential wave moving in plasma at velocity $U$ and at angle $\theta_{Im}$ to the magnetic field vector. Like analysis shows, a portion of plasma particles having finite temperature may be trapped by the wave and accelerated by force $qUB_0\Gamma/c$ to higher energies, when the inleak onto potential jump cannot overcome under certain conditions. Here, $q$ is the charge of particles, $B_{0\perp} = B_0 \sin \theta_{B_0}$ is the magnetic field component that is transverse to the wave motion direction and that has value $B_0$ in the reference frame associated with the rest plasma ahead of the front.

During the particle inleaking onto a potential jump, particles split into three groups: the first group overcomes the potential barrier and passes the shockfront, the second group represents the reflected particles, the third group is a very small fraction of particles trapped by a wave. Ideally trapped particles move strictly at the wave velocity and, theoretically, they will be trapped infinitely. In the wave reference frame, ideally trapped particles have a near-zero longitudinal velocity $v_\parallel \approx 0$ (longitudinal velocity $v_\parallel$ is a velocity of a particle along the wave motion direction). Although their cross speed $v_\perp$ is close to the speed of light ($v_\perp \approx c, G = [1 - (v_\perp^2 + v_\parallel^2)/c^2]^{-1/2} \gg 1$), the trapped particle “longitudinal” energy $\varepsilon_\parallel \approx Gm_1v_\parallel^2 \approx 0$ is not sufficient to overcome the potential height. In the wave reference frame, two forces affect a particle in the longitudinal direction: $eE_\parallel$ and $eB_{0\perp}v_\parallel/c$, where $E_\parallel$ is the value of the electric field longitudinal component in a point on the wave potential profile where a particle is; $B_{0\perp} = \Gamma B_0 \sin \theta_{B_0}$ is the value of the magnetic field transverse component in the wave reference frame in the same point. Let us designate the maximum value (amplitude) for the electric field longitudinal component on the wave profile as $E_{\parallel m}$, and the value for the magnetic field transverse component as $B_{0\perp m}$. When satisfying condition [5]

$$R = E_{\parallel m}/B_{0\perp m} > 1, \quad (1)$$

there will always be a point on the potential profile where these forces for an ideally trapped particle will be balanced: $E_\parallel = B_{0\perp}v_\parallel/c \approx B_{0\perp m}$. In this point on the potential profile, the trapped particle will stay indefinitely long, and, like analysis shows, its position in this point is stable.

A remarkable peculiarity of surfing is that both particle trapping and particle acceleration are ensured by the same electromagnetic fields existing in the potential jump vicinity; both electrons and ions can be accelerated to unlimited energies with equal efficiency due to surfing.

The most known and widespread wave formations containing a potential jump in magnetized plasma are: the high-amplitude Langmuir wave [9, 10] propagating in plasma in the presence of a weak magnetic field (high-frequency upper hybrid branch of oscillations) and the magneto-sonic shock (MSS) [4] (branch of the fast magnetic sound). Since the periodic plasma wave contains both positive and negative potential jumps, it is capable of accelerating both ions and electrons. MSS is characterized by the positive potential jump, therefore, only ions can be accelerated at the MSS front. Note that longitudinal plasma waves and MSSs are easily excited at abrupt variations of weakly magnetized plasma parameters and damp relatively weakly in the collisionless space plasma. We consider possible versions for excitation of waves under consideration by example of the near-Sun plasma. In the magnetospheric plasma, stationary magneto-sonic shocks are formed at the interaction of solar wind with magnetic fields of planets. The Earth’s bow shock may be an example. Most waves are excited in the solar atmosphere (chromosphere, corona). These waves propagate away from the Sun, thus, the most powerful waves, such as plasma ones and MSSs (e. g., interplanetary shocks), emerge during chromospheric flares and other similar explosive processes on the Sun. High-amplitude plasma waves may originate during various non-linear plasma processes, but, generally, their
formation occurs either due to the transformation of strong electromagnetic waves in plasma or during the development of plasma instabilities as fast beams of charged particles move through it. In the waves under consideration, epithermal particles from the tail of the plasma particle distribution function are trapped. A detailed consideration shows [7] that, with such a way of involving particles in the acceleration process, their quantity is enough to ensure the observed CR concentration in the galaxy.

One of the most remarkable surfing peculiarities is that a long-term trapping of a small fraction of plasma particles into a wave is possible at the front of a non-linear disturbance wave. To trigger trapping, another condition [8] should be satisfied for the field parameters at the front except condition (1):

$$\chi = \beta \Gamma tg \theta_{bn} \geq 1,$$

where $\beta = U/c$. Satisfying condition (1) is controlled by the electric field amplitude $E_{\parallel m}$ in relativistic waves and by the magnetic field in the wave that, by an order of magnitude, is equal to $B_{0 \perp}$. Estimating value $E_{\parallel m}$ provides the following values: $E_{\parallel m} \sim m_1 e^{\Gamma/2} \omega_{pe} / e$ – for Langmuir waves [8, 9] ($e$ and $m_1$ being the electron charge and mass, respectively, $\omega_{pe}$ is the electron plasma frequency in plasma before the wavefront) and $E_{\parallel 1} \sim m_1 e \omega_{pi} / Z e$ – for MSSs [8] ($m_i, Z, \omega_{pi}$ are the ion mass, the ion charge number, and the ion plasma frequency in plasma before the front, respectively).

Satisfying condition (1) for Langmuir waves for angles $\sin \theta_{bn} \sim 1$ may be written like

$$\omega_{pe}^2 / \omega_e^2 \sim 1 / e_e > \Gamma - 1 > \omega_e^2 / \omega_{pe}^2 \sim e_e,$$

where $\omega_e = eB_0 / m_e e, e_e = T / m_e e^2$ is dimensionless temperature normalized to the electron rest energy. According to these inequalities and accounting for interstellar medium parameters, we obtain the following results for relativistic factor $\Gamma$ [7]: its maximum is circa $5 \cdot (10^{-1} - 10^1)$, and its minimum is determined from the relation $(\Gamma - 1) \approx 2 \cdot (10^{-4} - 10^{-5})$. Satisfying condition (1) for MSSs provides limiting the values of parameter $\Gamma$ being circa an order of magnitude smaller [8].

Condition (2) superimposes limitation on the angle $\theta_{bn}$ value: the particle kinetic energy $\varepsilon$ is theoretically unlimited for angles $\theta_{bn}$ at $\chi \geq 1$, and, at $\chi < 1$, the it is limited by $\varepsilon_{mn} \approx 2m_1 e^2 \chi^2 / (1 - \chi^2)$[8]. Critical angle $\theta_{bn}^*$ separating these two acceleration modes is determined from the condition $\beta \Gamma = ctg \theta_{bn}^*$. For non-relativistic waves ($\beta << 1, \Gamma \approx 1$), critical angle $\theta_{bn}^* \approx \pi / 2$ and theoretically unlimited energy may be obtained only for the potential quasi-perpendicular wave. For relativistic waves ($\beta \approx 1, \Gamma >> 1$), critical angle $\theta_{bn}^* \approx 1/\Gamma$ may be very small: $tg \theta_{bn}^* \approx \theta_{bn}^* \approx 1/\Gamma << 1$, and the angle interval where the unlimited acceleration mode is possible appears great: $\pi / 2 \geq \theta_{bn} \geq 1 / \Gamma$.

3. Surfing and ultra-high-energy cosmic rays

One of the surfing basic advantages is the acceleration high rate, $d\varepsilon / dt$. The value $d\varepsilon / dt$ is the same both in the wave reference frame and plasma at rest. The simplest formula for the acceleration rate is expressed in the wave reference frame where it is $d\varepsilon / dt = qUB_0 \Gamma \sin \theta_{bn}$. In the plasma-at-rest reference frame, we obtain the formula $\varepsilon = e\Gamma B_0 U T_a \sin \theta_{bn}$ for the energy of accelerated particles in a potential wave, where $T_a$ is the acceleration time. Even under ideal conditions for surfing to occur (when the “perpetual” trapping is fulfilled, i.e., at $R > 1$ and $\chi = \beta \Gamma tg \theta_{bn} \geq 1$), the acceleration time in real situations is always restricted. For non-relativistic waves ($\beta = U / c << 1$), this time is restricted...
by transverse size $L_{\perp}$, and for the energy we will obtain the formula $\varepsilon = eZ\Gamma L_{\perp}B_0 \sin \theta_{bn}$, where $e$ is the electron charge, $Z$ is the charge number of an ion, $L_{\perp}$ is the distance characterizing the wave disturbance scale in the direction perpendicular to the wave vector. For relativistic waves ($\beta = 1$), the accelerated particle energy is

$$\varepsilon = eZ\Gamma^2 L_{\perp}B_0 \sin \theta_{bn}.$$  
(3)

This is true, if the limitation is associated with the travel time for the accelerated relativistic particle at distance $L_{\perp}$. If the time limitation is associated with a wave travel of longitudinal (along the wave motion direction) distances $L_{\parallel}$, the accelerated particle energy is

$$\varepsilon = eZ\Gamma L_{\parallel}B_0 \sin \theta_{bn}.$$  
(4)

One should pay special attention to the particle acceleration process due to surfing in gamma-bursts which are galactic-scale events. In the estimations below, we suppose that $\sin \theta_{bn} \sim 1$. As noted in [11], in the galaxy (where a gamma-burst takes place), the blast wave may travel a long distance $r \sim \Gamma^2 c \Delta t$ during a small observational time interval $\Delta t$. Taking this into account, and assuming that $\Delta t \sim 10\,\text{sec}$, $\Gamma \sim (10^3 - 10^5)$, we obtain $r \sim (10^3 - 10^5)\,\text{pc}$. If the blast wave has a spherical form, then, taking into account that $L_{\perp} \sim r$, we obtain $\varepsilon \sim 10^{14} - 10^{17}\,\text{eV}$ from formula (4) for the particle energy $\varepsilon = 10^{15} L_{\parallel} \Gamma \varepsilon$. If the blast wave has a flat front, then formula (3) is applied: $\varepsilon = 10^{15} L_{\parallel} \Gamma^2 \varepsilon$. Assuming, that the blast wave cross size is $L_{\perp} \sim L_{\parallel} \sim r$, we obtain $\varepsilon \sim 10^{16} - 10^{20}\,\text{eV}$ for the particle energy. Particles gain such an energy in the surfing process during a gamma-burst.

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