Relativistic waves as sources of ultrahigh energy cosmic rays

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Abstract: The paper discusses the possibility of particle acceleration up to high energies in relativistic shock waves generated by various explosive processes in the interstellar medium. Shock waves are assumed to be a type of magnetoacoustic shock waves (a branch of fast magnetic sound). We propose to use the surfatron mechanism of acceleration (surfing) of charged particles trapped in the front of relativistic shock waves as a generator of high-energy cosmic rays (CRs). Conditions under which surfing in the shock waves under consideration can be made are studied thoroughly. Ultrahigh energy CRs (up to 10^{20} eV) are shown to be obtained due to the surfing in relativistic plane and spherical shock waves generated, for instance, by relativistic jets or spherical formations that expand fast (fireballs).

Keywords: particle acceleration, relativistic waves, ultrahigh energy cosmic ray.

1 Introduction

When solving the problem of cosmic ray (CR) generation, some significant results have been achieved due to the Krymski acceleration mechanism which has a reliable theoretical and observational basis [1]. Remarkable results were obtained when investigating CR generation in supernova remnants and it was shown that in supernova shells particle energies may reach values of the order of 10^{15} *eV*. However, the estimations obtained in the most general view exhibit that, in principal, in supernova remnants accelerating particles to the energies over 10^{17}*eV* is impossible [2]. It is associated with low velocity of the supernova shell extension. Nowadays, it became clear that CRs with energies over 10^{17}*eV* are most likely generated in the vicinity of space objects moving at relativistic velocities. Application of the Krymski mechanism for particle acceleration at relativistic shocks is of great doubt [3], therefore, in this case it is necessary to attract other means of particle acceleration.

In this study, we pay attention to a principal possibility of CR generation up to ultrahigh energies (10^{20} *eV*) by the particle surfing acceleration (surfing) in potential waves moving in weakly magnetized space plasma. We will briefly consider the problems which arise when implementing the acceleration mechanism offered.

2 Surfing acceleration mechanism (surfing) and its characteristics.

2.1 Essence of surfing

Surfing occurs in weakly magnetized plasma. In this mechanism, particles are trapped and accelerated in potential wave with a steep forefront. 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 with velocity U at angle θ_{Bn} to the magnetic field vector.

As analysis shows, a portion of particles of plasma having finite temperature, when inleaking onto potential jump cannot overcome it and is reflected from the shockfront. Under certain conditions, the Lorentz force acting ahead of the shockfront can turn these reflected particles back towards the front and, thus, particles can appear trapped by the shock and can be accelerated by force $qUB_{0\perp}\Gamma/c$ to major energies (here q is the charge of particles, $\Gamma = (1 - U^2/c^2)^{-1/2}$, c is the speed of light, $B_{0\perp} = B_0 \sin\theta_{Bn}$ is the magnetic field component transversal to the shock direction traffic which in the reference frame associated with the static plasma ahead of the front has value B_0). A remarkable peculiarity of surfing is in that both trapping and acceleration of particles are ensured by the same electromagnetic fields existing in the vicinity of the shockfront, and through surfing it is possible to accelerate both electrons and ions to ultimate energies with equal efficiency.

2.2. Types of potential moving disturbances in which surfing is possible

The most known and widespread wave formations containing a potential jump in magnetized plasma are: the Langmuir wave of big amplitude [4,5] propagating in plasma in the presence of a weak magnetic field (high-frequency upper hybrid branch of oscillations) and the magneto-sonic shock (MSS) [6] (branch of fast magnetic sound). Since the periodic plasma wave contains both positive and negative potential jumps it can accelerate both ions and electrons. MSS is characterized by the positive jump of potential, therefore, only ions can be accelerated at the MSS front.

We note that in the collisionless space plasma longitudinal plasma waves and MSSs are easily excited at abrupt variations of weakly magnetized plasma parameters and fade relatively weakly. We consider possible versions of excitation of waves of the considered types 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 can be an example. The bulk of waves is excited in the solar atmosphere (chromosphere, corona). These waves are propagated away from the Sun, thus, the most powerful waves such as plasma ones and MSSs (e. g., - interplanetary shocks) emerge at chromospheric flares and other similar explosive processes on the Sun.

Plasma (Langmuir) waves of big amplitude can be born in various non-linear processes in plasma, but, generally, their formation occurs either due to the transformation of strong electromagnetic waves in plasma or during development of instabilities in plasma as fast beams of charged particles move in 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 at such a means of involving particles in the acceleration process their quantity is enough to ensure the observed concentration of CRs in the Galaxy.

2.3. Conditions necessary for surfing implementation

One of the most remarkable peculiarities of surfing is that at the front of a non-linear wave of disturbance a long-term trapping of a small share of plasma particles into a wave is possible for implementation of which satisfying two conditions for the field parameters at the front [8, 9] is necessary:

$$R > 1, \quad (1)$$

$$\chi = \beta \cdot \Gamma \cdot tg\theta_{Bn} \geq 1, \quad (2)$$

here $\beta = U/c$, parameter $R = E_{\parallel}/B_{0\perp}$, where $E_{\parallel}$ is the maximum value (amplitude) of the electric field longitudinal component in a wave potential, $B_{0\perp} = \Gamma B_0 \sin\theta_{Bn}$ is the value of the magnetic field transversal component in the wave system at the profile point of the wave in which the electric field is maximal.

Estimating value $E_{\parallel}$ leads to values: $E_{\parallel} \sim m_e c\, \omega_{pe0}/e$ - for Langmuir waves [4,5] (e and m_e being the electron charge and mass, respectively, ω_{pe0} is the electron plasma frequency in plasma before wavefront) and $E_{\parallel} \sim m_i c\, \omega_{pi0}/Ze$ - for MSSs [6] (m_i, Z, ω_{pi0} are the ion mass, the ion charge number, and the ion plasma frequency in plasma before front, respectively). Satisfying condition (1) for Langmuir waves may be written in the view [7,10]

$$\omega_{pe0}^2/\omega_{ce}^2 \sim 1/\varepsilon_e > \Gamma - 1 > \omega_{ce}^2/\omega_{pe0}^2 \sim \varepsilon_e,$$

where $\varepsilon_e = T/mc^2$ is dimensionless temperature normalized to the electron rest energy, $\omega_{ce} = eB_0/m_e c$. From these inequalities, accounting for the parameters of the interstellar medium, we obtain for relativistic factor Γ [7,10] that its maximum value is circa equal to $5\cdot(10^3\text{-}10^4)$, and the minimum value is defined from the relation $(\Gamma - 1) \approx 2\,(10^{-4} - 10^{-5})$. For MSSs satisfying condition (1) leads to limiting values of parameter Γ by circa order of magnitude greater.

Condition (2) superimposes limitation on the value of angle θ_{Bn}: for angles θ_{Bn}, satisfying the condition $\chi \geq 1$ the kinetic energy of particles $\mathscr{E}$ is theoretically unlimited, and at $\chi < 1$ the energy is limited by $\mathscr{E}_m \approx 2m_i c^2\chi^2/(1-\chi^2)$ [9]. Critical angle θ^*_{Bn}, separating these two acceleration modes is defined from the condition $\beta\,\Gamma = ctg\,\theta^*_{Bn}$. For nonrelativistic waves ($\beta << 1$, $\Gamma \approx 1$) critical angle $\theta^*_{Bn} \approx \pi/2$ and theoretically unlimited energy in this case can be obtained only for the potential quasiperpendicular wave. For relativistic waves ($\beta \approx 1$, $\Gamma > 1$) critical angle θ^*_{Bn} can be very small: $tg\,\theta^*_{Bn} \approx \theta^*_{Bn} \approx 1/\Gamma << 1$ and the interval of angles in which the unlimited acceleration mode is possible, appears to be great: $\pi/2 \geq \theta_{Bn} \geq 1/\Gamma$.

2.4. Estimating energy of the particles accelerated by surfing

One of the basic advantages of surfing is high rate of acceleration $d\mathscr{E}/dt$. The value $d\mathscr{E}/dt$ is the same as both in the wave frame and plasma at rest, and the simplest formula rate of acceleration is expressed in the wave system where it is equal to $d\mathscr{E}/dt = qUB_0\Gamma \sin\theta_{Bn}$. In the frame associated with plasma at rest, for energy of accelerated particles in a potential wave we obtain the formula $\mathscr{E} = eZ\,\Gamma\, B_0\, U\, T_a \sin\theta_{Bn}$, where T_a is acceleration time.

In ideal conditions for surfing to occur when the conditions for "perpetual" trapping are satisfied, i.e. at $R > 1$ and $\chi = \beta \cdot \Gamma \cdot tg\theta_{Bn} \geq 1$ the acceleration time in real situations is always restricted. For nonrelativistic waves ($\beta = U/c << 1$) this time is restricted by transverse size $L_\perp$ and for energy we will obtain the formula $\mathscr{E} = eZ\beta L_\perp B_0 \sin\theta_{Bn}$ [7,10]. $L_\perp$ is the distance characterizing the scale of wave disturbance in the direction perpendicular to the wave vector. For relativistic waves ($\beta = 1$) the energy of accelerated particles

$$\mathscr{E} = eZ\,\Gamma^2 L_\perp B_0 \sin\theta_{Bn}, \qquad (3)$$

if the limitation is associated with the travel time of the accelerated relativistic particle of distance $L_\perp$, and if time limitation is associated with a wave travel of longitudinal distances $L_\parallel$ (along the wave motion direction), then the energy is [7, 10]

$$\mathscr{E} = eZ\Gamma L_\parallel B_0 \sin\theta_{Bn}. \qquad (4)$$

3. Surfing and ultrahigh energy cosmic rays

3.1. An overall picture on generation of CRs of high energies

Ultimate energies which can be obtained by CRs in the Galaxy appear to be determined by maximum size of the Galaxy regions with a quasi-homogeneous magnetic field where non-linear waves can propagate [7,10,11]. In the particle acceleration model offered which is based on surfing, the scenario of consecutive energy increase by particles in the Galaxy is this. First, particles from plasma are trapped in the nonrelativistic MSSs and non-linear plasma waves. Like a detailed consideration shows [7,10], both in MSSs and in Langmuir waves propagating in space plasma with nonrelativistic velocities, charged particles can be accelerated at such stars like the Sun and in its vicinity (heliosphere) to energies of the order of 10^{10} *eV* and to energies of the order of 10^{15} *eV/nucleon* - in the interstellar medium. Further, ultrarelativistic particles which are retained by the magnetic field within the Galaxy can continue acceleration in relativistic MSSs and plasma waves. At sizes comparable with the thickness of the galactic disk (~ *100 nc*) they can obtain energies of the order of 10^{20} *eV*.

3.2. Cosmic rays and explosive processes in space

The most probable reason for forming CRs of ultrahigh energies may be explosive processes in space. On the basis of observational data, one may assert confidently enough that explosive processes are quite frequent phenomena in space medium. Explosions of supernovae, sparking X-ray stars - bursters, active processes in galactic nuclei, quasars, etc., may be representative. Typical explosive processes, solar flares, are permanently observed on the Sun, the most proximate star to the Earth. Many explosive phenomena are characterized by huge energy release a portion of which turns into kinetic energy of moving substance accelerated to high velocities. Thus the processes occurring, for example, in the vicinity of black holes lead to formation of relativistic jets moving with velocities close to the speed of light. A spherical expansion of so-called "fireballs" occurs to relativistic velocities. Due to uniqueness of the phenomena accompanying explosions in space, they have been drawing meticulous attention from researchers recently.

As a rule, the explosions under consideration occur in the presence of medium which in typical situations is weakly magnetized plasma. At such explosions, the surrounding plasma is transpierced by powerful energy flows in the form of electromagnetic radiations which can be converted, in particular, into plasma waves [12]. It is obvious that at the propagation of fast-moving disturbances of the substance ejected into the medium as a result of explosion, shocks are also formed. Thus, powerful relativistic shocks are excited at quick motion of masses in the vicinity of black holes, in particular, at relativistic jet ejection; at collision of neutron stars in a collapsing cluster; at the spherical expansion of fireballs into the interstellar medium and in many other cases.

In our solar system, solar flares are accompanied by the ejections of the substance whose motion in the heliosphere lead to formation of interplanetary shocks. The shocks originating in space medium are the most probable sources of high energy particles which, as a rule, are accelerated in the vicinity of shock fronts. We consider that the most probable type of shocks are MSSs, and we will confine ourselves to considering CR acceleration in the latter.

3.3. Estimations of CR energies in explosive processes

We will proceed to an estimation of energies which can be obtained during explosive processes in space. As an example, we will consider a surfing acceleration of protons in plane and spherical relativistic shocks. As an example of plane propagation, let us consider a shock with a plane front whose transversal size has a characteristic scale $L_\perp$. A shock of similar geometry can be excited, for example, by a relativistic jet. We consider the spherical case by example of so-called "fireballs". We consider that the condition of "perpetual" trapping particles in the shock front is satisfied, and angle θ_{Bn} fulfills the condition under which the energy unbounded particle acceleration mode is possible: $\pi/2 \geq tg\theta_{Bn} > 1/\Gamma$.

An estimation for the energy obtained by protons due to surfing in the plane shock front, is, according to formula (3), $\mathscr{E} \approx e\Gamma^2 B_0 L_\perp \sin\theta_{Bn}$. If energy be expressed in *eV*, the $L_\perp$ scale be in parsecs, magnetic field B_0 be in oersteds, then the formula for energy will be of the view $\mathscr{E} = 10^{21}\Gamma^2 B_0 L_\perp \sin\theta_{Bn}$. Assuming that the magnetic field value in the interstellar medium is $B_0 \sim 10^{-6}$ Э, we obtain the value $\mathscr{E} = 10^{15}\Gamma^2 L_\perp \sin\theta_{Bn}$ for energy, whence it follows that to obtain the energy of the order of $10^{20}eV$, the shockfront transversal size in parsecs is to be $L_\perp \sim 10^5/(\Gamma^2 \sin\theta_{Bn})$ which is quite real for large-scale relativistic shocks excited by explosions in space. For example, at $\Gamma \sim 100$, $\sin\theta_{Bn} \sim 1$ the $L_\perp$ transversal size will be of the order of *10 пс*.

To estimate the energies in a fireball we consider a simplest model within which we assume that 1) the ball under consideration is an ideal sphere which expands at $v(t)$, 2) the interstellar medium magnetic field surrounding the ball is permanent and homogeneous with value B_0. We analyze the protons motion in a spherical shock which we view in a plane passing through the sphere center and perpendicular the magnetic field vector. In the selected geometry, the shockfront will have the form of a circle with radius $r(t)$ equal to the ball radius. We assume that the condition under which ions appear "perpetually" trapped in the shockfront is satisfied, i.e. the ions move strictly together with the front at $v(t)$. Acceleration of the ions trapped by the shock occurs asimuthward, therefore, they, moving with radius together with the front, move round the circle at a velocity close to the speed of light. In the model accepted, $\sin\theta_{Bn} = 1$, therefore, the rate of acceleration will be equal to $d\mathcal{E}/dt = e\Gamma B_0 v$, and, hence, the energy will be $\mathcal{E} = e\Gamma B_0 \int v(t)dt = er\Gamma B_0$ (compare to the formula (4)). Assuming $B_0 \sim 10^{-6}$ Э, we obtain $\mathcal{E} = 10^{15}\, r\, \Gamma$ *eV* (r is in parsecs), whence it follows that to obtain the energy of the order of 10^{20}*eV*, product Γ is to be of the order of 10^5 which is quite accessible at reasonable values of Γ and r, for example, $\Gamma = 100$ and $r =$ *1 кпс*. Thus, at a particle acceleration due to surfing in a plane relativistic shockfront or at a spherical expansion of a fireball in the interstellar medium, protons can obtain energies of the order of 10^{20}*eV*. Summarizing the results stated above, we conclude that generating CRs of ultrahigh energies due to surfing in relativistic shocks excited by explosive processes in space plasma, is possible in principle.

4. Conclusion

The results of studying charged particle surfing accelerations testify to indisputable virtues of this acceleration method. One may even assert quite safely that within surfing it is possible to solve the bulk of the problems concerning CR acceleration in space plasma. Indeed, let us consider everything in succession. First, particles are trapped into waves directly from the galactic plasma in an amount sufficient to ensure the observed CR concentration in the Galaxy [7,10,11]. In other words, either circumstellar or interstellar plasma is that reservoir from where "ladled" are the particles composing cosmic rays. Second, within the same acceleration method particles are accelerated injection-freely from energies close to thermal in plasma to ultimate energies. Third, there is no difference acceleration of different charged particles: electrons and nuclei are accelerated equally and to the same ultimate energies (per unit charge). Further, since in surfing trapping particles into a wave occurs in a resonance fashion and the acceleration rate is constant, there is no risk of destruction for complicated nuclei during their acceleration. It is pertinent here to add the results of study [12]: at surfing, the CR differential energy spectrum is obtained close to the observed (the power-law index is close to 3).

And, finally, we give the most essential conclusions which follow from the acceleration model offered.

1. Formation of CR high-energy spectrum in the Galaxy is implemented in two phases. At the first phase, a small portion of the plasma charged particle distribution function epithermal part is trapped into nonrelativistic non-linear waves and, due to surfing, it is accelerated to 10^{13} *eV/nucleon* in stellar atmospheres and 10^{15} *eV/nucleon* in the galactic disk. At the second phase, these particles can obtain energies of $10^{16} - 10^{20}$ *eV/nucleon* due to surfing already in relativistic waves propagating in the magnetized plasma. It is interesting to note that the energy differentiating these two phases lies in the fracture area of the CR energy distribution curve (“knee”).
2. The ultimate energy of particles obtained due to surfing in non-linear waves is limited mostly by the size of a wave propagation region.
3. As a first approximation, one may neglect particle power losses associated with the known types of radiation, with the attenuation of waves owing to their energy losses for particle acceleration at surfing. It is especially necessary to note that at surfing particle acceleration there is the most dangerous channel of power losses by relativistic particles, a synchrotron radiation [7,10,11]. In particular, due to that electrons in the Galaxy, as well as nuclei, can be accelerated owing to surfing to energies of the order of 10^{20} *eV*.

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