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Ultimate Energy of Cosmic Rays Generated in Supernova Shells

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It is shown that the ultimate energy of cosmic rays accelerated in a supernova shell due to the surfing acceleration mechanism is determined by the shell radius and the interstellar magnetic field. The ultimate energy of cosmic rays accelerated in the supernova shock does not exceed 10^{17} eV for typical values of the interstellar magnetic field in the vicinity of a supernova and the radii of observed supernova shells.

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At present, it is generally believed that cosmic rays originate in supernova remnants (SNRs) [1–4], i.e., ejecta of exploded stars, which expand with high velocities into interstellar medium. Supernovae are used as an essential ingredient of cosmic-ray acceleration mechanisms since, first, the energy released by a supernova is extremely high, and even a small fraction (a few percent) of this energy is enough to satisfactorily explain the energy of the observed Galactic cosmic rays. Second, it is conventionally believed that the source of cosmic rays is the strong shock formed at the SNR front. In this case, the mechanism of charged-particle acceleration is associated with the long-term trapping of the accelerated particles in the vicinity of the SNR shock front. The most developed and widely known is the Krymsky (regular or diffusion) mechanism [1–6]. Recently, the so-called surfing acceleration mechanism has also been proposed as an efficient mechanism for the generation of high-energy particles in a collisionless shock front [7–12].

In this work, it is shown that the energy of cosmic rays generated in a SNR due to the surfing mechanism cannot exceed a certain fundamental ultimate value determined by the SNR radius and the regular magnetic field in the interstellar medium. This statement is proven using a simplified model, which is generally similar to the realistic one. Within the framework of the simplest model, it is assumed that (i) the supernova shell is a perfect sphere expanding with the velocity $v(t)$ and (ii) the interstellar magnetic field B surrounding the shell is constant and uniform. It is known [7–9] that the surfing mechanism accelerates only ions moving with the wave, i.e., the trapped ions, are accelerated, and the surfing efficiency is maximal if the shock front propagates exactly across the magnetic field. Taking these assumptions into account, we consider the ion motion in a shock. The analysis is completed for the plane comprising the sphere center and perpendicular to the magnetic field.

For the adopted geometry of the problem, the shock front is a sphere of radius $r(t)$ equal to the SNR radius. Within the framework of such a formulation, the shock can be considered as a transverse magnetosonic shock in which, in addition to jumps of hydrodynamic parameters, a positive jump of the potential also exists [7–11], which corresponds to a radial electric field $E(r)$ whose amplitude is denoted as E_A. Let the condition $E_A > B$ be valid, thus ensuring the "eternal" capture of ions in the shock front [7–10, 12]. Such eternal capture is possible due to the balance of three forces acting on a particle in the radial direction [13]. The electric force $qE(r)$ and the centrifugal force are directed radially away from the sphere center and are balanced by the force $qBv_\varphi/c \simeq qB$ directed toward the center (here, c is the speed of light, q is the ion charge, and v_φ is the azimuthal velocity of the particle, which is close to c at the relativistic stage).

Thus, the electromagnetic forces firmly trap a surfing particle at the shock front. The particle moves with the front with the velocity $v \ll c$ and gyrates with the velocity $v_\varphi \simeq c$. Within the framework of this idealized approximation, the ion gains energy due to the acceleration in the azimuthal electric field $E_\varphi = vB/c$. Since the shock width is negligibly small compared to the SNR radius, r can be considered as the coordinate of the ion captured by the shock, the shock coordinate, and the SNR radius.

The energy gained by an ion can be found from the equation $mc^2 d\gamma/dt = qv(t)Bv_\varphi/c$, where m is the ion rest mass and γ is the dimensionless total energy of a particle. Assuming that $v_\varphi \simeq c$ during the relativistic stage of acceleration, we estimate $\gamma \simeq \omega_B \int v(t)dt/c = \omega_B r/c$, where $\omega_B = qB/mc$ is the nonrelativistic Larmor frequency of ion gyration in a magnetic field. As a result, the ion energy $\mathcal{E} = mc^2\gamma$ per unit charge is given by $\mathcal{E}/q = Br$; i.e., this quantity is always entirely determined by the regular interstellar magnetic field and SNR radius. It is interesting that this formula is identical to the formula for the Larmor radius of a relativistic particle with charge q and energy $\mathcal{E}$ gyrating in the plane perpendicular to the magnetic field B.

Typical values of the interstellar magnetic fields are $B \sim 10^{-6}$ Oe. The typical radii of the majority of observed supernova remnants are about $r \sim 10$ pc. Therefore, the estimated proton energy cannot exceed $\mathcal{E} \sim 10^{17}$ eV. Since the most optimal conditions for proton acceleration were assumed, this estimate gives the ultimate energy of particles accelerated in supernova remnants. In our opinion, this is a fundamental limit. The surfing acceleration rate $d\mathcal{E}/dt = qvB$ is extremely high, for example, much higher than that for the Krymsky mechanism. Thus, other acceleration mechanisms cannot provide higher energies. The simple above estimates agree with the ultimate energies in supernova remnants obtained by complicated and detailed analytical and numerical calculations [2–4].

Let us consider the energy losses of accelerated particles. Particle gyration in the magnetic field gives rise to the most dangerous synchrotron losses. Let us show that these losses are negligible in this case by considering the ratio of the radiation power $\gamma^2[q^2/mc^2]^2cB^2$ to the acceleration rate qvB. As a result, this ratio can be written as $c\gamma^2B/vE_e$, where $E_e = q/r_0^2$ is the electric field of a point charge q at a distance equal to the classical radius $r_0 = q^2/mc^2$. The substitution of $B \sim 10^{-6}$ Oe and $c/v \sim 10^2$ gives the estimate $c\gamma^2B/vE_e \sim (\gamma/10^{13})^2$ showing that the radiation can drastically affect the proton acceleration only at energies exceeding 10^{22} eV. Hence, the synchrotron losses are negligible for surfing in supernova remnants.

The main conclusion following from the obtained estimates is that ions in the observed SNR shocks cannot gain an energy exceeding 10^{17} eV per charge. Alternative sources of the high-energy particle generation should be involved to explain the presence of cosmic-ray particles with energies exceeding 10^{17} eV per charge. Ultrarelativistic nonlinear or shock waves can be the most plausible sources, for example, a shock generated by a relativistic jet in a magnetized plasma [14] or a high-power plasma wave [15–17] propagating across a weak magnetic field (the upper-hybrid branch) [18]. In this case, the ultimate energy of the cosmic rays is increased by the Lorenz factor $(1 - v^2/c^2)^{-1/2} \gg 1$ [9, 19] and can reach 10^{20} eV [9, 15], i.e., the ultimate energy of cosmic rays observed on the Earth.

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