Strangelets accelerated by pulsars in galactic cosmic rays

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It is shown that nuggets of strange quark matter may be extracted from the surface of pulsars and accelerated by strong electric fields to high energies if pulsars are strange stars with the crusts, comprised of nuggets embedded in a uniform electron background. Such high energy nuggets called usually strangelets give an observable contribution into galactic cosmic rays and may be detected by the upcoming cosmic ray experiment Alpha Magnetic Spectrometer AMS-02 on the International Space Station.

I. INTRODUCTION

It has long been suggested that strange quark matter (SQM) composed of roughly equal numbers of up, down, and strange quarks plus a small number of electrons (to neutralize the electric charge of the quarks) may be absolutely stable, i.e., stronger bound than iron [1,2]. Later, predictions of increased SQM stability in some color-superconducting phases have made this conjecture more likely than previously believed [3]. For lumps of SQM the possible range of baryon number A is from $\sim 10^2$–10^3 (strangelets) to a few times 10^{57} (strange stars). Strangelets may exist in at least three possible varieties: ''ordinary'' (unpaired) strangelets [2], color-flavor locked strangelets [4], and two-flavor paired strangelets [5]. Strangelets may be accelerated to very high energies similar to atomic nuclei and observed as a component of cosmic rays (for review, see Ref. [6]). Searching for strangelets in cosmic rays is one of the best ways to test the possible stability of SQM.

At present, the production of strangelets and their subsequent acceleration are poorly known. It is usually assumed that strangelets are an outcome of strange star collisions [7] and the Type II supernova explosions, where strange stars form [8]. No realistic simulations of such processes have been performed to date. The value of the galactic production rate of strangelets used in different calculations of the strangelet flux in cosmic rays is rather an assumption than a calculable result and differ by several orders of magnitude [6,8,9]. Fermi acceleration in supernova shocks is considered as the mechanism of strangelet acceleration [8,9]. However, for Fermi acceleration there is a well known problem of particle ejection. The point is that only supra-thermal particles may be accelerated by shocks, and therefore, for acceleration by shocks the initial energy of strangelets has to be high enough. Since the energy distribution of strangelets formed in collisions of strange stars and supernova explosions is unknown, we have additional uncertainty in predictions of strangelet contribution in cosmic rays [10]. In this paper we consider other sources (pulsars) of high energy strangelets in the Galaxy. We estimate the mean production rate of strangelets and their typical energies within a factor of 2–3 or so.

II. STRANGELET PRODUCTION

Following Refs. [6,9] we assume that SQM is the ground state of strong interaction, and all compact objects identified with neutron stars (including radio pulsars) are, in fact, strange stars. Recently, it was shown that if Debye screening and surface tension may be neglected then the SQM surface of a strange star must actually fragment into a charge-separated mixture, involving positively-charged strangelets immersed in a negatively-charged background of electrons [5,11]. This results in formation of a normal-matter-like crust where strangelets are instead of atomic nuclei. For strangelets in such a crust the expected values of A and Z are $\sim 10^3$ and $\sim 10^2$, respectively, (cf. Sec. IV).

Strong electric fields are generated in the magnetosphere of a radio pulsar because of its rotation (e.g., [12]). The sign of the charge of particles that tend to be ejected from the pulsar surface by this field depends on the sign of $\boldsymbol{\Omega} \cdot \mathbf{B}$, where $\boldsymbol{\Omega}$ is the angular velocity of the pulsar rotation and $\mathbf{B}$ is the surface magnetic field. If $\boldsymbol{\Omega} \cdot \mathbf{B} < 0$ positively-charged particles (in our case, strangelets) are ejected, and the rate of strangelet ejection from the pulsar crust is

$$\dot{N}_{\rm str} \simeq 2\pi r_p^2 n_{\rm cr} c \simeq \frac{\Omega^2 R^3 B_p \cos\chi}{cZe}, \tag{1}$$

where $r_p \simeq (\Omega R/c)^{1/2} R$ is the radius of the polar cap around the magnetic pole from where strangelets flow away, $\Omega = |\boldsymbol{\Omega}|$, $R \simeq 10^6$ cm is the radius of the strange star, B_p is the magnetic field strength at the magnetic pole, χ is the angle between the rotational and magnetic axis, and

$$n_{\rm cr} \simeq \frac{\boldsymbol{\Omega} \cdot \mathbf{B}_p}{2\pi cZe} \simeq \frac{\Omega B_p \cos\chi}{2\pi cZe} \tag{2}$$

is the strangelet density that is necessary for screening of the electric field component along the magnetic field in the vicinity of the magnetic pole [13]. In spite of that the estimate of $\dot{N}_{str}$ is written here for a dipole magnetic field, it is also valid for more realistic magnetic fields. This is because the combination $\pi r_p^2 B_p$, which gives the total magnetic flux penetrating the pulsar light cylinder, is the value measured from deceleration of the pulsar rotation and does not depend on how the magnetic field varies from the light cylinder to the pulsar surface [13].

The total number of strangelets ejected from a pulsar from the time ($t_0 = 0$) of its formation at angular velocity Ω_0 to the time t when the angular velocity is Ω may be written as

$$N_{str} = \int_0^t \dot{N}_{str} dt = \int_{\Omega_0}^{\Omega} \frac{\dot{N}_{str}}{\dot{\Omega}} d\Omega. \tag{3}$$

where

$$\dot{\Omega} \simeq -\frac{\Omega^3 R^6 B_p^2}{c^3 I} \tag{4}$$

is the rate of the angular velocity decrease (e.g., [12–14]), and I is the moment of inertia of the strange star.

Equations (1), (3), and (4) yield

$$N_{str} \simeq \frac{c^2 I \cos\chi}{Ze R^3 B_p} \ln\frac{\Omega_0}{\Omega}. \tag{5}$$

The value of N_{str} weakly depends on the angular velocity that varies from $\Omega_0 \simeq 10^3$–10^4 s^{-1} at the pulsar formation to $\Omega_f \simeq 10^{-1}$ s^{-1} when the pulsar age is comparable with the age of the Universe ($\sim 10^{10}$ yr).

Substituting $\ln(\Omega_0/\Omega_f) \simeq 10$ into Eq. (5) we have the following estimate for the total number of strangelets ejected from a pulsar during its live:

$$N_{str} \simeq \frac{5c^2 I}{Ze R^3 B_p}. \tag{6}$$

Here we assume that directions of the rotational and magnetic axes of pulsars are independent, and the average value of $\cos\chi$ is 1/2.

Taking into account that the birthrate of pulsars is $\eta \simeq 1.4 \times 10^{-2}$ yr^{-1} [15], the mean production rate of strangelets in our Galaxy by pulsars is

$$\dot{\mathfrak{N}}_{str} \simeq \eta N_{str} \simeq 1.3 \times 10^{42} \Lambda \text{ yr}^{-1}, \tag{7}$$

where

$$\Lambda = \left(\frac{Z}{10^2}\right)^{-1} \left(\frac{I}{10^{45} \text{ g cm}^2}\right) \left(\frac{R}{10^6 \text{ cm}}\right)^{-3} \left(\frac{B_p}{10^{12} \text{ G}}\right)^{-1} \tag{8}$$

is near unity for typical choices of parameters.

If the assumptions formulated in the beginning of this session on the stability of SQM and the properties of strange stars are valid, Eq. (7) gives a low limit on the production rate of strangelets in the Galaxy because other mechanisms [7,8] may produce strangelets as well.

The production rate of mass in strangelets with $A \simeq 10^3$ is $\dot{\mathfrak{M}}_{str} \simeq A m_p \dot{\mathfrak{N}} \simeq 10^{-12} \Lambda M_\odot$ yr^{-1} that is hundred times smaller than the value suggested by Madsen [6,9], where m_p is the proton mass. The value of $\dot{\mathfrak{M}}_{str}$ increases with increase of A because the ratio A/Z increases. For ordinary strangelets ($Z \simeq 8A^{1/3}$) with $A \simeq 10^6$ (if they exist in the crusts) we have $\dot{\mathfrak{M}}_{str} \simeq 10^{-10} M_\odot$ yr^{-1} as Madsen suggested.

III. STRANGELET ACCELERATION

It is now commonly accepted that in the pulsar magnetospheres there are two regions where electric fields are very strong and may accelerate out-flowing particles to relativistic energies [12]. They are located near the polar caps and the light cylinders and called polar gaps and outer gaps, respectively. The electric potential at polar gaps weakly depends on the pulsar parameters, and it is $\Delta\Phi_p \simeq 3 \times 10^{12}$ V within a factor of 2–3 [13,16]. The typical energy of strangelets accelerated in polar gaps is

$$E_{str}^p \simeq Ze\Delta\Phi_p \simeq 3 \times 10^{14}(Z/10^2) \text{ eV}. \tag{9}$$

The injection rate of strangelets with this energy into the Galaxy is given by Eq. (7).

Outer gaps can operate only in the magnetospheres of young pulsars with the period $P = 2\pi/\Omega \lesssim P_d$, where P_d is somewhere between 0.1 s and 0.3 s [17,18]. For pulsars with $P \simeq P_d$ the polar gap size ($l_{out}^\perp$) across the magnetic field lines is about the radius of the light cylinder, i.e., $\sim c/\Omega$. In this case the main part of strangelets out flowing from the polar cap may be accelerated in the outer gap. At $P < P_d$ the value of $l_{out}^\perp$ decreases with decrease of P ($l_{out}^\perp \propto P^\alpha$, where α is ~ 1.2–1.3 [18]), and the fraction of strangelets accelerated in the outer gap deceases with decrease of P too. As a result, in the process of deceleration of the pulsar rotation the outer gap accelerates strangelets mainly at $P \sim P_d$ with more or less the same efficiency as the polar gap. Therefore, the total number of strangelets accelerated in the outer gap of a pulsar is nearly the value given by Eq. (5) only without $\ln(\Omega_0/\Omega)$ that is ~ 10. Hence, in the Galaxy the mean production rate of strangelets accelerated in outer gaps of pulsars is $\sim 0.1\dot{\mathfrak{N}}_{str}$.

The typical energy of strangelets accelerated in outer gaps is

$$E_{str}^{out} \simeq Ze\Delta\Phi_{out} \simeq 3 \times 10^{16}(Z/10^2) \text{ eV}, \tag{10}$$

where $\Delta\Phi_{out} \simeq 3 \times 10^{14}$ V is the outer gap potential for a pulsar at $P \simeq P_d$ [17,18].

IV. STRANGELETS IN COSMIC RAYS AND THEIR DETECTION

Strangelets ejected from pulsars undergo many processes such spallation, energy losses, and escape from the Galaxy. In our case when the strangelet energies given by Eqs. (9) and (10) are significantly higher than $10^{11}Z$ eV, the escape process dominates over others and determines the density of strangelets in the Galaxy [9].

At energies of $\sim 10^{14}$–10^{15} eV the expected flux of strangelets accelerated in the polar gaps of pulsars is

$$F_{str}^p \simeq \frac{\dot{\mathfrak{N}}_{str}\tau_{esc}(E_{str}^p, Z)c}{4\pi V} \simeq 25\Lambda (\text{m}^2 \text{ sterad yr})^{-1}, \quad (11)$$

where

$$\tau_{esc}(E, Z) \simeq \frac{1.7 \times 10^5}{n}\left(\frac{E}{E_{str}^p}\right)^{-0.6} \text{ yr} \quad (12)$$

is the average escape time from the Galaxy for particles with the energy E and the charge Z [9], V is the galactic volume, and n is the average hydrogen number density of the interstellar medium per cm^3. To obtain the estimate Eq. (11) we have used that the mass of interstellar hydrogen in the Galaxy is $m_p n V \simeq 5.5 \times 10^9 M_\odot$ [19].

At high energies ($\sim 10^{16}$–10^{17} eV) the expected flux of strangelets accelerated in the outer gaps of pulsars is

$$F_{str}^{out} \simeq 0.1\Lambda \text{ m}^{-2} \text{ yr}^{-1} \text{ sterad}^{-1}. \quad (13)$$

The parameters ($Z \simeq 10^2$ and $A \simeq 10^3$) of strangelets ejected from the crusts of strange stars (pulsars) and accelerated in polar gaps are within the interesting region for the upcoming cosmic ray experiment Alpha Magnetic Spectrometer AMS-02 on the International Space Station [20]. The acceptance of AMP-02 is about 0.5 m^2 sterad. AMS-02 will analyze the flux of cosmic rays in unprecedented details for three years. The strangelet flux (11) is high enough to be detected by AMS-02, especially if the mass (m_s) of strange quarks is rather small (cf. Ref. [21]). The point is that for strangelets the ratio Z/A is proportional to m_s^2 [22]. We used the strangelet parameters calculated for $m_s = 200$ MeV [5]. However, m_s may differ from this value by a factor of 2–3 or so, and Z may be at least several times smaller than the value we used. This may simplify detection of strangelets by AMS-02 because the flux F_{str}^p increases with decrease of Z while the energy of strangelets decreases. Besides, for the particle charge it is easy to be measured by AMS-02 if it is not too high (see Ref. [20]).

Plausibly, the polar gaps of pulsars are nonstationary [13], and an essential part of the out-flowing strangelets have energies that are significantly smaller than the value given by Eq. (9). This favors detection of strangelets ejected from strange stars (pulsars) by AMS-02.

The flux of high energy strangelets (13) is of the order of the flux of cosmic rays at the same energy [23] and may be detected in future.

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