Strangelets as Cosmic Rays beyond the Greisen-Zatsepin-Kuzmin Cutoff

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Strangelets (stable lumps of quark matter) can have masses and charges much higher than those of nuclei, but have very low charge-to-mass ratios. This is confirmed in a relativistic Thomas-Fermi model. The high charge allows astrophysical strangelet acceleration to energies orders of magnitude higher than for protons. In addition, strangelets are much less susceptible to the interactions with the cosmic microwave background that suppress the flux of cosmic ray protons and nuclei above energies of 10^{19}–10^{20} eV (the Greisen-Zatsepin-Kuzmin cutoff). This makes strangelets an interesting possibility for explaining ultrahigh energy cosmic rays.

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A long-standing puzzle in cosmic ray physics has been the nature of ultrahigh energy cosmic rays at energies well above 10^{20} eV. Protons and nuclei that are known to be responsible for a significant fraction of the cosmic ray flux at lower energies cannot easily be accelerated to these energies and, if they are, their interactions with photons in the cosmic microwave background radiation are sufficiently energetic to lead to photopion and photopair production, thereby reducing the energy. For nuclei photodisintegration is an additional important factor. This leads to an effective cutoff in flux [originally suggested by Greisen, Zatsepin, and Kuzmin (GZK) [1]; the GZK cutoff] at energies around 10^{19} eV for protons, and 10^{20} eV for the heaviest, abundant stable nucleus, iron. Nevertheless, the observed flux shows no clear cut at these energies (though the number of events is small, and some inconsistency between different experiments exists), with observed cosmic ray energies as high as 3×10^{20} eV [2]. Many suggestions have been made for the nature of cosmic rays beyond the GZK cutoff, ranging from very nearby sources (though there is no consensus regarding anisotropy in the data at the very highest energies), to "new physics" such as decaying ultraheavy, supersymmetric particles [2].

Here we suggest an alternative explanation for cosmic rays at the very highest energies—strangelets (stable lumps of quark matter with roughly equal numbers of up, down, and strange quarks), that due to a high-mass and charge but low charge-to-mass ratio in a natural way circumvent the acceleration problem, and move the GZK cutoff to much higher energies [3].

The possibility that strange quark matter may be absolutely stable [4,5] has gained renewed attention recently. Chandra x-ray observations of one unusually cold pulsar and another unusually small one [6] fit predictions for strange stars made of absolutely stable strange quark matter, though several other explanations are possible as well. An investigation of earthquake data has found unusual seismic events consistent with the passage of macroscopic quark matter lumps through Earth [7]. Predictions of increased quark matter stability in a color-flavor locked phase [8] have made stable strange quark matter in bulk, and perhaps in smaller strangelets [9], more likely than previously believed.

The present investigation shows that strangelets have properties that in a natural way circumvent the objections against protons and nuclei as ultrahigh energy cosmic rays. Strangelets, whether made of "ordinary" or color-flavor locked quark matter, have very low charge-to-mass ratios, but their absolute charges and masses can be extremely high compared to nuclei. Cosmic ray acceleration in astrophysical sources (e.g., in shock waves) is expected to cut off at some high particle rigidity $R = p/Z$, where R, p, and Z denote particle rigidity, momentum, and charge [2]. This rigidity is given by the value of R where the particle Larmor radius in the magnetic field (which is proportional to R) exceeds the size of the accelerator. For relativistic energies $p = E$, where E is the energy, so $E_{\max} = ZR_{\max}$. Thus, the higher Z, the higher $E_{\max}$. For typical cosmic ray nuclei, $Z \leq 26$, and certainly $Z < 100$. This makes it essentially impossible to reach the highest cosmic ray energies observed by means of astrophysical source acceleration of protons or nuclei, given the astrophysical source limitations on $R_{\max}$ [2]. As shown below, much higher charge and therefore maximal acceleration energy can be achieved for strangelets.

For protons, the GZK cutoff is caused by photopion production. Even though the average photon energy in the 3 K cosmic microwave background radiation is as low as $E_{3K} \approx 7 \times 10^{-4}$ eV, an ultrahigh energy cosmic ray proton with a Lorentz factor $\gamma_\pi > m_\pi/E_{3K} \approx 10^{11}$ will reach the threshold for the processes $p + \gamma \rightarrow \pi +$ nucleon, leading to significant energy loss and an expected drop in cosmic ray flux at proton energies above $\gamma_\pi m_p \approx 10^{20}$ eV (detailed calculations show that the drop actually sets in at energies more than an order of magnitude smaller [2]).

For nuclei, the photopion energy-loss cross section goes up as $A^{2/3}$, but the cutoff energy increases linearly with A. However, photodisintegration of nuclei has a threshold of only 10 MeV rather than m_π in the rest frame of the nucleus, so the cosmic ray flux of nuclei should drop at a Lorentz factor of order 10^{10}, corresponding to $E_{\rm GZK} \approx 10^{19} A$ eV (again, detailed calculations result in a drop at energies somewhat lower than found by these simple estimates).

Another important energy-loss mechanism is photo-pair production, which is possible when the microwave background photon in the cosmic ray restframe is seen to have an energy in excess of $2m_e \approx 1$ MeV. The threshold Lorentz factor for this process is 10^9, and the energy for baryon number A is $E_{\rm pp} \approx 10^{18} A$ eV. The energy-loss rate is proportional to $Z^2 A^{-1} \propto Z$ for nuclei with $Z \approx A/2$, so this mechanism is significantly more important for nuclei such as iron than for protons [2].

Strangelets may exist in two possible varieties: Ordinary strangelets [4,5,10] and color-flavor locked strangelets [9]. Both types of objects consist of almost equal numbers of up, down, and strange quarks so that the quark charges nearly cancel. The stability of strangelets depends on the strong interaction binding (in phenomenological models characterized by quantities such as the bag constant and the one-gluon exchange coupling constant) and the quark masses (especially the heaviest, strange quark). Finite size effects (surface tension and curvature energy) generally decrease stability at low baryon numbers relative to bulk strange quark matter, though increased stability occurs near closed shells. Ordinary strangelets are stable for a restricted range of parameters, and if quark matter is in a color-flavor locked state, as seems to be the case at asymptotically high density [8], the stability is improved by a significant binding energy in Cooper pairs coupling quarks of different flavor and color quantum numbers.

Ordinary strangelets have charge $Z \approx 0.1A$ for $A \ll 150$ and $Z \approx 8A^{1/3}$ for $A \gg 150$ [10,11], and color-flavor locked strangelets have $Z \approx 0.3A^{2/3}$ [9]. In both cases, the charge is much smaller than that of nuclei of the same mass number, A, because strangelets have almost equal numbers of up, down, and strange quarks so that the quark charges nearly cancel. Strangelet masses can be very large (in principle as large as the baryon number of a gravitationally unstable strange star, $A_{\max} \approx 2 \times 10^{57}$), so the quark charge Z can reach values much higher than those known for nuclei. What is here called the "quark charge" is the total charge of the quark core of the strangelet. For color-flavor locked strangelets, this charge is contributed by quarks only, but ordinary strangelets with $A > 10^7$ contain a small electron fraction in weak equilibrium; this has not been self-consistently included in the charge-mass relation.

Like nuclei may bind electrons to form neutral atoms, so a charge Z strangelet may bind electrons and create a neutral atomlike system, but to be accelerated as ultrahigh energy cosmic rays, atoms or strangelets must be ionized. Whereas atoms can be fully ionized to the nuclear charge, strangelet core charges can be high enough that one has to worry about QED effects. Of relevance for the ultrahigh energy cosmic rays is not the total quark charge (as defined above), but rather the net screened charge when electrons from QED effects are taken into account. This screened charge is in practice the net charge available for electromagnetic acceleration and interaction of a relativistic cosmic ray. In quantum electrodynamics, the maximum unscreened point charge is $1/\alpha \approx 137$. For higher charge, electron-positron pairs are created in the vacuum, the positron leaving the system, but the electron remaining to screen the central positive charge. For extended systems such as nuclei, the maximum charge goes up in principle [12], but no stable high charge nuclei seem to exist.

Strangelets have a lower charge density than nuclei, and color-flavor locked strangelets have the charge located in a thin surface layer. This leads to the expectation that the importance of charge screening due to electrons formed by QED effects is less pronounced than for nuclei [10]. This has been confirmed by relativistic Thomas-Fermi model calculations (following a procedure similar to the one adopted for nuclei in [12]). For a given unscreened charge above a few hundred, the net screened charge is highest for ordinary strangelets with the lowest charge density, and lowest (i.e., most affected by screening) for nuclear matter which has the highest charge density. The effects for color-flavor locked strangelets are intermediate.

Results for the net unscreened and screened charge of nuclear matter and strangelets are shown in Fig, 1 as a function of baryon number, A. Screened charges of several thousand are easily reached, and there is no formal maximum charge, though the screened charge increases only slowly with unscreened charge for high Z.

Relativistic strangelets are expected to be maximally ionized, that is, to a net charge comparable to the one shown in Fig. 1. In contrast, nonrelativistic strangelets are expected to be charge neutral or have a small net charge. This is the reason why we mainly discuss relativistic strangelets in the present investigation. Nonrelativistic strangelets could also have kinetic energies in the range of interest (above 10^{20} eV) if their masses are sufficiently large. They would be harder to accelerate, but would avoid the GZK constraint by the same arguments discussed for relativistic strangelets. We note that a strangelet moving in the galactic gravitational potential with speed of order 300 km/sec would have kinetic energy in the interesting range if its baryon number were of order 10^{17} (corresponding to a mass of 0.1 microgram).

Comparing with nuclei, the strangelet properties discussed above lead to the following observations for relativistic strangelets.

(1) For astrophysical acceleration mechanisms limited by a maximum rigidity $R_{\max}$, strangelets can reach higher energies than nuclei, since $E_{\max} = ZR_{\max}$.

(2) The photopion and photodisintegration energy cutoff moves upward proportional to A, as $E \approx 5 \times 10^{18} A$ eV for the latter. Thus, high-mass strangelets are

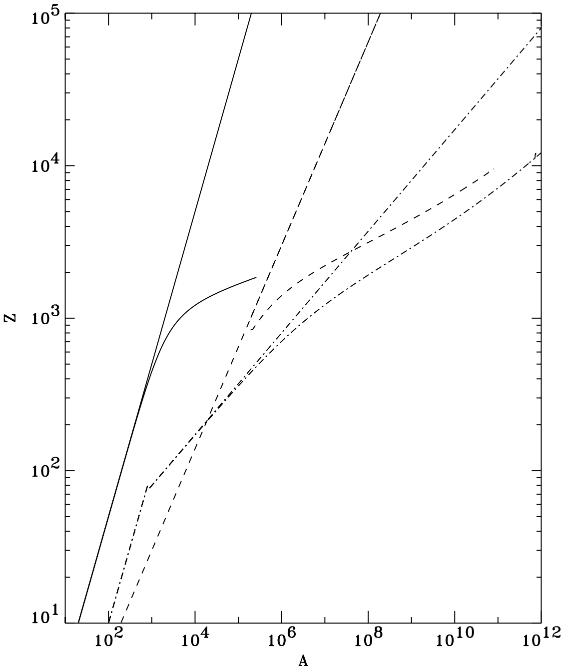

FIG. 1. Charge as a function of mass for nuclear matter (full curves), color-flavor locked strangelets (dashed curves), and ordinary strangelets (dash-dotted curves). In each case the upper curve shows the unscreened charge, whereas the lower curve is the net screened charge from relativistic Thomas-Fermi calculations including the supercritical vacuum.

not influenced by these processes at the energies of interest.

(3) Photopair production also sets in at energies that scale with A, and, furthermore, the energy-loss rate is proportional to Z^2A^{-1}, which is $\propto A \propto Z$ for nuclei, $\propto A^{1/3} \propto Z^{1/2}$ for color-flavor locked strangelets, and $\propto A^{-1/3} \propto Z^{-1}$ for ordinary strangelets, in all cases using the unscreened charge-mass relations, which significantly overestimate the relevant net charge of the system (cf. Fig. 1). Therefore, strangelets are much less susceptible to photopair energy loss than are nuclei.

(4) At a given energy, cosmic ray strangelets will be more isotropically distributed than protons and nuclei, since the radius of gyration (Larmor radius) in the galactic magnetic field ($B \approx 3\ \mu$G) is $r_{\rm gyro} = 36\ {\rm kpc}(E/10^{20}\ {\rm eV})(3\ \mu{\rm G}/B)Z^{-1}$ compared to a galactic radius of $r_{\rm gal} \approx 10$ kpc. Thus, low-Z nuclei and protons have $r_{\rm gyro} \approx r_{\rm gal}$, whereas higher-$Z$ strangelets have $r_{\rm gyro} < r_{\rm gal}$ and therefore appear to be more isotropically distributed (arrival directions do not point back to the source) for the energies of interest here, unless they originate from local sources. There is presently some discussion as to whether or not there is evidence for anisotropy in cosmic ray data at the highest energies [2], but this could be a distinctive feature for the strangelet scenario when higher statistics data emerge in the coming years.

(5) Extended air shower signatures [2] are consistent with primaries of ultrahigh energy cosmic rays being protons or ordinary nuclei. In contrast, more massive hadronic objects such as dust grains (which could have a high net charge) are inconsistent with air shower data if they contain more than a few thousand (probably even fewer) nucleons [13]. It is therefore legitimate to wonder why strangelets may avoid such limits. A detailed study of this would require simulations of strangelet cosmic ray air showers, but unfortunately a lot of the necessary interaction input physics is at best poorly known since strangelet studies have been performed only within simple phenomenological models. Estimates show that strangelets differ sufficiently from nuclei and dust to be viable candidates. Nuclei and dust grains colliding with atmospheric oxygen or nitrogen will rapidly fragment into their constituent nucleons. Each of these has roughly the original Lorentz factor, and therefore a kinetic energy lower by a factor A, so the shower starts higher in the atmosphere (because of a larger geometrical cross section of the primary) and develops more rapidly (because the particles have less energy to deposit) than for a proton of the same total kinetic energy. A strangelet may also start interacting high in the atmosphere, but the geometrical cross section may be a factor of a few smaller than expected for nuclear matter with similar A because the density of strange quark matter exceeds that of nuclear matter. This would cause mass A strangelets to interact similar to nuclei of significantly lower A, and therefore extend the range of compatibility with air shower data. Furthermore, strangelets may to some extent absorb and convert atmospheric nuclei into quark matter, and if and when they fragment, some of the fragments may themselves be strangelets with baryon numbers consistent with air shower data [14]. We consider it possible that the upper limit on A for low-mass strangelets consistent with the data could well be 10^4 or higher, but it depends on the input physics. Another window opens at higher A. Fragmentation of strangelets requires the total energy added in inelastic collisions with atmospheric nuclei to be at least of the order of the binding energy, which can be some tens of MeV per nucleon. The total column density of matter required for this [15] is $x \approx 4 \times 10^{-12} E_{B10} E_{20}^{-1} (\rho_s/\rho_n)^{2/3} A^{4/3}$, where x is measured in grams per cm^2, E_{B10} is the binding energy per baryon in units of 10 MeV, E_{20} is the cosmic ray kinetic energy in units of 10^{20} eV, and the factor $(\rho_s/\rho_n)^{2/3}$ takes into account that the strangelet cross section is smaller than that of nuclei because the strangelet density exceeds that of nuclei. Notice that strangelet cosmic rays will fragment easily for low A, but for $A > 10^{8-9}$ the critical column density becomes comparable to the fragmentation depth normally expected for nuclei, and in fact strangelets with $A \gtrsim 10^{11}$, that are only mildly relativistic at these energies, could penetrate to the surface without fragmentation ($x_{\rm surface} \approx 10^3$ g/cm^2). Furthermore, even if strangelets fragment, the shower development will be very different for fragmentation into A nucleons compared to fragmentation into low-mass strangelets.

Heavier, nonrelativistic strangelets would be able to reach the surface, and the detailed development of air showers would depend in a complicated manner on the electrostatic interactions of the strangelet plowing its way through the atmosphere in combination with the interactions of those hadrons and smaller strangelets, that would be formed in inelastic collisions. At the present level of understanding, we conclude that strangelets with mass up to or somewhat exceeding the limit for dust (maybe 10^4 baryons), and with $A > 10^{8-9}$ could be consistent with air shower observations, but that intermediate masses may also be consistent if fragmentation preferentially leads to formation of low-mass strangelets rather than nucleons.

Needless to say, many details that are beyond the scope of this investigation must be considered to decide if strangelets really are the ultrahigh energy cosmic rays beyond the GZK cutoff. Strangelet physics has thus far been studied only in phenomenological models such as the MIT bag model, so the understanding of strangelet stability, the strangelet charge-mass relationship, strangelet disintegration, etc., are all at a very crude level. However, the general features of importance for the present investigation, namely, the possibility of high strangelet mass and charge, but low charge-to-mass ratio, seem robust. Details of the origin and propagation of cosmic ray strangelets need further study [16], and the signature of ultrahigh energy strangelet air showers should be simulated and compared to the observations of cosmic ray air showers at the highest energies, though such simulations will be marred by the uncertainties in the underlying strangelet physics. Sources of cosmic strangelets could be strange star collisions in binary systems, supernova explosions, or perhaps gamma ray bursts, and acceleration could take place in these and other suggested cosmic ray engines but, again, many details remain to be studied.

But in spite of these issues we conclude, based on the present understanding of strangelet physics, that strangelets are interesting candidates for ultrahigh energy cosmic rays beyond the GZK cutoff. They have properties which circumvent both the acceleration problem and the energy-loss problems facing more mundane candidates such as protons and nuclei. A crucial test of the suggestion would be a direct measurement of the charge and/or mass of ultrahigh energy cosmic ray primaries. A search for cosmic ray strangelets at much lower energies will take place with the AMS-02 experiment on the International Space Station starting in 2005.

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