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Ultra High Energy Cosmic Rays: Strangelets? *

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The conjecture that ultra-high-energy cosmic rays (UHECRs) are actually strangelets is discussed. Besides the reason that strangelets can do as cosmic rays beyond the Greisen–Zatsepin–Kuzmin-cutoff, another argument to support the conjecture is addressed by the study of formation of TeV-scale microscopic black holes when UHECRs bombarding bare strange stars. It is proposed that the exotic quark surface of a bare strange star could be an effective astro-laboratory in the investigations of the extra dimensions and of the detection of ultra-high-energy neutrino fluxes. The flux of neutrinos (and other point-like particles) with energy larger than 2.3×10^{20} *eV could be expected to be smaller than* 10^{-26} *cm*$^{-2}$ *s*$^{-1}$ *if there are two extra spatial dimensions.*

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There are two puzzles in modern physics and astrophysics at least: what is the nature of ultra-high-energy cosmic rays (UHECRs)? Does strange (quark) matter exist? These two questions might be understood by offering a simple suggestion that UHECRs are actually strange matter, which does not conflict with the study of extra dimensions.

The UHECRs[1] detected with energy as high as 3×10^{20} eV cannot be usual cosmic rays (protons, nuclei) due to the Greisen–Zatsepin–Kuzmin (GZK) cutoff, and can also not be photons since photon–photon pair production can significantly loss the energy. Up to date, Various ideas have been appeared in literature to address the observations, including decaying of topological defects, and violation of the Lorentz invariance, etc. However, the more realistic candidates, within the framework of the standard model of particle physics, are neutrinos[2] and strangelets,[3] both of which are basically unaffected by the GZK-cutoff. Madsen and Larsen[3] suggested that UHECRs are strangelets (stable lumps of strange matter) since strangelets can have high mass (circumventing the GZK-cutoff) and charge (being helpful for acceleration) but low charge-to-mass ratio. In addition, many detected events (e.g., the Centauro events) of cosmic ray experiments were suggested to be strangelet-originated.[4] It is necessary and difficult to carried out the detailed Monte Carlo simulation of strangelet shower development, which is certainly important to obtain a certain conclusion. Actually the propagation of strangelets through the terrestrial atmosphere is considered,[5−7] by which some exotic cosmic ray events may be explained. If UHECRs are strangelets, they are very probably not neutrinos since no Greisen neutrinos (through the interaction of UHECRs with the cosmic microwave background) may be produced.

It is of fundamental importance to study strange matter in physics and astrophysics.[8] Strange matter may exist if the Bodmer–Witten conjecture is correct, while the most essential thing is how to find convincing evidence in laboratory physics and/or astrophysics. Previously it is a common opinion that strange stars are crusted, but this concept was criticized by Xu and Qiao,[9,10] who addressed that *bare* strange stars (BSSs, i.e., strange stars without crusts) chosen as the interior of pulsars have advantages. Up to now, there is actually possible evidence for BSSs:[10] drifting sub-pulses of radio pulsars, featureless thermal spectrum of compact stars, and super-Eddington luminosity of soft γ-ray repeaters. Besides being helpful to identify strange stars, the bare quark surface can be valuable in the study of the formation of TeV-scale black holes. Such miniature black hole formation is another astrophysical consequence of BSSs, and here we try to demonstrate that neutrinos as the candidates of UHECRs can also be excluded at least in the case of two extra dimensions.

A TeV-scale black hole is an addition to the old black hole family (primordial black hole, stellar black hole, and supermassive black hole). Recently, a great deal of attention is paid to the possibility that our space has more than three dimensions,[11,12] especially after Arkani-Hamed *et al.*[13,14] suggested that the compactified extra dimensions could be as large as $\sim 1\,\mathrm{mm}$. It is well known that the Plank scale is $M_{\rm pl} = \sqrt{\hbar c/G} \simeq 1.2\times10^{19}\,\mathrm{GeV}/c^2$ ($\hbar$ if the Plank constant, c is the speed of light, and G is the Newtonian gravitational constant), but $M_{\rm pl}$ may be meaningless if the space of our universe is actually of $D = 3+n$ dimensions, with n extra spatial dimensions. The fundamental gravity scale M_* for D spatial dimensions is then

$$M_*^{n+2} \simeq \left(\frac{\hbar}{c}\right)^n M_{\rm pl}^2 R^{-n}, \tag{1}$$

if the n-dimensional extra space is flat and is compact with radii of the order of R. Arkani-Hamed *et al.*[13]

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assume $M_* \sim 1\,\mathrm{TeV}$ in order to solve the hierarchy problem of the standard model, i.e., the problem why there exists such a large "desert" between the electroweak scale (of the order of $M_{\mathrm{EW}} \sim 1\,\mathrm{TeV}$) and the Plank scale ($M_{\mathrm{pl}} \sim 10^{16}\,\mathrm{TeV}$). One can obtain $R \simeq (\hbar/M_* c)(M_{\mathrm{pl}}/M_*)^{2/n}$ from Eq. (1). The extra dimensions should be $n \geq 2$, because of $R = 2.8 \times 10^{15}\,\mathrm{cm}$ for $n = 1$ which is in conflict with the observations.

In the string theory, the extra dimensions can be as large as $n = 7$, we thus list the compact radii in the case of $M_* = 1\,\mathrm{TeV}$ for indications: $R = 0.24\,\mathrm{cm}$ for $n = 2$, $R = 1.0 \times 10^{-6}\,\mathrm{cm}$ for $n = 3$, $R = 2.2 \times 10^{-9}\,\mathrm{cm}$ for $n = 4$, $R = 5.3 \times 10^{-11}\,\mathrm{cm}$ for $n = 5$, $R = 4.5 \times 10^{-12}\,\mathrm{cm}$ for $n = 6$, and $R = 7.8 \times 10^{-13}\,\mathrm{cm}$ for $n = 7$. Only black holes with mass $M > M_*$ may be expected to form since many unknown quantum gravity effects (e.g., the string excitations) could play important role for $M < M_*$. The Schwarzschild radius for a spatial D-dimensional, neutral, non-rotating black hole with mass M_{BH} is[15]

$$r_{\mathrm{s}} = \frac{\hbar}{\sqrt{\pi} c M_*}\left[\frac{M_{\mathrm{BH}}}{M_*}\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right]^{1/n+1}. \qquad (2)$$

For TeV-scale black holes, $M_{\mathrm{BH}} \sim M_* \sim 1\,\mathrm{TeV}$, one has $r_{\mathrm{s}} \sim (1.54, 1.49, 1.50, 1.54, 1.58, 1.63) \times 10^{-17}\,\mathrm{cm}$ for $n = 2, 3, 4, 5, 6, 7$, respectively.

It is found that R is much larger than r_{s}.

If UHECRs with energy $\gtrsim 10^{19}\,\mathrm{eV}$ are structureless point-like particles in the standard model, miniature black holes may form when they bombard BSSs.[16]

Without loss of generality, let us assume that UHECRs are neutrinos, then we have the following discussion.

When such a neutrino with energy E_ν interacts with a quark with mass m_{q} in a BSS, a TeV-scale black hole may form if the centre-of-mass energy $E_{\mathrm{cm}} = \sqrt{2c^2 m_{\mathrm{q}} E_\nu} > M_* \sim 1\,\mathrm{TeV}$ and the interaction is within a scale of $\sim r_{\mathrm{s}}$ ($M_{\mathrm{BH}}c^2 \sim E_{\mathrm{cm}}$).

As the neutrino and the quark are extremely close, with a scale of R, they may feel extra dimensions by much strong gravitational interaction since gravitons can propagate in bulk although most of the other particles are in brane only.

Once a TeV-scale miniature black hole forms, it decays,[16,17] radiating thermally, over a surface area A, at the Hawking temperature T_{H},

$$A = r_{\mathrm{s}}^{n+2} \cdot \frac{2\pi^{(n+3)/2}}{\Gamma(\frac{n+3}{2})},$$

$$T_{\mathrm{H}}(M_{\mathrm{BH}}) = \frac{\hbar c}{k} \cdot \frac{n+1}{4\pi r_{\mathrm{s}}}, \qquad (3)$$

where k is the Boltzmann constant, unless T_{H} is small enough,[16]

$$T_{\mathrm{H}}(E_{\mathrm{cm}}/c^2) < T_{\mathrm{eff}} \equiv T_{\mathrm{F}}\sqrt{\gamma}[1 + (1 - \gamma^{-2})/3]^{1/4}, \quad (4)$$

where T_{F} is the Fermi temperature of quarks, and $\gamma = (E_\nu + m_{\mathrm{q}}c^2)/E_{\mathrm{cm}}$ is the Lorentz factor of the newborn miniature black hole after the initial collision.

The initially produced hole increases mass by absorption of another particle if Eq. (4) is satisfied, and will continue to accrete to a mass of E_ν, in a scale ($\sim 0.1\,\mathrm{mm}$) being much smaller than the radius of a BSS, before it stops[16] (i.e., with $\gamma = 1$).

At this time, the miniature black hole causes eventually a catastrophic collapse of all of the BSS into a stellar black hole if $T_{\mathrm{H}}(E_\nu/c^2) < T_{\mathrm{F}}$. Therefore, neutrino-induced collapse of BSSs requires both $T_{\mathrm{H}}(E_{\mathrm{cm}}/c^2) < T_{\mathrm{eff}}$ and $T_{\mathrm{H}}(E_\nu/c^2) < T_{\mathrm{F}}$.

We calculated for these two requirements by choosing $M_* = 1\,\mathrm{TeV}$, $T_{\mathrm{F}} = 0.5\,\mathrm{GeV}$, and $m_{\mathrm{q}} = m_{\mathrm{s}} = 200\,\mathrm{MeV}$ (m_{s} is the current mass of strange quark). The results are shown in Fig. 1.

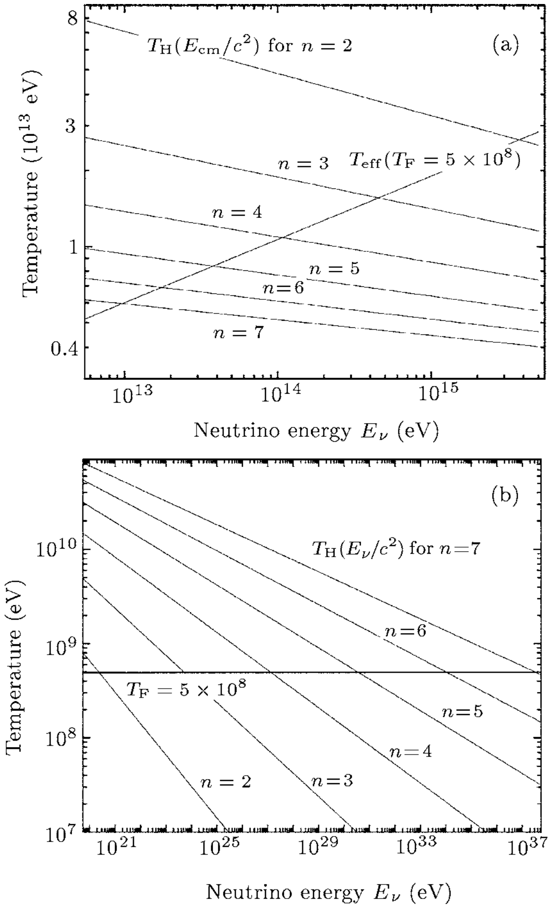

Fig. 1. Black hole temperature (T_{H}) and environment temperature (T_{eff} and T_{F}) versus neutrino energy (E_ν). (a) A TeV-scale black hole can form if $T_{\mathrm{H}}(E_{\mathrm{cm}}/c^2) < T_{\mathrm{eff}}$, through an initial collision between the neutrino and a quark. (b) The whole BSS may collapse into a stellar black hole if $T_{\mathrm{H}}(E_\nu/c^2) < T_{\mathrm{F}}$ by effective accretion. In the calculation, we take $M_* = 1\,\mathrm{TeV}$, $T_{\mathrm{F}} = 0.5\,\mathrm{GeV}$, and $m_{\mathrm{q}} = m_{\mathrm{s}} = 200\,\mathrm{MeV}$.

It is found that, for n from 2 to 7, the neutrino energy at which $T_{\mathrm{H}}(E_{\mathrm{cm}}/c^2) < T_{\mathrm{eff}}$ is fulfilled is much lower than that at which $T_{\rm H}(E_\nu/c^2) < T_{\rm F}$ is satisfied.

This means that it is easier for an ultra-high-energy neutrino to trigger the formation of a TeV-scale black hole which may eventually decay by Hawking radiation, whereas neutrino-induced collapse of the whole star into a stellar black hole needs much higher E_ν.

Therefore, one can follow a scenario for a neutrino with $E_\nu > (10^{13} \sim 10^{15})$ eV when it collides a BSS: it either leads formation of a TeV-scale black hole which evaporates soon, or results in a collapse of the BSS into a stellar black hole if E_ν is high enough.

However, for such a neutrino bombarding a neutron star or a crusted strange star, only a TeV-scale black hole with substantial Hawking radiation can be created and the formation of a stellar black hole is impossible, since the mean free length ($\sim \rho r_{\rm s}^2/m_{\rm u} \sim$ 1 cm, with the outer-crust density $\rho \sim 10^{10}$ g/cm^3 and the atomic mass unit $m_{\rm u}$) of the black hole production is much smaller than the thickness (~ 0.5 km) of the crusts.[16]

It is worth noting that the extra dimensions are supposed to be flat in the above calculations. A study of warped extra dimensions, as in the model of Randal & Sundrum, is necessary, which may results in the suppression of black hole growth.[19]

The exotic quark surface of a bare strange star could thus be an effective astro-laboratory in the investigations of the extra dimensions and of the detection of ultra-high-energy neutrino fluxes.

Generally, the age of BSSs should be greater than $10^{7\sim 9}$ year if BSSs are the nature of pulsars. This gives a limit of neutrino flux smaller than 10^{-26} cm^{-2} s^{-1} for $\{E_\nu > 2.3\times 10^{20}\,{\rm eV}, n=2\}$ ($\{E_\nu > 5.1\times 10^{23}\,{\rm eV}, n=3\}$, $\{E_\nu > 1.3\times 10^{27}\,{\rm eV}, n=4\}$, $\{E_\nu > 3.5\times 10^{30}\,{\rm eV}, n=5\}$, $\{E_\nu > 1.0\times 10^{34}\,{\rm eV}, n=6\}$, $\{E_\nu > 3.2\times 10^{37}\,{\rm eV}, n=7\}$), based on Fig. 1(b).

This upper limit is in conflict with the observation of $n=2$, and the UHECRs events with the energy of $\gtrsim 10^{20}$ eV motivated Gorham *et al.*[16] to address that $n=2$ is excluded. Nonetheless, because of the advantages[3] of strangelets as UHECRs (Firstly, higher electric charge is helpful to accelerate to much higher energy. Secondly, more massive strangelets can easily go beyond the GZK-cutoff), one cannot simply ruled out $n=2$.

If our universe has really two extra dimensions, the observed events may, in fact, be a hint of UHECRs being strangelets (rather than structureless particles, e.g., neutrinos), since increasing possible evidence for BSSs appears.[10]

Furthermore, if one can identify astrophysical events, with rate of $\mathcal{R}_{\rm BSS\to BH}$, of neutrino-induced collapse of BSSs to black holes in the future, we could obtain the observational constrain on the extra dimensions by combining the studies of the neutrino spectrum (if being known) and of $\mathcal{R}_{\rm BSS\to BH}$.

It is worth noting that, if the recently discovered UHECRs with energy $\sim 10^{20}$ eV are actually strangelets, no TeV-scale black hole may be found in the future neutrino Detectors,[20] (e.g., ICECUBE, RICE) at least the event numbers would be much smaller than that expected previously.[2]

We note here that Kravchenko *et al.*[21] have not found an actually clear event of ultra-high-energy neutrino interacting with ice by analysing the date from the RICE antenna array, but put only upper limits on the flux of such neutrinos, which could be significantly smaller than the results of Fly's Eye and AGASA (see Fig. 8 in Ref. [21]).

What is the astrophysical origin of strangelets with ultra-high-energy?

One possibility of the creation is during supernova exploration since strangelets produced at a very early history of the Universe would have evaporated for a long time.[22] However, few theoretical works are carried out to explain the strangelet production in this way, including the mass distribution of strangelets ejected from a protostrange star and the full emerging spectrum in mass-energy after the strangelets pass through the expanding shell.[23]

Strong magnetic field ($\sim 10^{12}$ G) is created soon,[24] and a strangelet with baryon number $A \sim 10^9$ can be accelerated to $\sim 10^{20}$ eV in the unipolar induced electric field ($\sim 6\times 10^{16}/P_{10}^2$ volts, with P_{10} the initial rotation period in 10 ms, $P_{10} \sim 1$) if the strangelet have charge[3] $Z \simeq 8A^{1/3}$ and is almost totally ionized.

The Lorentz factor of a strangelet with baryon $A \sim 10^9$ and energy $\sim 10^{20}$ eV is only $\gamma \sim 10^2$, and the radiative energy losses proposed[25] is thus negligible because of high baryon numbers (the radiation efficiency is proportional to $(Z/A)^2 \sim A^{-2/3}$).

The energy per quark in such a strangelet is only $\sim 10^{11}$ eV, which is too low to trigger the formation of a TeV-scale black hole.

There are some other astrophysical indications of strange matter ejected during supernova explorations. For example, pulsar planets were discovered[26] but their astrophysical origin is unknown with certainty.[27] An alternative and simple suggestion is that they are, in fact, strange (matter) objects which were ejected with a velocity being smaller than the escaping velocity from stellar surface and then fell back to planet orbits.

Strange objects with mass much smaller than planet one, in a fossil disc formed after supernova exploration, may sometimes accrete on to the centre star as accretion flow falls toward the star. If the star is a BSS, the gravitational energy release in this process may trigger an extremely super-Eddington burst, such as the one observed in soft γ-ray repeaters (SGRs).

As is addressed in the literature,[28,29] it may be natural to explain the burst with peak luminosity $\sim 10^7$ times of the Eddington one, and the light curves in a framework that a comet-like object falls to a BSS.

We propose that these comet-like objects are actually strange objects. For such an object with $\sim 10^{24}$ g, its radius is $\sim 10^8$ cm if its density $\sim 1\,\mathrm{g/cm^3}$, but is only ~ 10 m if it is a strange object. As is well know, pulsar-like stars have a typical radius $\sim 10^6$ cm, because of the strong tide effect near the star, the comet-like objects cannot be composed of water, dust, or other ordinary matter, but of strange matter.

In addition, the gravitational microlensing study reports the objects with much low mass,[30] which may also be composed of strange matter.

References

[1] Wu F and Xu R X 2002 *Prog. Astron.* (at press) (in Chinese)

[2] Feng J L and Shapere A D 2002 *Phys. Rev. Lett.* **88** 021303

[3] Madsen J and Larsen J M 2002 *Preprint* astro-ph/0211597

[4] Wilk G and Wlodarczyk Z 1996 *J. Phys. G: Nucl. Part. Phys.* **22** L105

[5] Banerjee S, Ghosh S K, Raha S and Syam D 1999 *J. Phys. G: Nucl. Part. Phys.* **25** L15 (nucl-th/9811004)

[6] Banerjee S, Ghosh S K, Raha S and Syam D 2000 *Phys. Rev. Lett.* **85** 1384 (hep-ph/0006286)

[7] Banerjee S, Ghosh S K, Mazumdar A, Raha S and Syam D 2000 *Astrophys. Space Sci.* **274** 655 (astro-ph/0006354)

[8] Xu R X 2002 *High Energy Processes, Phenomena in Astrophysics* ed Li X D, Wang Z R and Trimble V (at press) (astro-ph/0211348)

[9] Xu R X and Qiao G J 1998 *Chin. Phys. Lett.* **15** 934 (astro-ph/9811197)

[10] Xu R X 2002 *The 6th Pacific Rim Conf. on Steller Astrophysics* ed Cheng K S, Leung K C and Li T P (at press) (astro-ph/0211563)

[11] Rubakov V A 2001 *Phys. Usp.* **44** 871

[12] Landsberg G 2002 *Preprint* hep-ph/0211043

[13] Arkani-Hamed N, Dimopoulos S and Dvali G 1998 *Phys. Lett.* B **429** 263

[14] Antoniadis I, Arkani-Hamed N, Dimopoulos S and Dvali G 1998 *Phys. Lett.* B **436** 257

[15] Argyres P C, Dimopoulos S and March-Russell J 1998 *Phys. Lett.* B **441** 96

[16] Gorham P, Learned J and Lehtinen N 2002 *Preprint* astro-ph/0205170

[17] Tu H 2002 *Preprint* hep-ph/0205024

[18] Wu S Q and Cai X 2001 *Chin. Phys. Lett.* **18** 485

[19] Fairbairn M and Elewyck V V 2002 *Preprint* hep-ph/0206257

[20] Halzen F and Hooper D 2002 *Rept. Prog. Phys.* **65** 1025 (astro-ph/0204527)

[21] Kravchenko I et al 2002 *Astropart. Phys.* (submitted) (astro-ph/0206371)

[22] Alcock C and Farhi E 1985 *Phys. Rev.* D **32** 1273

[23] Vucetich H and Horvath J E 1998 *Phys. Rev.* D **57** 5959

[24] Xu R X and Busse F H 2001 *Astron. Astrophys.* **371** 963

[25] Medvedev M V 2003 *Phys. Rev.* E (at press) (astro-ph/0303271)

[26] Wolszczan A and Frail D A 1992 *Nature* **355** 145

[27] Miller M C and Hamilton D P 2001 *Astrophys. J.* **550** 863

[28] Zhang B, Xu R X and Qiao G J 2000 *Astrophys. J.* **545** L127

[29] Usov V V 2001 *Phys. Rev. Lett.* **87** 021101

[30] Sahu K C et al 2001 *Nature* **411** 1022