Prospects for strangelet detection with large-scale cosmic ray observatories

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Quark matter which contains s-quarks in addition to u- and d- could be stable or metastable. In this case, lumps made of this strange matter, called strangelets, could occasionally hit the Earth. When travelling through the atmosphere they would behave not dissimilar to usual high-velocity meteors with only exception that, eventually, strangelets reach the surface. As these encounters are expected to be extremely rare events, very large exposure is needed for their observation. Fluorescence detectors utilized in large ultra-high energy cosmic ray observatories, such as the Pierre Auger observatory and the Telescope Array are well suited for a task of the detection of these events. The flux limits that can be obtained with the Telescope Array fluorescence detectors could be as low as $5 \times 10^{-22} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ which would improve by 1.5 orders of magnitude the strongest present limits obtained from ancient mica crystals.

1. Introduction.

True ground state of nuclear matter could be realized in ultra-dense lumps consisting of u-, d-, s- quarks, so-called “strange” matter [1, 2]. Though properties of this phase of matter is not exactly known, calculations show that these lumps could be stable in extremely wide range of baryon numbers $A$: $O(1) < A < 10^{57}$. When these clumps are of stellar masses they are usually called ‘strange stars’, whereas somewhat lighter clumps are dubbed strangelets. Strangelets could have been produced in the very early Universe, though only the most massive ones could survive to the present time. The compact objects akin to neutron stars could be ‘strangelet factories’ now: some collapsing objects could convert usual neutron star into a strange one (see below). Some compact binaries, coalescing less than in the Hubble time, could eject up to $0.1 \, M_\odot$ at the final stage of merging, if some of these stars had been strange, the ISM would be thoroughly polluted with strangelets [3, 4]. Also, the strangelets could possibly be created in the heavy-ion collision experiments, and because of that they sometimes emerge in some ‘Doomsday scenarios’ [5]. Strangelet cores themselves have much smaller $Z/A$ than normal nuclei. Core charge is neutralized by leptonic cloud surrounding it, and when the baryon number begin to grow, then after the threshold $A_0 \sim 10^{15}$ the core size exceeds the cloud size and the core engulfs the leptons. Regardless the baryon number strangelets are neutral to outside observers. Strangelets could interact with the normal matter in two different ways: if the core charge is positive then the repulsive forces acting on normal nuclei allow only collisions. This barrier, however, is absent if the core charge is negative – in this case colliding normal nuclei would be converted to strange matter with simultaneous release of large amount of energy. There is no potential barrier for neutron-strangelet interaction, that is why neutron stars could serve as perfect detectors for presence of strangelets in the Galaxy.

Strangelets impinging on the Earth could manifest themselves in different ways [6]: energy that is deposited during their passage through medium could be detected in a host of experiments [7, 8, 9, 10, 11]. Alternatively, huge exposure of ancient ($\sim 10^9$ years) mica crystal [12] or meteorites [13] could be used. These methods allows to constrain flux of the strangelets in a broad range of their masses.

In this paper it is suggested to constrain the strangelet flux using observations of the fluorescence detectors of large cosmic-ray experiments such as the Pierre Auger observatory (PAO) [14] and the Telescope Array(TA) [15]. Massive strangelets traversing the atmosphere would emit prodigious amount of light [6] which in turn could be detected using fluorescence detectors [16]. Large exposure of these instruments could allow one to obtain competitive constraints on the flux of strangelets.

2. Prospects for observations.
Strangelets are small objects with a density slightly exceeding the nuclear one \cite{17}:
\[
    \rho_s = 3.6 \times 10^{14} \text{g cm}^{-3}.
\]  
\[\text{(1)}\]
As stated above, their intrinsic charge is neutralized by leptons. For small strangelets \(A < 10^{15} \ (m < 1.5 \text{ ng})\) this cloud has a fixed radius \(r_0 \sim 10^{-8} \text{ cm}\) that is close to the size of usual atoms. For more massive strangelets their neutralizing leptons are hidden inside their cores and their radii begin to grow with the mass:
\[
    r(M) = \left( \frac{3M}{4\pi \rho_s} \right)^{1/3}.
\]  
\[\text{(2)}\]
As a strangelet passes through the Earth’s atmosphere it losses its energy through the collisions with the atmosphere nuclei
\[
    dE/dx = -\rho \sigma v^2,
\]  
\[\text{(3)}\]
where \(\rho\) is the air density, \(\sigma = \pi v^2\) is the cross section and \(v\) is the velocity of the strangelet. As it would be shown below, only the massive strangelets \((A > 10^{20})\) are objects of the primary interest for the proposed approach. Such objects lose negligible fraction of their kinetic energy when travelling through the atmosphere thus \(v\) could be regarded as a constant and the total energy loss \(\Delta E\) could be straightforwardly calculated:
\[
    \Delta E = \sigma X_{\text{atm}} v^2 ,
\]  
\[\text{(4)}\]
where \(X = \int \rho dx\) is the column density of the atmosphere, \(X_{\text{atm}} \sim 1000 \text{ g cm}^{-2}\).

These estimates of the energy loss are the lower limits – if there are some additional contributions to it the loss rate would be higher and the constraints could be pushed to smaller cross-sections/masses. This technique is also applicable to many other exotic candidates such as Q-balls\cite{18} or antiquark nuggets \cite{19, 20}, where additional contributions to the loss rate could come from catalysis of baryon decay or annihilation. The upper limits on the energy loss could be estimated as \(\sim \sigma X c^2\) and could be larger than ones given by Eq\[4\] by 6 orders of magnitude (assuming for the strangelets typical galactic velocities \(v \sim 300 \text{ km s}^{-1}\)). In sharp difference with the case where the energy loss proceeds through collisions only, a strong emission of high energy particles is expected and that makes possible to detect these objects not only with the fluorescence but with the surface detectors of ultra-high energy cosmic rays (UHECR) observatories as well \cite{19}. The concrete estimate of the projected sensitivity of the technique was done with respect to the Telescope Array. TA is the largest in the Northern hemisphere UHECR detector located in Utah, USA which has been fully operational since March 2008. It consists of 507 scintillator detectors covering the area of approximately 700 km\(^2\) \cite{21}. 38 fluorescence telescopes arranged in 3 stations overview the atmosphere over the surface array \cite{15}. The basic idea of the fluorescence observations is rather simple: particles in the electromagnetic component of a shower caused by a UHECR excite nitrogen molecules. These molecules emit UV-light in the wavelength range 300-400 nm when de-excited, and this light could be detected on the ground, thus allowing to observe the shower profile. Though only a minor part \((10^{-4} – 10^{-3})\) of the initial energy of the UHECR goes into the fluorescence, this method allows to detect particles with energies \(> 10^{18} \text{ eV}\) at distances larger than 30 km.

The crucial part of the problem is the threshold mass of the strangelets that could be detected with this technique. It could be roughly estimated as the mass of the strangelet that produces the same amount of radiation as an \(E_0 = 10^{18} \text{ eV}\) UHECR. Energy dissipation in strangelet’s case is very close to meteor’s, though such processes as ablation are understandably absent. It was shown that luminous effectiveness of meteors lies in \(10^{-2} – 10^{-1}\) range, depending on velocity and composition of meteors \cite{22}. Note that it is the \textit{bolometric} effectiveness, and because fluorescence detectors observe in a quite narrow band 300-400 nm, it should be scaled down. As this band resides close to the maximum of the Planck’s distribution for temperatures of \(\sim\) several eV which are typical for these phenomenae it is robust to use \(10^{-2}\) as the rescaling factor. So it could be adopted that both UHECRs and strangelets have the same luminosity effectiveness, \(10^{-4}\) in the relevant passband.

Then, the threshold radius \(r_0\) and mass \(M_0\) would be defined as follows
\[
    r_0 = \left( \frac{E_0}{\pi X_{\text{atm}} v^2} \right)^{1/2} = 8 \times 10^{-7} \left( \frac{300 \text{ km s}^{-1}}{v} \right) \text{ cm}
\]  
\[\text{(5)}\]
\[
    M_0 = \frac{4\pi \rho_s r_0^3}{3} = \frac{4\rho_s}{3\sqrt{\pi}} \left( \frac{E_0}{\pi X_{\text{atm}} v^2} \right)^{3/2} = 6 \times 10^{-4} \left( \frac{300 \text{ km s}^{-1}}{v} \right)^3 \text{ g}
\]  
\[\text{(6)}\]

The threshold was set at \(m_0 = 6 \times 10^{-4} \text{ g} \sim 4 \times 10^{20} \text{ GeV}/c^2\) and all derived limits are applicable to strangelets with larger masses. It is worth noting that at masses \(M > 9\pi X_{\text{Earth}}/16\rho_s^2 \sim 10 \text{ g} \ (A \sim 10^{25})\), where \(X_{\text{Earth}} = 10^{16} \text{ g cm}^{-2}\) is the column density of the Earth, strangelets begin to travel through the Earth.
almost unimpeded and the corresponding field of view of the detectors approaches $4\pi$. Also, for more massive strangelets corresponding effective area grows significantly, by factor 5 for $A > 10^{23}$ (equivalent to a cosmic ray with the energy $\sim 10^{19.5}$ eV).

The TA fluorescence detectors are adapted for the observations of the UHECRs which travel at the speed of light: they are triggered if there is a signal in $\geq 5$ adjacent photo-multiplier tubes (PMT) in 25.6 $\mu$s time window, each PMT having a field of view $\sim 1^\circ$ [24]. Strangelets are supposed to travel with non-relativistic velocities, $v \sim 10^{-3}c$, so they cannot trigger the instrument by themselves. However, in addition to instant radiation from the strangelet one would expect bright meteor-like wake radiation, that lasts $10^{-3} - 10^{-1}$ s [22]. This wake emission would be observed as short trail after the strangelet and would trigger the detectors.

The limits on the flux of the strangelets that could be potentially detected with this technique could be readily estimated.

$$\Phi \sim \frac{1}{2\pi A t} = 5 \times 10^{-22} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (7)$$

where $A \sim 10^3$ km$^2$ is the effective area of TA FD at energies $10^{18}$ eV [23], and $t = 3 \times 10^7$ s is the total duration of the observations taking into account their 10 – 12\% duty cycle.

It should be mentioned that the data from the fluorescence detectors of the PAO [14] could be used in this technique as well and that could lead to even deeper limits, taking into account longer duration of observations and the effective area of the FD detectors that is larger by factor 2.

Finally, though there is a possibility that there exist meteors moving with 'galactic' velocities [24], strangelets could be fairly easily distinguished from them using difference in their trail profiles: usual meteor-like wake radiation, that lasts $10^{-3} - 10^{-1}$ s [22].

## 3. Conclusions

The proposed technique could be used to constrain flux of strangelets (also, Q-balls of the strong interacting variety, antiquark nuggets and related exotica) impinging upon the Earth. For strangelets with baryon number $A > 4 \times 10^{20}$ it is possible to reach limit of $\Phi \sim 5 \times 10^{-22} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, the limits are stronger by an order of magnitude for $A > 10^{25}$. These limits would improve by 1.5 (2.5) orders of magnitude the strongest present ones obtained from ancient mica crystals.

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1. A. R. Bodmer, Phys. Rev. D 4, 1601 (1971).
2. E. Witten, Phys. Rev. D 30, 272 (1984).
3. J. Madsen, Lect. Notes Phys. 516, 162 (1999) astro-ph/9809032.
4. J. Madsen, astro-ph/0612740.
5. A. Dar, A. De Rujula and U. W. Heinz, Phys. Lett. B 470, 142 (1999) hep-ph/9910471.
6. A. De Rujula and S. L. Glashow, Nature 312, 734 (1984).
7. I. A. Belolaptikov et al., astro-ph/9802223.
8. E. N. Alekseev, M. Boliev, A. E. Chudakov, B. A. Makoev, S. P. Mikheev and Y. V. Stenkin, Lett. Nuovo Cim. 35, 413 (1982).
9. M. Ambrosio et al. [MACRO Collaboration], Eur. Phys. J. C 13, 453 (2000) hep-ex/9904031.
10. S. Cecchini et al. [SLIM Collaboration], Eur. Phys. J. C 57, 525 (2008) arXiv:0805.1797 [hep-ex].
11. V. Van Elewyck [ANTARES Collaboration], Nucl. Instrum. Meth. A 742, 63 (2014) arXiv:1311.7002 [astro-ph.HE].
12. P. B. Price and M. H. Salamon, Phys. Rev. Lett. 56, 1226 (1986).
13. A. B. Alexandrov et al., Meteoritics and Planetary Science Supplement 76, 5265 (2013).
14. L. Prado, B. R. Dawson, S. Petrera, R. C. Shellard, M. G. do Amaral, R. Caruso, R. Sato and J. A. Bellido, Nucl. Instrum. Meth. A 545, 632 (2005).
15. H. Tokuno et al., Nucl. Instrum. Meth. A 676, 54 (2012) arXiv:1201.0002 [astro-ph.IM].
16. M. Bertains, A. Cellino, F. Ronga., Experimental Astronomy, 10.1007/s10686-014-9375-4 (2014)
17. S. A. Chin and A. K. Kerman, Phys. Rev. Lett. 43, 1292 (1979).
18. A. Kusenko, V. Kuzmin, M. E. Shaposhnikov and P. G. Tinyakov, Phys. Rev. Lett. 80, 3185 (1998) hep-ph/9712212.
19. K. Lawson, Phys. Rev. D 83, 103520 (2011) arXiv:1011.3288 [astro-ph.HE].
20. P. W. Gorham, Phys. Rev. D 86, 123005 (2012) arXiv:1208.3697 [astro-ph.CO].
21. T. Abu-Zayyad et al. [Telescope Array Collaboration], Nucl. Instrum. Meth. A 689, 87 (2012) arXiv:1201.4964 [astro-ph.IM].
22. Z. Ceflecha et al., Space Sci. Rev. 84, 327 (1998)
23. Y. Tameda et al., Nucl. Instrum. Meth. A 609, 227 (2009).
24. V. L. Afanasiev, V. V. Kalenichenko and I. D. Karachentsev, Astrophys. Bull. 62, 301 (2007) arXiv:0712.1571 [astro-ph].