IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **34** (2007) 597–605 doi:10.1088/0954-3899/34/3/017

Propagation of strangelets in the Earth's atmosphere

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Received 26 October 2006
Published 12 February 2007
Online at stacks.iop.org/JPhysG/34/597

Abstract

A new model for the description of the behaviour of strangelets in the Earth's atmosphere is presented. Strangelet fission induced by collision with air nuclei is included. It is shown that strangelets with certain parameters of initial mass and energy may reach depths near sea level, which can be examined by ground-based experiments.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In a seminal work about two decades ago, Witten proposed that strange quark matter (SQM), the combination of roughly an equal number of up, down and strange quarks, might be the true ground state of quantum chromodynamics (QCD) [1]. Later calculations have shown that in spite of the effect of their finite volume, small nuggets of SQM in a form of 'strangelets' can also be stable as long as the baryon number exceeds a critical value A_{crit} [2]. On one hand, various theoretical scenarios have provided chances for strangelet formation [3, 4]. They could be produced in highly energetic nuclear collisions [5], might originate from the collisions of two strange stars [6] and could also be ejected by supernova explosions [7]. On the other hand, several exotic cosmic ray events have been reported by balloon and mountain experiments [8–10], which are considered to be ideal candidates for strangelets. The ultra-high energy cosmic ray (with energy $>10^{19}$ eV) events could also be the results of extensive air showers of relativistic strangelets accelerated in pulsar magnetospheres [3, 11]. Interestingly, one doubly charged event, with a charge-mass ratio of $\sim$0.1, has been detected by the AMS experiment in space [12] and suggested to be strangelet originated. This idea could be tested in the future AMS02.

Since the existence of stable SQM would have a remarkable consequence in cosmology and astrophysics, what is experimentally important is to find out strangelets' contribution to cosmic ray flux and the mechanism for the propagation of strangelets in the Earth's atmosphere, both of which are helpful to confirm their existence. Recently, Madsen has estimated the flux of strangelets in cosmic rays incident on the Earth [13]. As for the latter, unfortunately, the necessary interaction input physics is at best poorly known.

Different phenomenological models of strangelet penetration in the atmosphere have been used by several authors to explain exotic cosmic ray events. Wilk *et al* conjectured that although the initial mass of strangelets might be quite large, it decreases rapidly due to collisions with air molecules, until the mass reaches a critical value below which the strangelet disintegrates into neutrons [14]. Banerjee *et al* provided a quite different scenario in which a strangelet picks up mass from atmospheric atoms [15]. Monreal novelly discussed the issue of strangelet accumulation in the atmosphere [16].

In the present work, we will reinvestigate this issue within the framework of a rotating liquid drop model, which is still a phenomenological model. We assume that SQM nuggets produced from any cosmological or astrophysical object do reach the surface of the atmosphere, and we evaluate their behaviour in the atmosphere. We find that strangelets with a particular initial baryon number and particular initial Lorentz factor can reach mountain altitudes, even the sea level ($\sim$1000 g cm^{-2}).

In the following sections, we will first provide revised results of ground state strangelet calculated from the liquid drop model. Then, we will investigate the colliding cross section between a liquid strangelet and an air nucleus. Finally, we will give numerical results about the propagation of strangelets in the atmosphere. It should be mentioned that, for the sake of simplicity, our calculation is limited to the ordinary (unpaired) strangelets, i.e. the possible colour-superconductivity effect of strangelets has not been considered.

2. Ground state properties of strangelets

It was argued that the phenomenal bag model first used by Alcock and Farhi [17] may not suit for strangelets. Nevertheless, at the present level, the bag model is still the most effective way to understand the properties of strangelets, such as ground state energy per baryon, charge-to-mass ratio, fissionability, etc.

Within the framework of the liquid drop model, He *et al* [18] studied ground state properties of strangelets at finite temperature, by minimizing free energy of the system at a fixed baryon number. The Coulomb energy was neglected there because the term contributes little to the system energy. In this section, we just go one step further to include Coulomb energy. Although Coulomb energy is negligible in computing E/A, it can greatly affect Z/A, and hence the fissionability parameters.

We consider strangelet as gas of u, d, s quarks, their antiquarks and gluons confined in an MIT bag model. The grand potential of the system $\Omega = \sum_i \Omega_i + BV$, where B is the bag constant and V is the volume, and the grand potential of species i is

$$\Omega_i = \mp T \int_0^\infty \mathrm{d}k\, \rho_i(k) \log\left(1 \pm \exp\left(-\left(\sqrt{k^2+m_i^2} - \mu_i\right)\Big/T\right)\right). \tag{1}$$

In the above equation, '$\pm$' denotes fermions/bosons, μ is the chemical potential, $\rho(k)$ denotes the density of states, which is given by

$$\rho(k) = \frac{1}{2\pi^2}k^2 V + f_S\left(\frac{m}{k}\right)kS + f_C\left(\frac{m}{k}\right)C, \tag{2}$$

where S ($= 4\pi R^2$ for a sphere) is the surface area and C ($= 8\pi R$ for a sphere) is the curvature. The surface and curvature term for quarks are $f_S^{(q)}(m/k) = -(1/8\pi)(1-(2/\pi)\arctan(k/m))$ and $f_C^{(q)}(m/k) = (1/(12\pi^2))(1-(3k/2m)(\pi/2 - \arctan(k/m)))$, respectively; for gluons, $f_S^{(g)} = 0$, $f_C^{(g)} = -1/(6\pi^2)$.

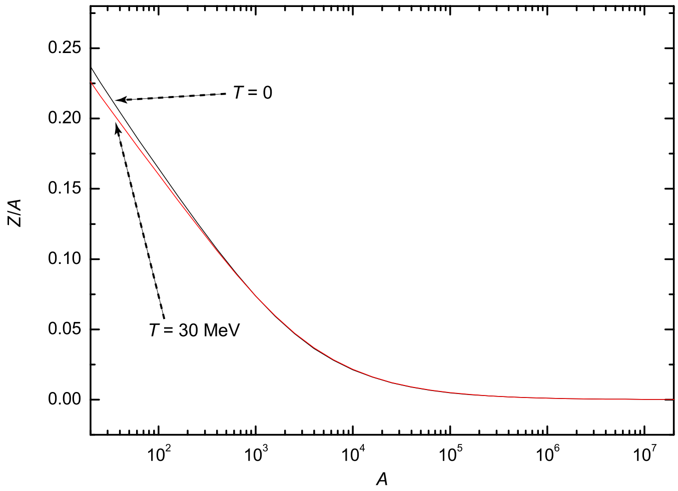

Figure 1. Charge-to-mass ratio of strangelets.

The free energy of the system is given by

$$F = \sum_i (\Omega_i + N_i\mu_i) + E_{\mathrm{coul}} + BV, \tag{3}$$

in which the term of Coulomb energy $E_{\mathrm{coul}} = (3/5)\alpha Z^2/R$ if electric charge is uniformly distributed in the sphere, where α is the fine structure constant and Z is the total electric charge. Since Coulomb energy is taken into account, the chemical potential of up quark and down quark (strange quark) is no longer identical.

By minimizing F, the chemical potentials, the charge-to-mass ratio and energy per baryon at any given baryon number and temperature can be calculated. Taking strange quark mass $m_s = 150$ MeV and bag constant $B = (145\ \mathrm{MeV})^4$, we get the following fitting values for the parameters. At zero temperature,

$$M_{\mathrm{str}}/A = (314.6(4)A^{-0.532(4)} + 875.9(1))\ \mathrm{MeV}; \tag{4}$$

therefore, the minimum baryon number for stability ($M/A < 930$ MeV) is $A_{\mathrm{crit}} = 27$. The surface energy is

$$E_S/A^{2/3} = (69.0(2)A^{-0.466(3)} + 77.9(1))\ \mathrm{MeV}, \tag{5}$$

and the rescaled radius is

$$r_0 = R/A^{1/3} = (0.124(1)A^{-0.445(3)} + 0.941(1))\ \mathrm{fm}. \tag{6}$$

The numbers in parenthesis following each value indicate just the fitting uncertainties of the value in the last digit. The charge-to-mass ratio with respect to the equivalent baryon number is shown in figure 1.

As for a strangelet at excitation states to de-excite, γ-ray emission, hadron emission and fission into small parts should be under consideration. γ-ray emission and meson emission do not change the baryon number a little. According to the CEFT model [19], baryon evaporation is suppressed in terms of meson evaporation due to much smaller probability to simultaneously form two quark–antiquark pairs than one pair. Banerjee *et al* [20] and Sumiyoshi *et al* [21] have calculated meson and baryon evaporation rates of QGP ($\mu_q = 0$), respectively. As for a strangelet, in which the quarks have non-zero chemical potentials, the numerical results are as follows. The energy loss rate caused by baryon evaporation is

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\mathrm{baryon}} = -6.23 \times 10^{19} A^{2/3} T^2 \exp(-999.9/T) \text{ MeV s}^{-1}, \tag{7}$$

while the energy loss rate caused by meson evaporation is

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\mathrm{meson}} = -1.12 \times 10^{20} A^{2/3} T^2 \exp(-381.1/T) \text{ MeV s}^{-1}. \tag{8}$$

Therefore, in the de-excitation process the only effective way to change the baryon number of the strangelet is the fission. Note that a strangelet at excited states will rapidly release its energy in about 10^{-18}–10^{-15} s, which is negligible compared with colliding time intervals.

3. Fission of strangelets by colliding with air nuclei

Now we investigate the stability of strangelets using the rotating liquid drop model. In the case of non-rotating systems, the relation between the nature of the stationary points and the stability of a system is simple; a maximum in one or more degrees of freedom indicates instability. However, the case for rotating systems is more subtle.

Consider a configuration of a rotating incompressible uniformly charged fluid endowed with a surface tension. The effective potential energy is given by

$$E = E_S + E_C + E_R, \tag{9}$$

where E_S is the surface energy, E_C is the electrostatic energy and E_R is the rotational energy. We neglect the curvature energy because it contributes little to the issue we consider.

We may write the deformation energy, measured with respect to the energy of the sphere, in the following dimensionless form, familiar in the literature of nuclear fission:

$$\xi = \frac{E - E^{(0)}}{E_S^{(0)}} = (B_S - 1) + 2x(B_C - 1) + y(B_R - 1). \tag{10}$$

Here $B_S = E_S / E_S^{(0)}$, $B_C = E_C / E_C^{(0)}$, $B_R = E_R / E_R^{(0)}$, and the two dimensionless parameters x and y specify the ratios of electrostatic and rotational energies of the sphere to the surface energy of the sphere, which are defined as $x \equiv E_C^{(0)} / 2E_S^{(0)}$ and $y \equiv E_R^{(0)} / E_S^{(0)}$, respectively. According to our calculations, we found that the fissionability parameter x of strangelets varies from 0.001 to 0.030, which is much smaller than normal nuclei. Therefore, we take $x = 0$ for simplicity in the following calculations.

If there is no rotation ($y = 0$), the ground state is a sphere and the saddle shape is the configuration of two tangent spheres. With increased rotation, the ground state sphere is flattened into axially symmetric (Hiskes) shapes, and the saddle varies with the so-called Pik–Pichak shapes. If y is even larger, the ground state will convert to a triaxial (Beringer–Knox) shape, which is quite close in appearance to the Pik-Pichak saddle. In fact, there exists a critical value y_{crit} above which the fission barrier vanishes, which implies a maximum rotation for stability.

Cohen *et al* [22] have calculated the ground state and fission barrier energy measured with respect to the energy of the sphere,

$$\xi_{\mathrm{ground}} = y(-0.056 + 0.049y - 1.358y^2 + 0.946y^3), \tag{11}$$

$$\xi_{\mathrm{barrier}} = 0.280 - 0.778y + 0.622y^2 - 0.105y^3. \tag{12}$$

For $x = 0$, $y_{\mathrm{crit}} = 0.79$.

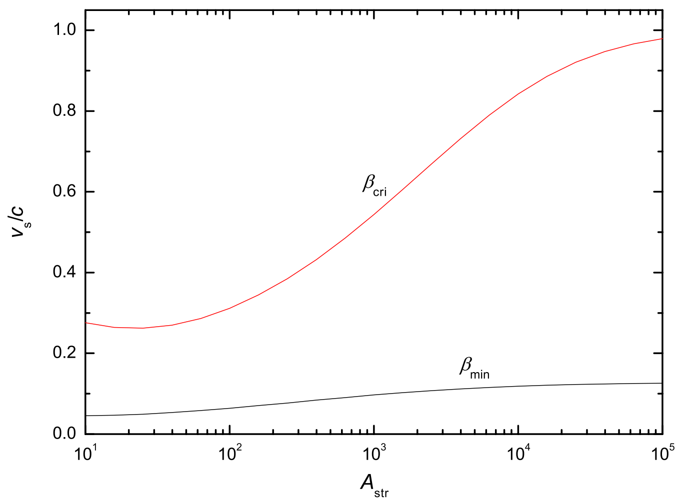

Figure 2. Critical value of strangelet velocity. The upper curve represents the fission threshold of a non-rotating strangelet and the lower curve represents the collision threshold.

Now we consider a cosmic ray strangelet incident on the Earth's atmosphere. The centre-of-mass energy $E_{\mathrm{cm}} = \left(M_{\mathrm{str}}^2 + M_{\mathrm{air}}^2 + 2\gamma M_{\mathrm{str}} M_{\mathrm{air}}\right)^{1/2} - M_{\mathrm{str}} - M_{\mathrm{air}}$, where $M_{\mathrm{air}} = 14M_0$ (M_0: approximately the proton mass) is the mass of the air nucleus, M_{str} and γ is the mass and the Lorentz factor of the strangelet, respectively. There exists a non-zero colliding cross section as long as the strangelet has enough kinetic energy to overcome the Coulomb barrier E_v between the strangelet and the air nucleus, i.e. if $E_{\mathrm{cm}} > E_v$, they will have a chance to 'fusion' into a compound strangelet. In other words, the strangelet 'absorbs' the air nucleus.

After fusion of the two, the excitation energy $E_e = E_{\mathrm{cm}} - E_v - E_R^{(0)} - E_{\mathrm{ground}}$. According to the rotating liquid drop model, if the projectile strangelet is energetic enough, E_e will be higher than the fission barrier E_b, the newly formed compound strangelet will fission into two smaller strangelets which have nearly equal baryon numbers.

However, with the increasing kinetic energy of projectile strangelet, the effect of rotation should no longer be neglected, since if the fission barrier of a rotating compound system approaches zero, no compound strangelet will form. It is reasonable to suppose that the interaction time scale in this case is much shorter than the former.

The geometric cross section for contact is $\sigma_{\mathrm{geo}} = \pi\left(r_0 A_{\mathrm{str}}^{1/3} + 1.12 A_{\mathrm{air}}^{1/3}\right)^2$, which is used by some earlier studies for crude calculations. However, the cross section is not always σ_{geo} for different baryon numbers and different velocities. The cross section for close collision can be written as

$$\sigma_{\mathrm{col}} = \sigma_{\mathrm{geo}}(1 - Z_{\mathrm{str}} Z_{\mathrm{air}} e^2/(R_{\mathrm{str}} + R_{\mathrm{air}}) E_{\mathrm{cm}}), \tag{13}$$

and the cross section for fusion is

$$\sigma_{\mathrm{cri}} = 2\pi y_{\mathrm{crit}} I_0 E_s^{(0)} \left(M_{\mathrm{str}}^2 + M_{\mathrm{air}}^2 + 2\gamma M_{\mathrm{str}} M_{\mathrm{air}}\right) \big/ \left((\gamma^2 - 1) M_{\mathrm{str}}^2 M_{\mathrm{air}}^2\right). \tag{14}$$

Figure 2 gives the critical value of velocity for fusion and fission as a function of baryon number. The relation between the impact parameter b in a collision between the two masses and the velocity of the strangelet is shown in figure 3.

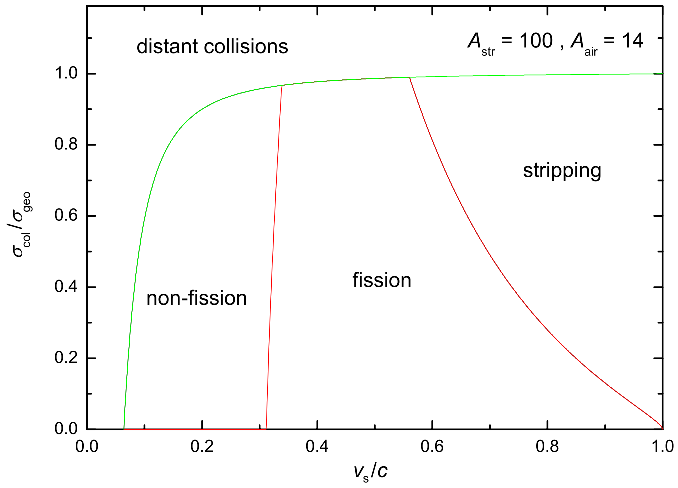

Figure 3. A collision diagram of square of the impact parameter b (times π) versus the velocity of a strangelet with $A_{str} = 100$, for the bombardment of an air nucleus by the strangelet.

4. Propagation of strangelets in the atmosphere

We consider strangelets with zero zenith angle of trajectory in this work, and the influence of gravity force is neglected because of its small contribution to the issue. Therefore, strangelet–air collision and ionization effect are what we are mainly concerned with.

In our model, there exists a critical velocity of the strangelet in the strangelet–air collisions below which the air nucleus will be fused with the strangelet, and above which some mass will be stripped from the strangelet. The model is based on the analogical result in nuclear collisions, i.e. the linear momentum transfer between the strangelet and the air nucleus reaches a maximum around some critical energy.

When fusion happens, the velocity of the strangelet drops to

$$\gamma' = (\gamma M_{str} + M_{air}) \Big/ \left(M_{str}^2 + M_{air}^2 + 2\gamma M_{str} M_{air}\right)^{1/2} \tag{15}$$

after each collision, and particularly if $E_e > E_b$, the strangelet will fission into two smaller strangelets with an equal baryon number $0.5(A_{str} + A_{air})$ and probably equal longitudinal velocity.

When the strangelet is more energetic, no compound strangelet will form. If the experimental law in nuclear collision is adaptable in this case, the velocity of the strangelet is assumed to drop to

$$\gamma' = \gamma - (\gamma_{cri} - \gamma'_{cri}), \tag{16}$$

where γ_{cri} is the critical gamma factor for fusion, and γ'_{cri} can be deduced from equation (15) given $\gamma = \gamma_{cri}$. The value of γ_{cri} can be found by solving the equation $\sigma_{cri} = 0.5\sigma_{col}$, i.e. the watershed of fusion-dominated and stripping-dominated collisions. It should also be mentioned that we assume new strangelet will have a baryon number of $(A_{str} - A_{air})$ after each collision in numerical calculations. Indeed, at the present level, the mass and energy spectra of decay products in this range are quite uncertain. Although our supposition is somewhat crude, it nevertheless provides some important information.

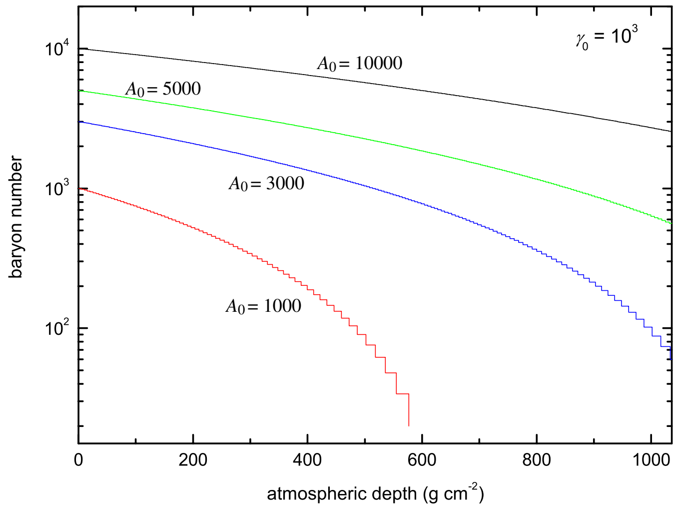

Figure 4. Mass evolvement of strangelets with $A_0 = 1000, 3000, 5000, 10000$ and $\gamma_0 = 10^3$ as a function of atmospheric depth.

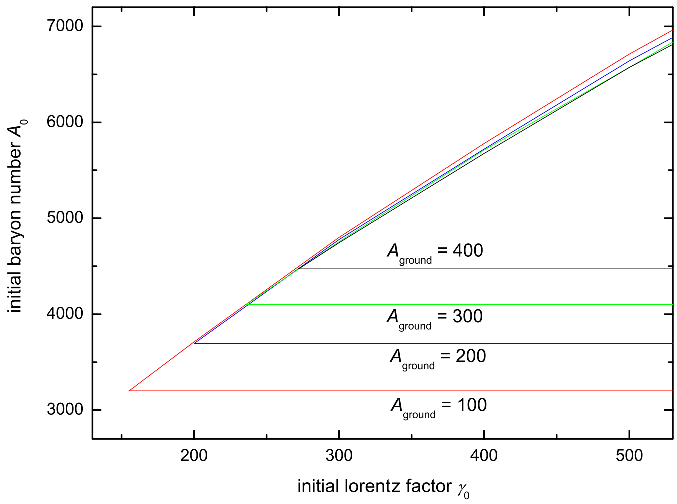

Figure 5. Final mass distribution of strangelets ($x = 1036$ g cm^{-2}) as a function of an initial baryon number and Lorentz factor.

In addition to the effect of colliding with air nuclei, the issue of the energy loss of the strangelet through ionization of surrounding media cannot be avoided, which is described by the Bethe–Bloch stopping power formula [23],

$$\mathrm{d}E/\mathrm{d}x = -0.153\beta^{-2}Z_{\mathrm{str}}^2(\ln(\gamma^2 - 1) - \beta^2 + 9.39)\ \mathrm{MeV}\ (\mathrm{g\ cm^{-2}})^{-1}. \qquad (17)$$

If $v < v_0 Z_{\mathrm{str}}^{2/3}$, where $v_0 = 2.2 \times 10^8$ cm s^{-1} is the speed of electron in the first Bohr orbit, the effective charge $Z_{\mathrm{str}} \rightarrow (v/v_0)Z_{\mathrm{str}}^{1/3}$ due to the effect of electron capture [24].

The following figures show our numerical results. In figure 4, we present the mass evolvement of strangelets with $\gamma_0 = 10^3$ as a function of atmospheric depth. It is obvious that the larger the γ_0 and A_0, the more possible that the strangelet reaches the sea level. In figure 5,

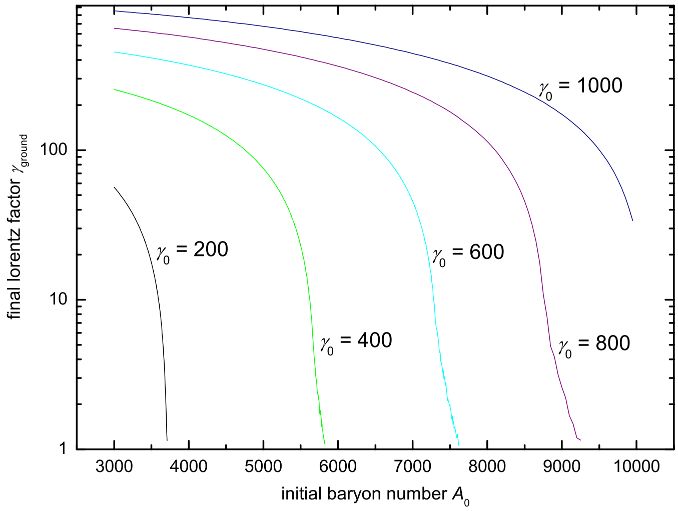

Figure 6. Final Lorentz factor ($x = 1036$ g cm^{-2}) as a function of the initial baryon number with $\gamma_0 = 200, 400, 600, 800, 1000$.

we show the distribution of a particular final ($x = 1036$ g cm^{-2}) baryon number of strangelets as a function of an initial baryon number and gamma factor. The upper oblique dashed lines correspond to products of fission (lower energy), and the lower transverse lines correspond to products of stripping (higher energy). We find that if the initial strangelets have $A_0 \geqslant 3000$ or $\gamma_0 \geqslant 140$, they will have a chance to be detected by ground-based experiments. In figure 6, we give the final Lorentz factor as a function of the initial baryon number.

5. Conclusions

From the above discussion, it is reasonable to make a conclusion that strangelets with large mass and energy have the chance to penetrate the atmosphere to reach the sea level. Our model gives a lower limit of the initial baryon number, that is, $A_0 \geqslant 3000$ or $\gamma_0 \geqslant 140$. Relevant flux for ordinary strangelets is unclear yet, but as predicted by Madsen [13], it is about 1–10 m^{-2} year^{-1} sterad^{-1}, so there is a possibility for ground-based experiments to detect them. Madsen [13] predicts a flux of strangelets with a velocity spectrum (an event with $\gamma = 140$ could be very unlikely there) in a model where strangelets originate only by merging of binary strange stars. However, the γ factor of strangelets produced in other ways (e.g., ejected and accelerated in pulsar's magnetospheres [11, 25, 26]) may be greater than 140, and the possibility of an event with higher γ could then not be ruled out yet.

Acknowledgments

This work is supported by National Natural Science Foundation of China (nos. 10421503, 10575003, 10528510, 10573002), by the Key Grant Project of Chinese Ministry of Education (no. 305001) and by the Research Fund for the Doctoral Program of Higher Education (China).

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