Strange quark matter in cosmic ray flux and exotic events

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Abstract

There have been several reports of exotic nuclear fragments, with highly unusual charge to mass ratio, in cosmic ray experiments. Although there exist experimental uncertainties which make them, at best, only candidate "exotic" events, it is important to understand what they could be, if they are eventually confirmed. Among other possible explanations, some authors have interpreted them to be lumps of strange quark matter (strangelets). A major problem with such an interpretation is that to reach the earth’s surface, they must possess an unusually high penetrability through the terrestrial atmosphere. We show that a recently proposed mechanism for the propagation of strangelets through the earth’s atmosphere, together with a proper account of charge capture and ionisation loss, would solve this problem. We also argue that this could lead to viable strategies for definitive detection of strange quark matter in cosmic ray flux using a ground based large area array of passive detectors.
There exists a proposal in the literature [1] that strange quark matter (SQM), consisting of approximately equal numbers of up, down and strange quarks, represents the true ground state of Quantum Chromodynamics (QCD), the underlying theory of strong interaction physics. The characteristic feature of stable (or metastable) small lumps of SQM would be very abnormal electric charge ($Z$) to mass ($A$) ratio ($Z/A \ll 1$). The existence of such objects had also been postulated earlier by other authors (see, eg [2]), but the seminal work of Witten [1] provided the theoretical basis for the study of SQM within the framework of QCD. It has since been argued in the literature that a definitive confirmation of the existence of stable (or metastable) lumps of SQM (referred to in the following as strangelets) can shed light on some of the most intriguing aspects of present day physics and astrophysics, like the cosmological dark matter problem [3], cosmological QCD phase transition or abundance of strange stars [4].

There have indeed been several reports of events with $A \sim 350 - 500$ and $Z \sim 10 - 20$ in cosmic ray experiments [3, 1, 7], the so-called exotic cosmic ray events. Although these observations come from different groups, the existence of such objects cannot yet be taken as confirmed, due to various experimental uncertainties like switch between gondolas, ambiguities associ-
ated with the calibration of Cerenkov counter output, detector noises, dead
time etc, in the different experiments. These events, thus, are, at best,
candidate events. Nonetheless, it is an important task to understand what
these objects, if they are eventually confirmed, could be and several authors
have put forward various suggestions as to the nature of these exotic objects.

An essential feature of these objects appears to be their unusual penetra-
bility through the terrestrial atmosphere, allowing them to reach mountain
altitudes. To account for such stability, although in the light of a differ-
ent cosmic ray event called the "Centauro event" found in the Brazil-Japan
collaboration experiment at Mt. Chacaltaya, Bjorken and McLerran
assumed, following De Rújula, Giles and Jaffe, the liberation of a frac-
tionally charged free massive quark which would absorb a large number of
nucleons and constitute a metastable blob of superdense quark matter. Chin
and Kerman proposed the existence of metastable multiquark states of
large strangeness within the framework of the MIT bag model. All such
scenarios can be mostly accommodated within the premise of Witten’s con-
jecture of SQM as the true ground state of QCD. However, the fraction of

\footnote{We thank the referee for emphasizing this point to us.}
such heavy objects ($A \sim 300 - 500$) in the primary cosmic ray flux may be exceedingly small.

It should be mentioned at this juncture that only strangelets with very large $A$ were initially thought to be favourable in the context of stability. Indeed, De Rújula and Glashow \cite{13} considered the possibility of detecting large lumps of SQM, called ”nuclearites”, of $A < 10^{15}$ and $Z$ ”well beyond any published periodic table”. Recent calculations, however, have shown that also small strangelets with $A = 6, 18, 24, 42, 54, 60, 84, 102$ etc are possible stable configurations, due to an underlying shell-like structure \cite{14, 15}. The flux of such objects in cosmic rays could thus be sizable enough to be looked for, at least in large area detectors, hence ground based experiments. It is thus imperative to know if these strangelets can traverse the earth’s atmosphere and reach the surface. Moreover, the candidate events ($A \sim 350 - 500$ and $Z \sim 10 - 20$) have vastly different charge-to-mass ratios than those referred to above. It needs to be investigated whether these are related in any manner.

Recently, a dynamical scenario for the propagation of strangelets through the earth’s atmosphere has been worked out \cite{14}, where the stability of SQM plays a very important role. In particular, the propagation of strangelets through the earth’s atmosphere has been described by the differential equa-
where a strangelet of low mass \((A = 64 \text{ amu})\) and charge \((Z = 2 \text{ units})\) enters the upper layer of the atmosphere \((\sim 25 \text{ km from the sea level, above which the density of the atmosphere is negligibly small})\). The speed of the strangelet at that altitude has to be \(\geq 0.2c\) \((c\) being the velocity of light\), for a geomagnetic latitude of \(30^\circ N\), in order to overcome the geomagnetic barrier. While the first two terms in equation (1) have obvious significance, the third term accounts for the deceleration of the strangelet due to its peculiar interaction with the air molecules; strangelets can readily absorb matter and become more strongly bound, unlike the normal nuclear fragments which tend to break up [1]. Using straightforward geometrical considerations, it has been shown [14] that the strangelet grows from \(A = 64 \text{ amu}\) to \(A \sim 340 \text{ amu}\) by the time it reaches an altitude of \(\sim 3.5 \text{ km}\), the altitude of a typical mountain peak with adequate accessibility for setting up a large detector array. This remarkable possibility makes it imperative to explore the consequences of this novel mechanism with greater care, especially taking proper account of not only accretion of mass but also that of charge as well as the dissipation
of energy due to ionisation loss.

Thus the operative equation (1) becomes modified to

\[
\frac{d\vec{v}}{dt} = -\vec{g} + \frac{q}{m_s}(\vec{v} \times \vec{B}) - \frac{\vec{v}}{m_s}\left(\frac{dm_{sn}}{dt} + \frac{dm_{sp}}{dt}\right) - \frac{f(v)}{\sqrt{3m_s}} \vec{v}
\]

(2)

where \(\frac{dm_{sn}}{dt}\) (\(\frac{dm_{sp}}{dt}\)) denotes the accretion to the strangelet due to its interaction with neutrons (protons) of the air (primarily \(N_2\) molecules). It should be noted that absorption of neutrons would lead only to mass increase while that of protons would increase both mass and charge of the strangelets. In equation 2, \(\frac{dm_{sn}}{dt}\) is related to \(\frac{dm_{sp}}{dt}\) by the following relation,

\[
\frac{dm_{sp}}{dt} = \frac{\sigma_p}{\sigma_n} dm_{sn} \equiv f_{pn} \frac{dm_{sn}}{dt}
\]

(3)

where \(\sigma_n\) and \(\sigma_p\) represent the cross sections for the absorption of the neutron and the proton, respectively, by the strangelet. Thus, \(f_{pn}\) determines the relative probability for a proton to undergo the above process vis-a-vis a neutron, and is less than one, on account of the coulomb barrier present at the surface of the strangelet. The factor \(f(v)\) represents the rate of energy loss due to ionisation of the surrounding medium by the positively charged strangelet [17, 18]. The rate of absorption of protons by the strangelet, given by eq.(3), determines the rate of change in the charge \(q\) of the strangelet.
The set of equations is solved numerically, using the 4th order Runge-Kutta method. The results are shown in Figs. 1 and 2. As can be readily seen from Fig. 1, the initial strangelet of $A = 64$ and $Z = 2$ evolves into a state of $A \sim 455$ and $Z \sim 14$, very similar to what have been reported in the literature.

Special attention should be paid to Fig. 2. It is found that ionisation loss leads to a considerable dissipation of energy and consequent slowdown. It is however most interesting to note that at altitudes $\sim 3.5$ km from the sea level, the strangelet has a velocity of the order of 0.0063c, corresponding to a total energy of $\sim 8.5$ MeV. For the present scenario, this energy (which corresponds to $dE/dx \simeq 2.35$ MeV/mg/cm$^2$ in the passive solid state nuclear track detector CR-39), although very small, is just above the threshold of detection with CR-39, for which $dE/dx|_{\text{critical}}$ turns out to be around 1 MeV/mg/cm$^2$.

The experimental verification of SQM in cosmic ray flux (and the mechanism of their propagation through the earth’s atmosphere) is thus possible with a suitable ground based detector set up at high altitudes of about 3 to 5 km. At such altitudes, the predicted energy range of the resulting penetrating particles with mass $M$ between 300 and 400 and $Z$ between 10 and 15
should lie between 5 to 50 MeV. (This estimate corresponds to an averaging over all angles of incidence at the top of the atmosphere, taken to be 25 km here, as mentioned above. The estimate of flux would be strongly affected by the angle of incidence; this is currently under investigation.) A suitable locality for such observations at an altitude of about 3.5 km above the sea level has been identified at Sandakphu, in the middle ranges of the eastern Himalayas, with adequate accessibility and climatic conditions. Continuous exposure for months or years at a stretch of a detector assembly with stacks of SSNTDs like CR-39, covering a total area of about 400 m², is planned there. (The number of events due to strangelets may be as few as 5 - 10 per 100 m² per year, according to our approximate estimates.) The major considerations in this respect are cost, structural simplicity, and long time stability of the detection sensitivity against temperature fluctuations of several tens of Celsius degrees between summer and winter months and the ruggedness of the passive detectors. Regarding all these aspects, commercially available CR-39 appears to be the most suitable choice, which has been shown in NASA SKYLAB experiments [13, 20] to be capable of detecting heavy ions with energies upto 43 MeV/u. The signatures produced in such detectors in terms of mass, charge and energy of detectable strangelets
can be evaluated in the expected $dE/dx$ range by measurements of track
dimensions. For this purpose, additional calibration experiments, exposing
CR-39 samples to heavy ions with variable charge states at almost similar
energy ranges, are necessary which can be made at several existing heavy ion
accelerator facilities. With efficient etching and automated track measure-
ments, backgrounds of low energy secondary radiation with lower charge or
mass are not expected to pose any serious problems. Due to specific inherent
technical problems like "fading" of thermoluminescent materials over a long
interval of time, they do not seem to be practical in our experimental con-
ditions. CR-39 has an additional advantage over the other types of passive
semi-conductor detectors using co-polymers like SR6, CN85 or Lexan; a large
amount of characteristic experimental data are already available for CR-39
in the existing literature. As alternatives, Mica or Overhead Transparency
Foils may also be considered and calibration experiments using these materi-
als will be conducted at accelerator facilities to judge their suitability. Other
active detectors and devices do not appear to be suitable for installation at
proposed mountain heights for stand alone operation over long periods and
are therefore not being considered at present.

We thus conclude by arguing that detection of strangelets in the cosmic
ray flux is quite possible, using ground based large area passive detectors at mountain altitudes.

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Figure Caption:

Figure 1. The variation of mass $m_s$ (in amu) and charge $q$ of the strangelet with altitude (in km).

Figure 2. The variation of energy $E$ (in MeV) and velocity $\beta$ with altitude (in km). The inset shows a zoomed view of the graphs for altitude between 5 to 3 km.
