

Strange quark matter in the cosmic radiation

Zouleikha Mohammed Sahnoun*, Reda Attallah† and Ahmed Chafik Chami‡

*Astrophysics Department, Centre de Recherche en Astronomie, Astrophysique et Geophysique,
B.P. 63 Bouzareah, 16340 Algiers, Algeria.

†Physics Department, Université Badji-Mokhtar, B.P. 12, 23000 Annaba, Algeria.

‡Physics Department, Université des Sciences et de la Technologie Houari Boumediene,
B.P. 32 El-Alia, Bab-Ezzouar, Algiers, Algeria.

Abstract. We discuss the possibility for nuggets of strange quark matter to be a cosmic ray component. We investigate their propagation and interaction processes through matter and into the Earth atmosphere with the goal of obtaining a recognisable signature in forthcoming cosmic ray experiments. The constraints on the mass and velocity ranges for the detection of such lumps of strange quark matter at different levels are finally discussed.

Keywords: Strange Quark matter, dark matter, cosmic rays.

I. INTRODUCTION

It was conjectured by E. Witten [1] about two decades ago that Strange Quark Matter (SQM), consisting of roughly equal number of up, down and strange quarks could have energy per baryon lower than that of nuclear matter. SQM nuggets could be stable for all baryon number ranging from a few hundreds to as large as 10^{57} (SQM stars) and could have been produced in the early Universe [1], [2], and could be present in the cosmic radiation as a possible component of the galactic cold dark matter (with typical velocities of $\sim 10^{-3}c$). Strange Quark Matter, if stable, can still be produced in dense stellar objects (neutron and quark stars) [1], [3], [4]. High energetic processes involved in the collision of binary systems containing such objects could therefore produce small lumps of SQM ($A < 10^6$), we shall call ‘‘Strangelets’’ which ones would contribute to the cosmic radiation permeating the Galaxy.

Among the properties of strangelets, their unusual relatively small positive electric charge is considered to be a key feature for their experimental identification [5], [6], [7]. Asymptotical limits for this charge Z as a function of baryon number A were evaluated in [6]:

$$\begin{aligned} Z &\approx 0.1 \left(\frac{m_s}{150 \text{ MeV}} \right)^2 A && \text{for } A \ll 10^3 \\ Z &\approx 8 \left(\frac{m_s}{150 \text{ MeV}} \right)^2 A^{1/3} && \text{for } A \gg 10^3 \end{aligned} \quad (1)$$

where m_s is the strange quark mass usually considered to be $m_s \sim 150 \text{ MeV}$.

A more accurate formula valid for the whole mass range can be found in ref. [6].

In ref. [7] it was shown that an even more stable state of nuclear matter could exist, the so called *Colour-Flavour Locked (CFL) SQM*, because of the possible occurrence of a Cooper-like pairing between quarks of different colour and flavour quantum numbers. For Color-Flavor Locked strangelets the charge to mass relation is given by [7]

$$Z \approx 0.3 \left(\frac{m_s}{150 \text{ MeV}} \right) A^{2/3} \quad (2)$$

Anomalous massive particles were recorded in the past by different cosmic ray experiments [8], [9], [10] and seem to be consistent with a Strangelet interpretation. However recent results from the SLIM experiment [11], [12] who searched for magnetic monopoles and strange quark matter showed no candidate event putting upper limits on the strangelet flux.

Strangelets interaction and propagation in terrestrial atmosphere is poorly known. Some phenomenological models were proposed in literature among them Wilk et al. [13], [14] suggest that strangelets lose mass in each interaction with air nuclei when penetrating into the Earth’s atmosphere, until they reach a critical mass and begin to evaporate neutrons. A quite different scenario was developed by Banerjee et al. [15], [16], [17], in which small stable or metastable strangelets (with $A \sim 42, 54, 60, 84, 102, \dots$) would pick-up neutrons and protons as they traverse the Earth’s atmosphere, increasing in charge and mass at different rates.

In the present work, we re-investigated strangelets interactions with atmospheric nuclei computing the interaction cross sections as from Wilk’s model with the introduction of the collision dynamics and the energetic losses from nuclear and atomic collisions. It is shown that new constraints on initial mass and energy can be retrieved for strangelets detection on high altitude experiments but also at sea level.

II. STRANGELETS PROPAGATION

As from Wilk et al. model [13], [14], we consider that nuggets of Strange Quark Matter penetrating into atmosphere might undergo multiple collisions with air nuclei leading to the loss of $3 A_{air}$ quarks in every consecutive interaction, where A_{air} is the mean mass

number of an atmospheric nuclei ($A_{air} = 14.5$ for 20% oxygen and 80% nitrogen).

The mean interaction free path of a strangelet of mass number A in atmosphere should be:

$$\lambda_{S-air} = \frac{A_{air} m_N}{\pi (1.12 A_{air}^{1/3} + r_0 A^{1/3})^2} \quad (\text{g/cm}^2) \quad (3)$$

Where r_0 , the re-scaled radius was determined by the number density of the strange matter in the scope of the Fermi gas model with the values commonly accepted [5], [18], [19] for the mean chemical potential $\mu = 300$ MeV and the strange quark mass $m = 150$ MeV, respectively. m_N is the mean nucleon mass.

Thus, the mean atmospheric depth penetrated by the strangelet before reaching its critical stability mass A_{crit} is given by the sum of the consecutive interaction mean free paths $\lambda(k)$:

$$\Lambda = \sum_{k=0}^N \lambda_k \quad (4)$$

Where $N = \frac{A_0 - A_{crit}}{A_{air}}$ the total number of interactions, A_0 is the baryon number of the initial strangelet on top of the atmosphere and A_{crit} ($\sim 300 - 400$) is the critical size below which strangelets are no more stable against neutron emission. It is estimated comparing the so-called separation energy dE/dA to neutron mass.

The interaction between the SQM and air nuclei is treated as a two-body reaction considering the products to be the new strangelet and an “effective nucleus” composed of the remainder of quarks and eventually nucleons that were involved in the reaction. As for the moment we are only interested on the strangelet being able to reach detector level and not on the whole shower dynamics we are not drawing attention to the details of the effective nucleus. In each collision, in order for 3 A_{air} quarks to be pulled out from the SQM lump the available energy in the center of mass system must be larger than “ A_{air} times the binding energy per baryon” in the SQM i.e $A_{air} \times 56$ MeV. 56 MeV per baryon being the binding energy of bulk strange quark matter, as computed by Madsen in ref. [20], [21]. The deflection angles in each collision are assumed to be negligible, strangelets being much heavier than normal nuclei. If we assume that strangelets have no associated electrons then their interaction with matter is expected to be similar to heavy ions but with a different Z/A . So, the energy losses between two consecutive interactions can be computed from the Bethe-Block formula at relativistic velocities or by an extension of Ziegler tables [22], at lower velocities. Strangelets charge is considered as from Madsen [7] ($Z \approx 0.3 A^{2/3}$).

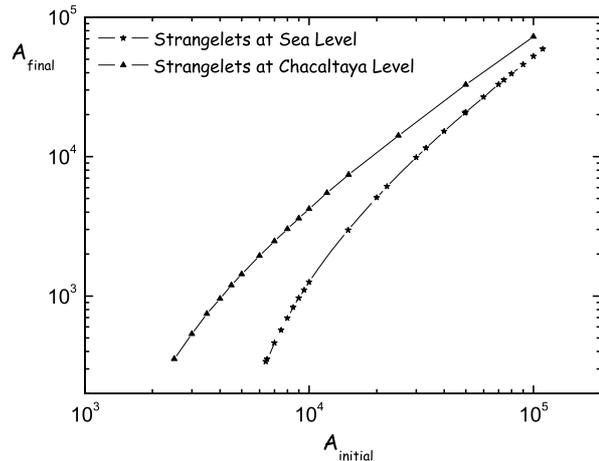


Fig. 1: The final Mass number of strangelets reaching Chacaltaya and sea level as a function of the initial baryon number.

We also consider the gravitational effect although it is not significant.

Finally, strangelets velocity and mass are computed at different depths along the path and the propagation is stopped in any of these cases:

- i) The final strangelet reaches its critical size (taken to be $A_{crit} \sim 320$) and is evaporated.
- ii) The velocity decreases to an order of $10^{-8} c$ for which the strangelet is considered to be lost.
- iii) The strangelet reaches detector level.

In the first and second case the height above detector level is recorded whereas in the third case it is the final velocity that is registered.

III. RESULTS AND DISCUSSION

Our model is applied for a number of incident Strangelets reaching the top of the Earth's atmosphere with different masses and incident velocities. We investigated the particular case of detectors operated at high altitude, here Mount Chacaltaya (5200 m a.s.l) and also at sea level. As can be seen from Fig. 1, a first step was to find out what type of strangelets if any are able to reach detectors operated at Chacaltaya and Sea level. The minimum strangelet mass number allowing this penetration is $A_{min} = 2470$ amu and $A_{min} = 6370$ amu for Chacaltaya and Sea level, respectively.

In Figs. 2 and 3 are given the minimum initial velocities of strangelets to reach detector level. The behavior of such a velocity with initial mass number seems to follow a simple exponential law dependent on the critical evaporation mass and the minimum initial mass:

$$\beta_{0-min} = P1 \exp \frac{P2 \cdot A_{crit}}{A_{initial} + A_{min}} \quad (5)$$

with parameters $(P1, P2)$ equal $(0.36, 12.47)$, $(0.37, 34.04)$ for chacaltaya and sea level, respectively. The

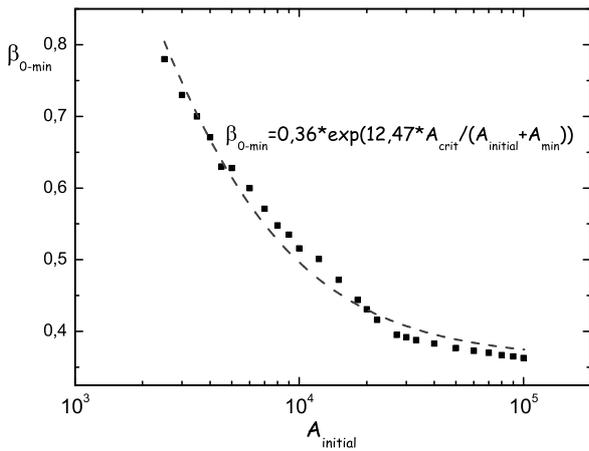


Fig. 2: The minimum initial velocity for strangelets to reach Chacaltaya level as a function of the initial baryon number.

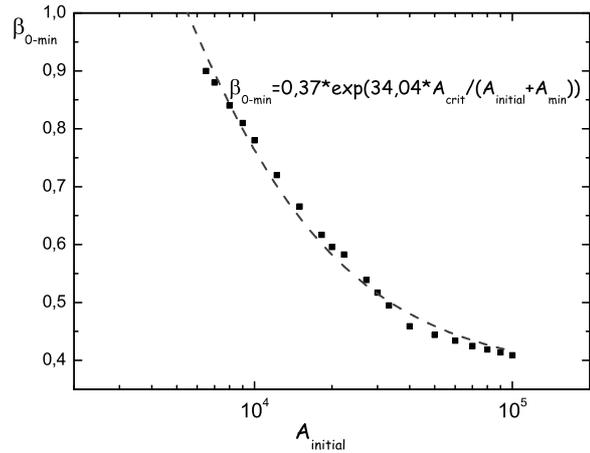


Fig. 3: The minimum initial velocity for strangelets to reach Sea level as a function of the initial baryon number.

minimum initial velocities above sea level given by the model which required for arrival at detector level appear to be important. However, they seem to decrease significantly when the strangeletes masses increases.

IV. CONCLUSION

A model for the propagation of strange quark matter in earth's atmosphere was developed. It was found that under certain circumstances of initial mass and velocity the Strangelets may reach depths near sea level. Our model gives lower limits on initial baryon number and velocity of Strangelets to reach Mountain Altitudes and sea. From this work strangelets with sufficiently large mass and energy appear to have a chance to be detected by future generation dedicated instruments operated at any atmospheric depth between mountain altitudes and sea level. The detection efficiency and relevant fluxes are unclear yet and recent experimental results seem to put very low upper limits (see ref[12] for example). In ref. [23] the strangelets flux in interstellar medium was estimated and found to be correlated to both charge to mass ratio and velocity above rigidity cutoff of strangelet. This point should be discussed in a forthcoming work.

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