A study of strangelets propagation through terrestrial atmosphere

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Abstract: The propagation of relativistic strangelets in terrestrial atmosphere is investigated. A model is proposed taking into account strangelets fragmentation when colliding with air nuclei together with the successive energy losses during penetration. New constraints on initial mass and energy are yielded for arrival at various depths and the detection capabilities of high altitude cosmic ray experiments are discussed.

Introduction

It was conjectured by E. Witten [23] about two decades ago that Strange Quark Matter (SQM), consisting of roughly equal number of up, down and strange quarks have energy per baryon lower than that of nuclear matter and then might be the true ground state of Quantum Chromodynamics (QCD). Many works were devoted to the investigation of the properties of such strange matter [9, 7, 8, 11] and it was shown that it can be absolutely stable for baryon numbers ranging from a few hundreds to as large as 10^{57} (SQM stars). If nuggets of Strange Quark Matter could have been produced in the early Universe [23], they would probably have evaporated a long time ago [1, 3, 17, 18]. However, Strange Quark Matter, if stable, can still be produced in dense stellar objects (neutron stars and quark stars) [23, 10, 2]. High energetic processes involved in the collision of binary systems containing such objects could therefore produce small lumps of SQM ($A < 10^6$), called "Strangelets" which ones would contribute to the cosmic radiation permeating the Galaxy.
Among the properties of strangelets, the unusual small charge to mass ratio (Z/A) is considered to be a unique and crucial signature for their experimental identification. Anomalous massive particles were recorded so-far in different cosmic ray experiments [19, 21, 12] and seem to be consistent with a Strangelet interpretation. Other candidates are the *Centauro* events [13] characterized by a deep penetration into atmosphere ($\sim 500 g/cm^2$), a large hadron content and almost no neutral component.
Strangelets interaction and propagation in terrestrial atmosphere is poorly known. Some phenomenological models were proposed in literature among them Wilk et al. [20, 22] suggest that a lump of strange quark matter of high mass number A when penetrating into atmosphere decreases rapidly due to collisions with atmospheric nuclei. The cascade ends up when the strangelet reaches a critical size of stability bellow which it evaporates by the emission of neutrons. A quite different scenario was developed by Banerjee et al. [4, 5, 6], in which strangelets with low mass numbers ($A < 100$) arrive on top of the atmosphere and attach neutrons increasing in mass during their successive interactions with air nuclei.
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 see level. (implications for the forthcoming experiments are discussed)

Strangelets Propagation

As from Wilk et al. model [20, 22],we consider that nuggets of Strange Quark Matter penetrating into atmosphere will 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 is given by:

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

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 [9, 7, 8] 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 $\lambda(k)$:

$$\Lambda = \sum_{k=0}^{N} \lambda_k \tag{2}$$

Where $N = \dfrac{A_0 - A_{crit}}{A_{air}}$ 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 is the binding energy of bulk strange quark matter, as demonstrated by Madsen in ref. [14, 16]. The deflection angles in each collision are neglected, strangelets being much heavier than normal nuclei and energy losses between two consecutive interactions are computed from Bethe-Block formula or by an extension of Ziegler tables [24]. Strangelets charge is considered as from Madsen [15] $Z \approx 0.3\ A^{2/3}$.
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.

Results and Discussion

Our model is applied for a number of incident Strangelets reaching the top of the Earths 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 Chacalataya and Sea level. The minimum strangelet mass number allowing this penetration is $A_{min} = 2470$ amu and $A_{min} = 2470$ amu for Chacalataya and Sea level, respectively.

In Figs. 2 and 3 are given the minimun initial velocities of strangelets to reach detector level. The behavior of such a velocity with initial mass number seems to follow a simple low dependent on the critical evaporation mass and the minimum initial mass: $\beta_{0-min} = P1 * exp(\frac{P2.A_{crit}}{(A_{initial}+A_{min})})$, with parameters $(P1, P2)$ equal (0.36,12.47), (0.37,34.04) for chacaltaya and sea level, respectively.

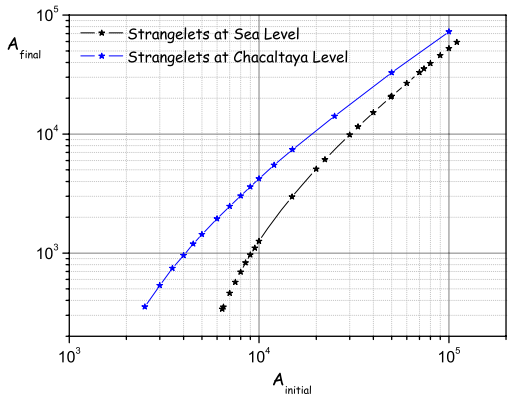

Figure 1: The final Mass number of strangelets reaching Chacaltaya and sea level as a function of the initial baryon number.

Conclusion

A model for the propagation of strange quark matter in earths 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. So, in conclusion it seems reasonable to say that Strangelets with sufficiently large mass and energy have the chance to be detected by present and next generation dedicated instruments operated at any atmospheric depth between mountain altitudes and sea level. The detection efficiency and relevant flux of Strangelets is unclear yet and have to be studied in details.

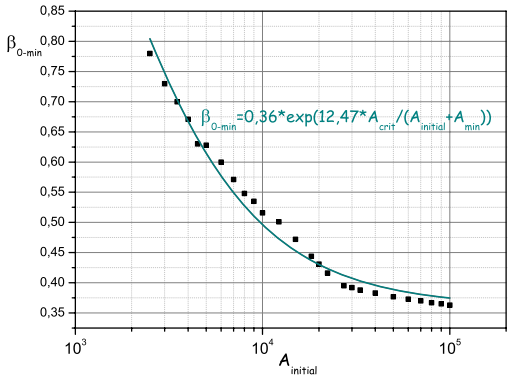

Figure 2: The minimum initial velocity for strangelets to reach Chacaltaya level as a function of the initial baryon number.

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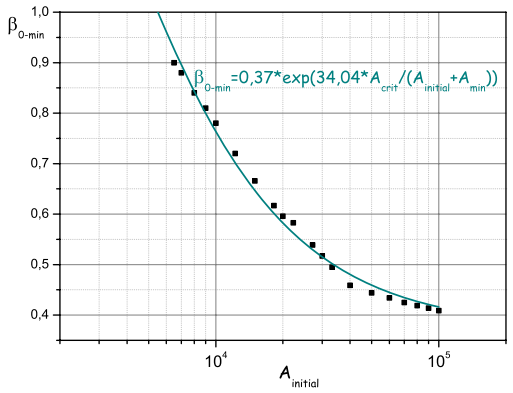

Figure 3: The minimum initial velocity for strangelets to reach Sea level as a function of the initial baryon number.

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