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 [1] 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 so might be the true ground state of QCD. Strange quark matter can be absolutely stable for baryon numbers ranging from a few hundreds to as large as 10^{57} (SQM stars). If nuggets of SQMs produced in the early Universe [1] have probably evaporated a long time ago [2-4], small lumps can still be produced in dense stellar objects (neutron and quark stars) [1,5,6]. High energetic processes involved in the collision of such objects could therefore eject low mass SQMs ($A<10^6$), 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 ($Z/A \ll 1$) is considered to be a crucial signature for their experimental identification. Anomalous massive particles were recorded so-far in different cosmic ray experiments [7-9], some with a very deep penetration into atmosphere, and seem to be consistent with a Strangelet interpretation.

Strangelets interaction and propagation in terrestrial atmosphere is poorly known. Two types of phenomenological models are found in literature, the first one from Wilk et al. [10] suggests that a huge lump of strange quark matter when penetrating into atmosphere decreases rapidly by collision with air nuclei. The second one, developed by Banerjee et al. [11], assumes that low mass metastable strangelets ($A<100$) when penetrating into atmosphere attach neutrons and protons increasing in mass and charge.

In the present work, we reinvestigated 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. New constraints on initial mass and energy are retrieved for strangelets detection on high altitude experiments but also at see level.

Model:

As from Wilk et al. model [10], we consider that nuggets of Strange Quark Matter penetrating into atmosphere will undergo multiple collisions with air nuclei leading to the loss of $3A_{air}$ quarks in every consecutive interaction, where A_{air} is the mean mass number of an atmospheric nuclei (A_{air}=14.5). The mean interaction free path of a strangelet of mass number A in atmosphere is given by:

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

Where r_0, the re-scaled radius was determined by the number density of strange matter in the scope of the Fermi gas model with the values commonly accepted [9,7,8] for the mean chemical potential μ = 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 $\lambda(k)$:

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

Where $N = (A_0 - A_{crit})/A_{air}$, the mean number of interactions, A_0 is the baryon number of the initial strangelet on top of the atmosphere and A_{crit} ~320.

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 nucleons involved in the reaction. We do not draw attention to the details of the effective nucleus as we are only interested on the strangelet being able to reach detector level.

In each collision, in order for $3A_{air}$ 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 (56 MeV as demonstrated by Madsen [14, 16].)" in the SQM.

The deflection angles are neglected, and the energy losses between two consecutive interactions are computed from Bethe-Block formula or by an extension of Ziegler tables [24] depending on the range. Strangelets charge is considered as from Madsen [15] $Z \approx 0.3A^{2/3}$.

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 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. ➔ Can be 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 Mount Chacaltaya (5200 m a.s.l) and also at sea level.

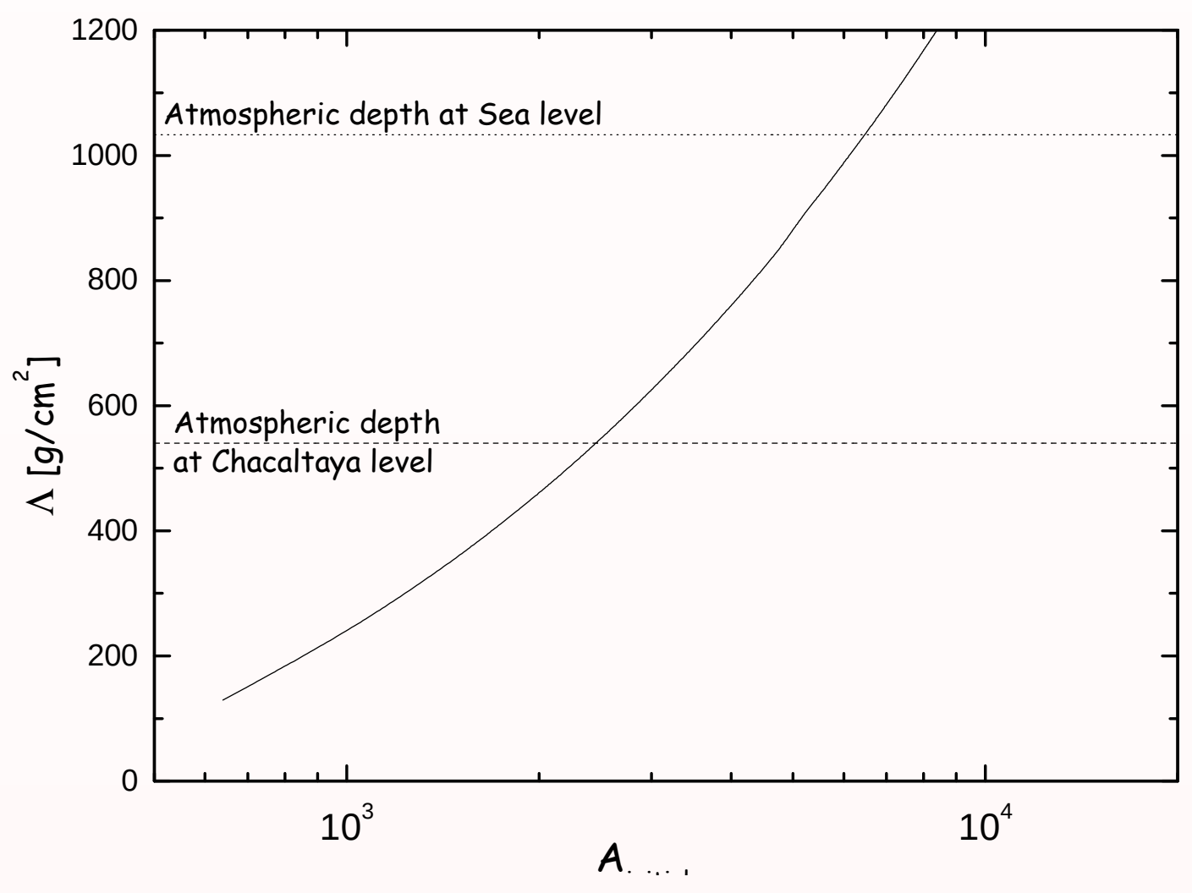

Fig.1: The final depth reached by strangelets of various initial Mass numbers.

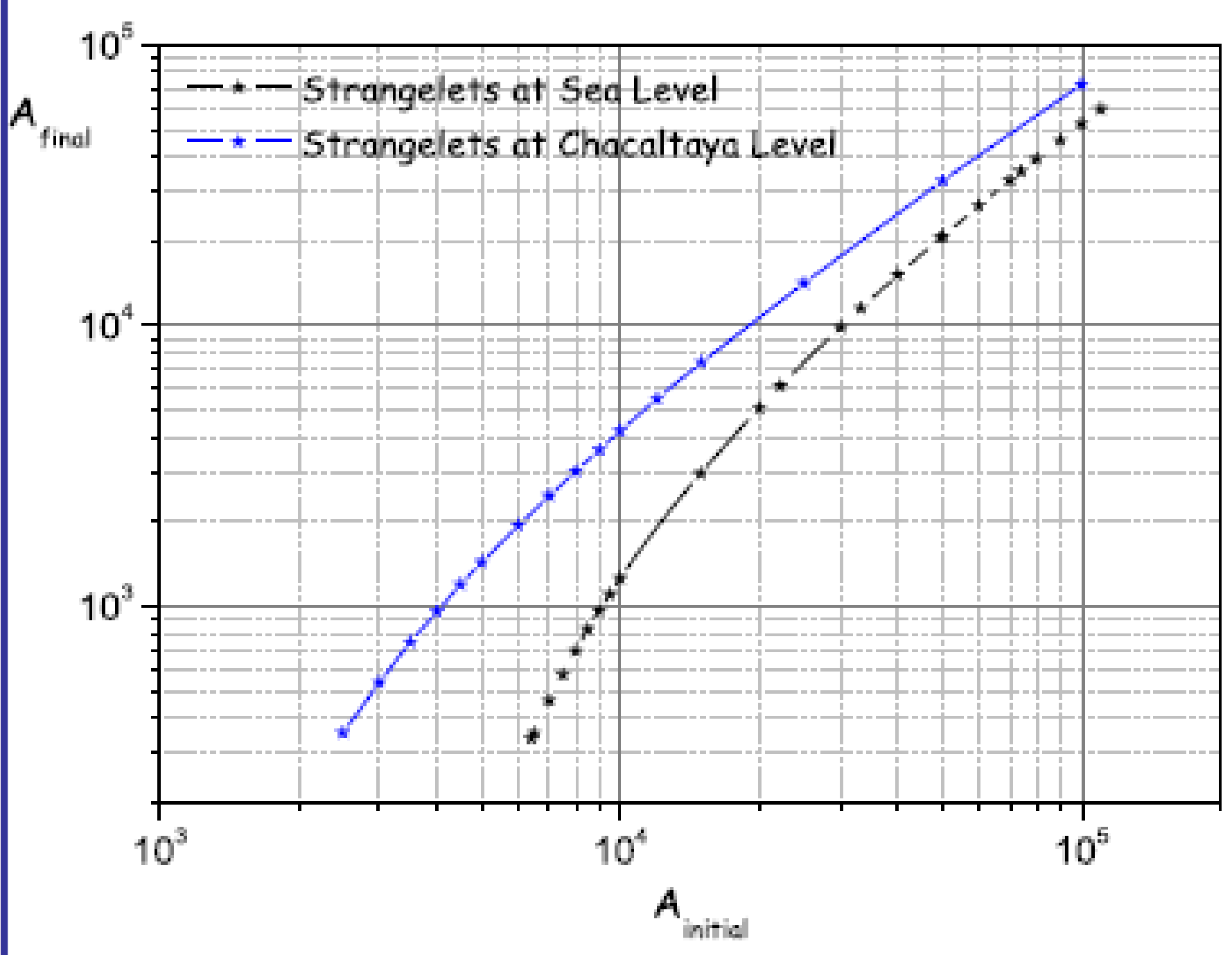

Fig.2: The final Mass number of strangelets reaching Chacaltaya and sea level as a function of the initial baryon number.

As can be seen from Figs. 1 and 2, a strangelets must be heavy enough to be able to reach any detector level on earth.

The minimum strangelet mass number allowing penetration to Mount Chacalataya and Sea level is:

A_{min} = 2470 amu at Chacalataya and A_{min} = 6400 amu at Sea level.

The heaviest the initial strangelet is, the deeper it can penetrate. But this is highly energy dependent as if the strangelet initial velocity is not sufficient the cascade will never be initiated or might soon be ended!

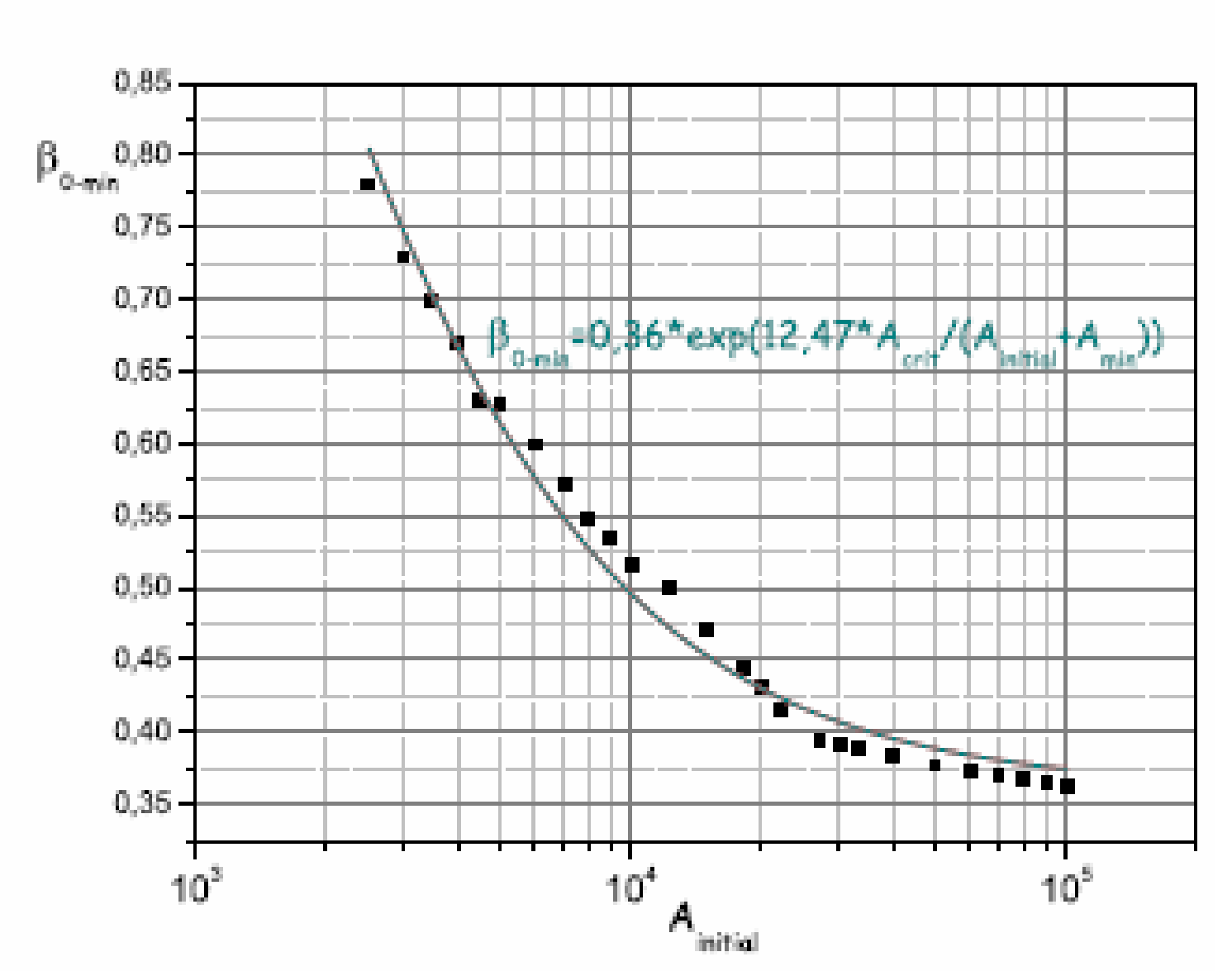

Fig.3: The minimum initial velocity for strangelets to reach Chacaltaya level as a function of the initial baryon number.

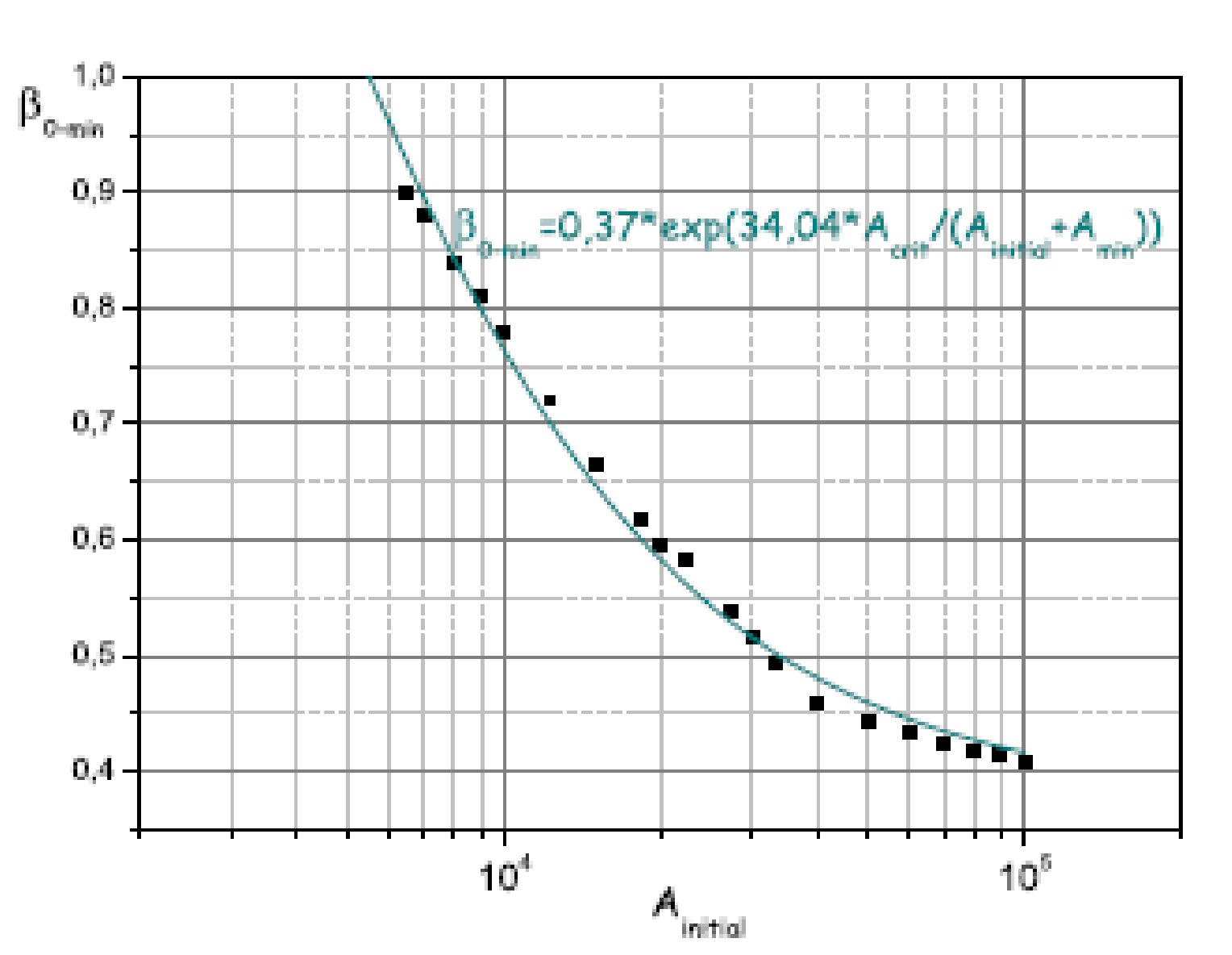

Fig.4: The minimum initial velocity for strangelets to reach Sea level as a function of the initial baryon number.

In Figs. 3 and 4 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 low; dependent on the critical evaporation mass and on the minimum initial mass:

$$\beta_{0-min} = P1 * \exp(\, P2.A_{crit}/(A_{initial}+A_{min})\,)$$

with parameters (P1, P2) = (0.36, 12.47) for Mount Chacaltaya.
= (0.37, 34.04) at sea level.

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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 Strangelets may reach depths near sea level. Although in a preliminary stage, our model gives lower limits on initial baryon number and velocity of Strangelets to reach Mountain Altitudes and sea level. Efforts are made to retrieve these thresholds for a large range of atmospheric depths and find a correlation between their behavior versus the initial mass and the detectors' depth. Finally, it seems reasonable to expect Strangelets to be detected in present and next generation ground based experiments albeit the detection efficiency and relevant flux of Strangelets are yet unclear. This have to be studied in details in future works.

N.B. We do apologize for not being able to present this work due to unexpected difficulties. However, any question or comment are welcome and can be sent to F. Z. Mohammed Sahnoun whose e-mail is given above.