

Strangelets at Chacaltaya^(*)

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Summary. — We discuss the possible imprints of strangelets (*i.e.* lumps of strange quark matter) in Chacaltaya experimental data using model of propagation of such objects through the atmosphere developed by us recently.

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1. – Introduction: strangelets and their propagation

Chacaltaya Laboratory offers a unique possibility to observe possible imprints of strangelets arriving from the outer space. They are lumps of Strange Quark Matter (SQM), a new possible stable form of matter (cf. [1-6] for details). Following [7] it is fully sensible to search for strangelets in cosmic ray experiments, especially at Chacaltaya level (540 g/cm² of atmosphere) because [7] the specific features of strangelets [4] allow them to penetrate deeply into the atmosphere [8]. The point is that there exists some critical size of strangelet given by the critical value of its mass number $A = A_{\text{crit}} \sim 300\text{--}400$ such that for $A > A_{\text{crit}}$ strangelets are absolutely stable against neutron emission. (However, small strangelets might probably also gain stability due to the shell effect [5].) Below this limit strangelets decay rapidly evaporating neutrons. The geometrical radii of strangelets turn out to be comparable to the radii of ordinary nuclei [7], *i.e.* their geometrical cross-sections are similar to the normal nuclear ones. To account for their strong penetrability one has to accept that strangelets reaching deeply into the atmosphere are formed in many successive interactions with air nuclei by the initially very heavy lumps of SQM entering the atmosphere and decreasing due to the collisions with air nuclei (until their

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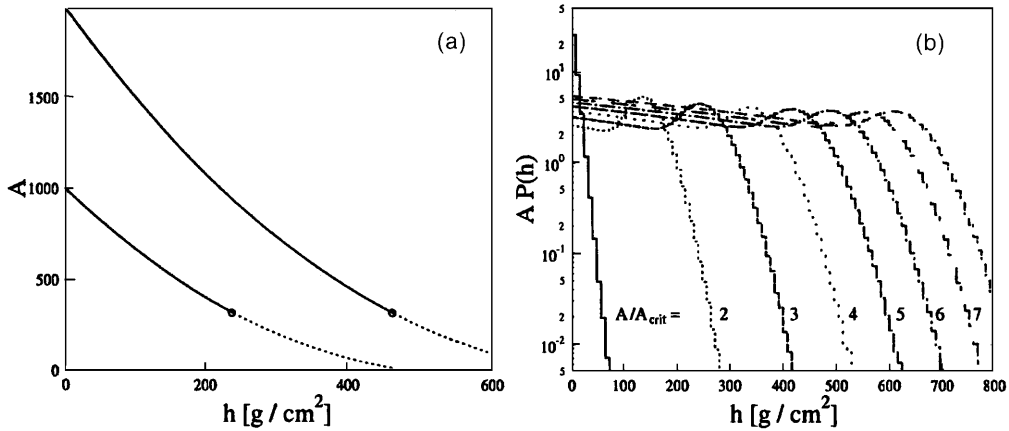


Fig. 1. – (a) An example of the predicted decrease of the actual size of strangelet A with depth h of the atmosphere traversed for two different initial sizes: $A_0 = 1000$ and 2000 (dotted lines correspond to $A < A_{\text{crit}}$). (b) Number of nucleons released in 1 g/cm^2 at depth h of the atmosphere from the strangelet with mass number ratios $A_0/A_{\text{crit}} = 1, 2, \dots, 8$, respectively.

A reaches the critical value A_{crit} [7]). The opposite scenario advocated recently in [9] faces some difficulties and will not be discussed here.

Such scenario is fully consistent with all present experiments [7]. In this scenario interaction of strangelet with target nucleus involves all quarks of the target located in the geometrical intersection of the colliding air nucleus and strangelet. It is assumed that each quark from the target interacts with only one quark from the strangelet; *i.e.* during interaction the mass number of the strangelet is diminished to the value equal to $A - A_t$ at most. This procedure continues unless either strangelet reaches Earth or (most probably) disintegrates at some depth h of the atmosphere reaching $A(h) = A_{\text{crit}}$. This results, in a first approximation (in which $A_t \ll A_{\text{crit}} < A_0$), in total penetration depth of the order of $\Lambda \simeq \frac{4}{3} \lambda_{NA_t} (A_0/A_t)^{1/3}$. The characteristic features of strangelets propagation are illustrated in fig. 1. All numerical calculations presented here were done using suitable modifications of the SHOWERSIM [10] modular software. Strangelets propagation and nuclear-electromagnetic cascades through the atmosphere were simulated with primaries (p, Fe and strangelets) initiating showers sampled from the power spectrum $F(E) \sim E^{-2.7}$ with energies above 1000 TeV per particle. EAS detected at Chacaltaya with $N_e = 10^6 - 10^7$ were then analysed.

2. – Cosmic nuclearities and exotic events

There are several reports suggesting existence of direct candidates for SQM [11] (characterized mainly by their very small ratios of Z/A). All of them have mass numbers A near or slightly exceeding A_{crit} (including Centauro event which contains probably ~ 200 baryons [12]). Analysis of these candidates for SQM shows [7] that the abundance of strangelets in the primary cosmic ray flux is $F_S(A_0 = A_{\text{crit}})/F_{\text{tot}} \simeq 2.4 \cdot 10^{-5}$ at the same energy per particle. Efficiency for registration of strangelets at Chacaltaya level is shown in fig. 2a. To detect strangelets with $A > A_{\text{crit}}$ at Chacaltaya the mass of the initial strangelet should be $A_0 \simeq 7A_{\text{crit}}$ that leads to $\sim 10^{-11}$ as the relative abundance of such strangelets. For normal flux of primary cosmic rays [13] the expected flux of

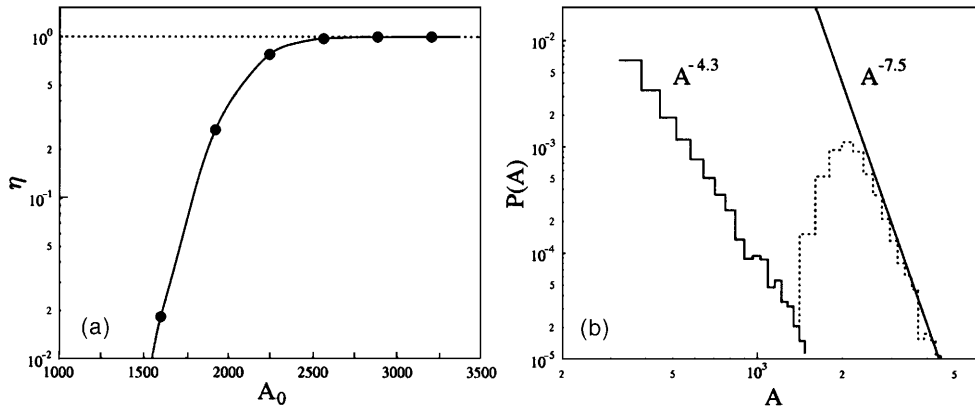


Fig. 2. – (a) Registration efficiency for strangelet with mass number $A > A_{\text{crit}}$ at the Chacaltaya level as a function of initial mass number A_0 . Consecutive full circles indicate (for $A_0 > 1600$) points where $A_0/A_{\text{crit}} = 5, 6, 7, 8, 9, 10$, respectively. (b) Mass distribution of strangelets at Chacaltaya level (solid histogram) resulting from primary mass spectrum $A^{-7.5}$ (solid line). The corresponding initial mass distribution for detected strangelets is shown by dotted histogram.

strangelets is then equal to $F_S = 7 \cdot 10^{-6} \text{ m}^{-2}\text{h}^{-1}\text{sr}^{-1}$ for the energy above 10 GeV per initial strangelet. The high-altitude exposure of passive nuclear track detector arrays [14] and their operation for one year allow therefore detection of such objects. In fact, the exposed CR39 detector should detect at least 6 strangelets with masses above A_{crit} and with energies per registered strangelet above 1 GeV. The mass distribution of strangelets, that can be observed at Chacaltaya, is shown in fig. 2b.

Experimental results obtained at Chacaltaya show a wide spectrum of exotic events (Centaurus, superfamilies with “halo”, strongly penetrating component, etc.) which are clearly incompatible with the standard ideas of hadronic interactions known from the accelerator experiments. Some new mechanism or new primaries are therefore needed. Assuming that strangelets represent such new primaries one is able to explain [15] (at least to some extent) a strong penetrating nature of some “abnormal” cascades associated with their very slow attenuation and with the appearance of many maxima with small distances between them (about 2–3 times smaller than in the “normal” hadron cascades).

Already mentioned Centauro (and mini-Centauro) events, characterized by the extreme imbalance between hadronic and gamma-ray components among produced secondaries, are probably the best known examples of such exotic events. They require deeply penetrating component in cosmic rays. We claim that they can be products of strangelets penetrating deeply into the atmosphere and evaporating neutrons [8]. Both the flux ratio of Centauros registered at different depths and the energy distribution within them can be successfully described by such a concept.

Another example of exotic event is the phenomenon of alignment of structural objects of gamma-hadron families near a straight line in the plane at the target diagram [16]. The excess of aligned families observed is incompatible with any conventional concept of interaction. One can speculate therefore that it is caused by the arrival of strangelets with high spin ($J \sim A^2$) gradually dispersing their masses $A(h)$ when propagating through the atmosphere.

Anomalous events have been reconfirmed by measuring extensive air showers

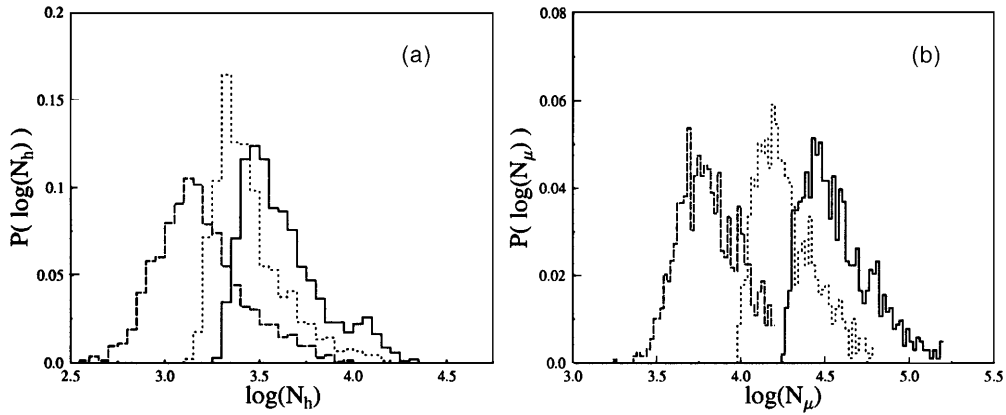


Fig. 3. – Multiplicity distribution of (a) hadrons and (b) muons in EAS with size $N_e = 10^6$ – 10^7 detected at Chacaltaya and initiated by primary protons (dashed), iron nuclei (dotted) and strangelets with $A_0 = 400$ (solid histogram).

(EAS) [17]. Among them was the striking observation [18] of extremely long-delayed neutrons in conjunction with the large EAS which cannot be explained by the known mechanism of hadronic cascades development. Also muon bundles of extremely high multiplicity observed recently by ALEPH detector (in the dedicated cosmic ray run) can originate from strangelets collisions with the atmosphere [19]. As an illustration of sensitivity of EAS characteristics on primary strangelets we show in fig. 3 our predictions for the corresponding distributions of hadrons and muons in EAS detected at Chacaltaya.

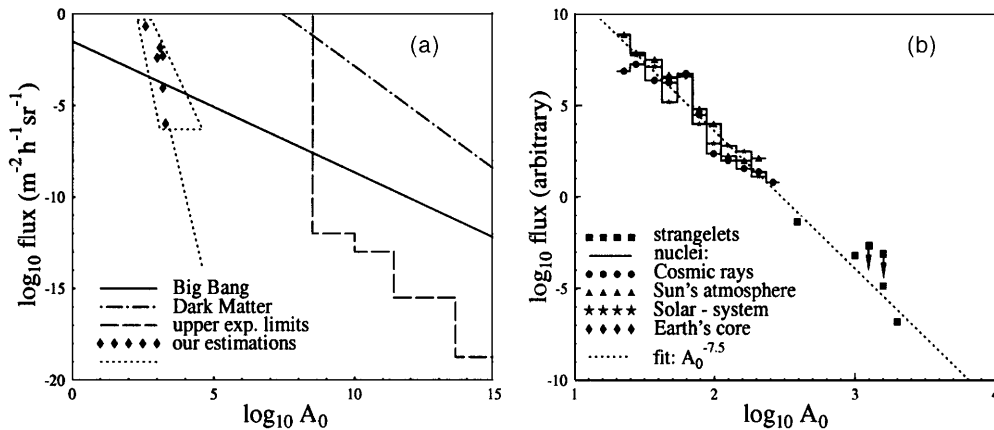


Fig. 4. – (a) The expected flux (our results) of strangelets compared with the upper experimental limit, compiled by Price [20], and predicted astrophysical limits: Big Bang estimation comes from nucleosynthesis with quark nuggets formation; Dark Matter one comes from local flux assuming that galactic halo density is given solely by quark nuggets. (b) Comparison of the estimated mass spectrum $N(A_0)$ for strangelets with the known abundance of elements in the Universe [21].

3. – Final remarks

The experimental data mentioned before lead to the flux of strangelets which is consistent (cf. fig. 4a) with the astrophysical limits and with the upper limits given experimentally [20]. There follows the $A_0^{-7.5}$ behaviour, which coincides with the behaviour of abundance of normal nuclei in the Universe (fig. 4b) [21]. The fascinating subject of searches for strangelets as a new form of matter can be successfully realised at experiments located in the mountain region of Chacaltaya. Interpretation of indirect observations (anomalous events observed in emulsion chambers and results from the measurements of EAS) can provide signals of strangelets. Moreover, direct identification (by implementing passive nuclear track detector arrays) of SQM is quite realistic in the near future. All this justifies interest in further experimental search for the SQM and for its cosmological and elementary particle physics aspects.

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