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Can indirect observations provide sign of strangelets?

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Abstract. We discuss the possible imprints of strangelets in experimental data from mountain altitudes. In particular we investigate: i) exotic events interpreted as signals of strangelets; ii) families and EAS induced by strangelets; iii) muon bundles and delayed neutrons. We also point out the possibility that extreme energy cosmic rays are the results of the decay of unstable primordial objects.

1 Introduction

In the astrophysical literature (Klingenberg, 1999) one can find a number of phenomena which can be regarded as a possible manifestation of the existence of the so called Strange Quark Matter (SQM) (in the form of lumps called strangelets), extremely interesting possibility of a possible new stable form of matter. There is some critical size of strangelets given by the value of its mass number $A = A_{crit} \sim 300 \div 400$ above which $A > A_{crit}$ strangelets are absolutely stable. Below this limit strangelets decay rapidly by evaporating neutrons. It is fully sensible to search for the strangelets in cosmic ray experiments, because the specific features of strangelets allow them to penetrate deeply into the atmosphere. The geometrical radii of strangelets turn out to be comparable to those of the ordinary nuclei, i.e. their geometrical cross sections are similar to the normal nuclear ones (Wilk and Wlodarczyk, 1996). To account for their strong penetrability one has to assume that strangelets penetrating deeply 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 collisions with air nuclei (until their A reaches the critical value A_{crit} (Wilk and Wlodarczyk, 1996)).

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2 Cosmic exotic events

There are several reports suggesting the existence of direct candidates for SQM (characterized mainly by very small ratios Z/A). All of them have mass numbers A near or slightly exceeding A_{crit} (including Centauro events, which contains probably ~ 200 barions (Bjorken and McLerran, 1979). Analysis of these candidates for SQM shows (Wilk and Wlodarczyk, 1996) that abundance of strangelets in the primary cosmic ray flux is $F_S(A_0 > A_{crit})/F_{tot} \simeq 2.4 \cdot 10^{-5}$ at the same energy per particle.

Unique possibility to observe possible imprints of strangelets offers Chacaltaya Laboratory ($540\ g/cm^2$). To detect strangelets with $A > A_{crit}$ at Chacaltaya, the mass of the initial strangelet should be $A_0 \simeq 7 \cdot A_{crit}$ what leads to $\propto 10^{-11}$ as the relative abundance of such strangelets. Experimental results obtained at Chacaltaya show a wide spectrum of exotic events (Centauros, superfamilies with 'halo', strongly penetrating components) which are clearly incompatible with the standard ideas of hadronic interactions known from accelerator experiments.

Already mentioned Centauro (and mini-Centauro) events, characterized by the extreme imbalance between hadronic and gamma-ray components among the 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 atmosphere and evaporating neutrons (Wilk and Wlodarczyk, 1997). Both flux ratio of Centauros registered at different depths and energy distribution within them can be successfully described by such concept. Another example of exotic events is phenomenon of alignment of structural objects in gamma-hadron families near a stright line in the plane at the target diagram (Borisov et al., 2001). The excess of the observed aligned families is incompatible with any conventional concept of interaction. One can speculate here on the possible action caused by the arrival of strangelets with high spin ($J \sim A^2$) with their gradual dispersion of mass $A(h)$ when propagating through the atmosphere.

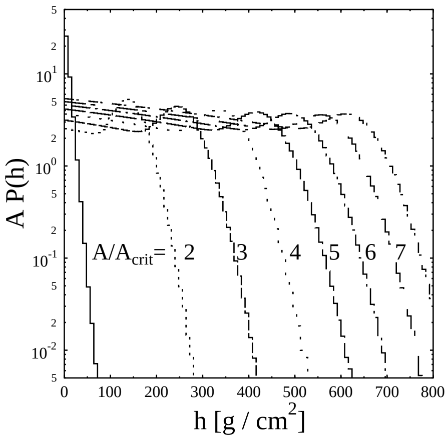

Fig. 1. Number of nucleons relased in $1\,g/cm^2$ at depth h of the atmosphere from the strangelet with mass number ratios $A_0/A_{crit} = 1, 2, ..., 8$, respectively.

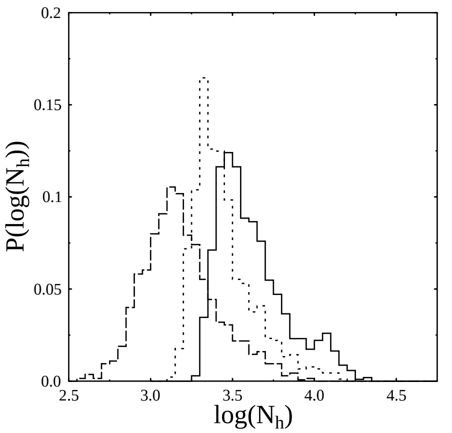

Fig. 2. Multiplicity distribution of hadrons in EAS with size $N_e = 10^6 \div 10^7$ detected at Chacaltaya and initiated by primary protons (dashed), iron nuclei (dotted) and strangelets with $A_0 = 400$ (solid histogram).

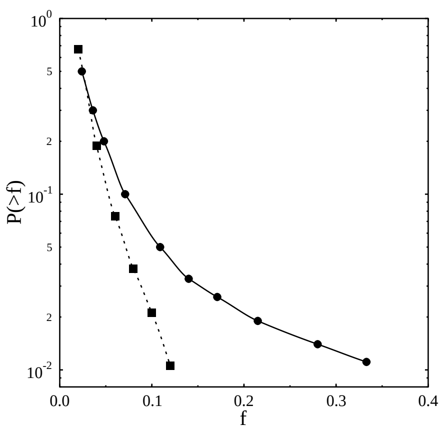

Fig. 3. Integral $f = E/\sum E$ distribution in families with $\sum E = 100 \div 200$ TeV initiated by primary protons (dots) and SQM (squares).

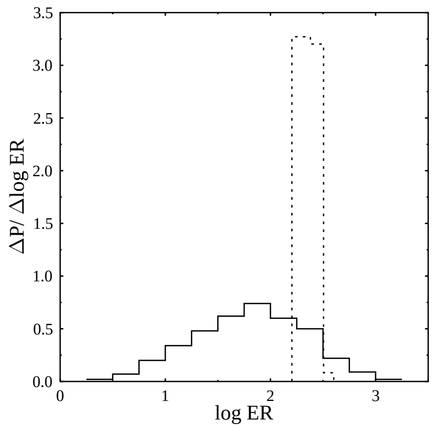

Fig. 4. ER distribution in families with $\sum E > 200$ TeV induced by primary protons (full line) and SQM (dashed line).

3 Families and EAS induced by strangelets

The characteristic features in strangelets propagation in the atmosphere are illustrated in Fig.1. Many characteristics of the families and EAS are sensitive to existence of primary strangelets. As an illustration we show in Fig.2 corresponding distributions of hadrons in EAS detected at Chacaltaya. Analysis of gamma-ray families induced by cosmic rays also shows significant differences between SQM and 'normal' hadronic matter.

On Fig.3 we show differences in $f = E/\sum E$ distribution in families with $\sum E = 100 \div 200$ TeV initiated by primary protons and SQM. Another differences show distribution of ER i.e. product of energy E and radial distance R from center of family (c.f. Fig.4).
Families from SQM are much more broader and are characterized by soften energy spectrum then those induced by primary proton.

4 Muon bundles from CosmoLEP

We would like to bring ones attention to the data from the cosmic-ray run of the ALEPH detector at the CosmoLEP experiment. Data archives from the ALEPH runs have revealed a substantial collection of cosmic ray muon events (CosmoLEP Report 1, 1999). More than $3.7 \cdot 10^5$ muon events have been recorded in the effective run time 10^6 seconds. Multi-muon events observed in the $16\,m^2$ time projection chamber with momentum cut-off $70\,GeV$ have been analyzed and good agreement with the Monte Carlo simulations obtained for multiplicities N_μ between 2 and 40. However there are 5 events witch unexpectedly large multiplicities N_μ (up to 150) which cannot be explained, even assuming pure iron primaries.

We shall estimate the production of muon bundles of extremely high multiplicity in collisions of strangelets with atmospheric nuclei (Rybczynski et al., 2001). Monte Carlo simulation describes the interaction of the primary particles

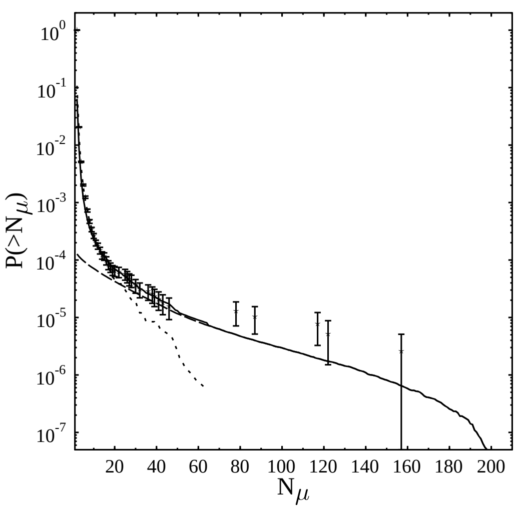

Fig. 5. Integral multiplicity distribution of muons for the CosmoLEP data (CosmoLEP Report 1, 1999) (stars). Monte Carlo simulations for primary nuclei with 'normal' composition (dotted line) and for primary strangelets with $A = 400$ (broken line). Full line shows the summary (calculated) distribution.

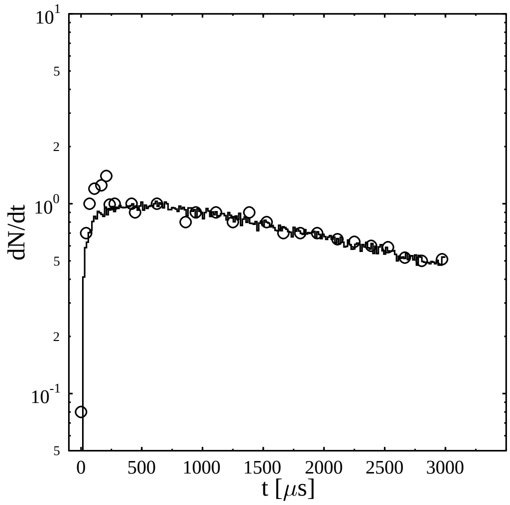

Fig. 6. Temporal distribution of highest multiplicity neutron event (circles) recorded by boron neutron counter (Antonova et al., 1999) compared with Monte Carlo simulations (full line) with mean lifetime of strangelet $\tau = 2000\ \mu s$.

at the top of atmosphere and follows the resulting electromagnetic and hadronic cascades through the atmosphere down to the observation level. The integral multiplicity distribution of muons from ALEPH data is compared with our simulations in Fig. 5. We have used here the so-called 'normal' chemical composition of primaries with 40% protons, 20% helium, 20% CNO mixture, 10% Ne-S mixture, and 10% Fe. It can describe low multiplicity ($N_\mu \leq 20$) region only. Muon multiplicity from strangelet induced showers are very broad. As can be seen, the small amount of strangelets (with the smallest possible mass number $A = 400$ (the critical mass to be $A_{crit} = 320$ here)) in the primary flux can accommodate experimental data. Taking into account the registration efficiency for different types of primaries one can estimate the amount of strangelets in the primary cosmic flux. In order to describe the observed rate of high multiplicity events one needs the relative flux of strangelets $F_S/F_{tot} \simeq 2.4 \cdot 10^{-5}$ (at the same energy per particle).

It can be interesting to point out that the high multiplicity events discussed here (with $N_\mu \simeq 110$ recorded on $16\ m^2$) corresponds to ~ 5600 muons with $E_\mu \geq 70\ GeV$ (or 1000 muons with energy above $220\ GeV$). These numbers are in surprisingly good agreement with results from other experiments like Baksan Valley where 7 events with more than 3000 muons of energy $220\ GeV$ were observed (Bakatanov et al., 1993).

5 Delayed neutrons

In the last years some evidences have been found (Auschev et al., 1997) for the existence of abnormal large events in neutron monitors that we shall call delayed neutrons. These phenomena could not be explained by the known mechanisms of hadronic cascades development.

Delayed neutrons may appear after decay of small, unstable strangelet, which was created as a result of interaction of primary cosmic rays with air nuclei. Mean lifetime of that strangelet may be few thousands μs long (Crawford et al., 1992; Berger and Jaffe, 1987). We calculated arrival time distribution of neutrons, like shown in (Ambrosio et al., 1999). We used this distribution for simulation of the time distribution of delayed neutrons which appear after decay of the strangelet. In Fig.6 we show experimental data from standard neutron supermonitor 18NM64 (Antonova et al., 1999) in comparison with our simulations. If we assume mean lifetime of a strangelet being $\tau \simeq 2000\ \mu s$ it describes satisfactory experimental data.

6 Interactions with background radiation

In analysis of cosmic rays propagation through the Universe one should consider their interaction with background radiation. In the region of high energies, the main processes are: pair production $p + \gamma \to p + e^+e^-$, photoproduction $p + \gamma \to p + \pi^0$ and nuclei photodisintegration. The energy losses of nuclei with mass A during their interaction with background photons given by (Berezinsky et al., 1990) shows remarkable Z^2/A behaviour ($\sim A^{-1/3}$ in the case of strangelets). In Fig.7 we show the energy losses of nuclei and strangelets due to interactions with the background radiation. As can be seen, strangelets due their large mass number A can propagate through the Universe with very small energy losses. Critical energy for strangelets is seemighty larger then this for protons (c.f. Fig.8).

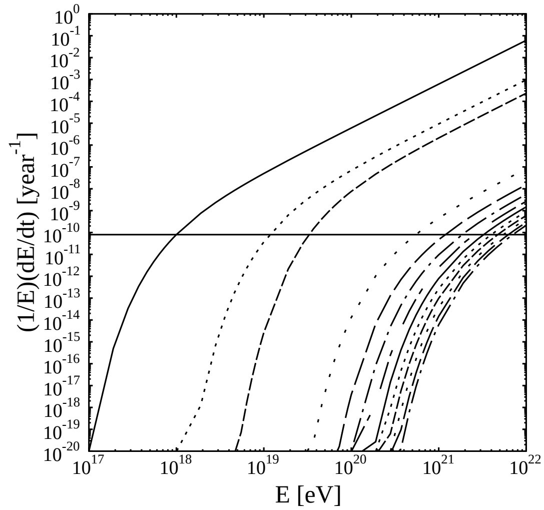

Fig. 7. Energy losses of protons, O, Fe, and some strangelets with mass number $A = 320, 640, ..., 3200$ (respectively from left) due to interaction with cosmic background radiation. Horizontal line shows red shift limit.

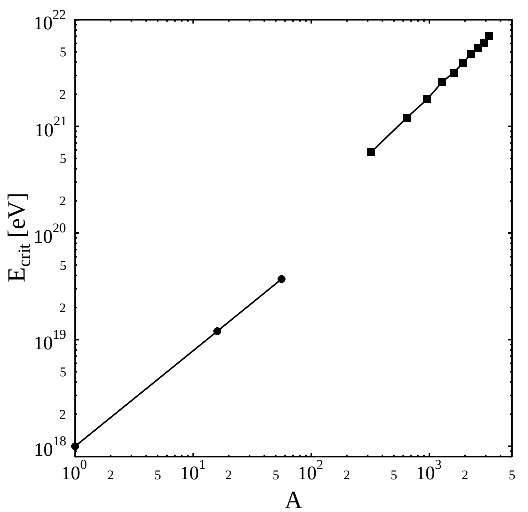

Fig. 8. GZK cutoff E_{crit} as a function of mass number A. Dots represents normal nuclei, squares - strangelets.

7 Summary and conclusions

Problem of possible Strange Quark Matter existence in the Universe were discussed from many year. There are large amount of phenomena that cannot be explain without assuming of existence of SQM. We demonstrated only few examples from various fields of cosmic ray physics. In particular we showed that extremely high energy cosmic ray can exists. They can be results of the decay of unstable primordial objects. Strangelets may be primordial remnant of the Big Bang.

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