# Famous stratospheric superfamilies with $E_0 \approx 10^{16}$ eV

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***Abstract*. In the world statistics of available data on CR there are only 2 stratospheric superfamilies with $E_0 \approx 10^{16}$ eV. Their important feature is the generation presumably from a single nuclear interaction, that is an essential difference from the events detected by XEC (X-ray emulsion chambers) in mountain experiments. Here especial interest is conditioned for lack of so high energy events at accelerators for the time being.**

**A comparative analysis of the cosmic ray superfamily "STRANA" detected by an emulsion chamber aboard the Russian stratospheric balloon and the superfamily JF2af2 detected by an emulsion chamber during a high-altitude flight of the supersonic aircraft Concord (international experiment) is performed. Both events with $E_0 \approx 10^{16}$ eV are characterized by the pronounced alignment effect and very large transverse momenta of secondary particles.**

***Keywords*: alignment, nuclear interaction, emulsion chambers.**

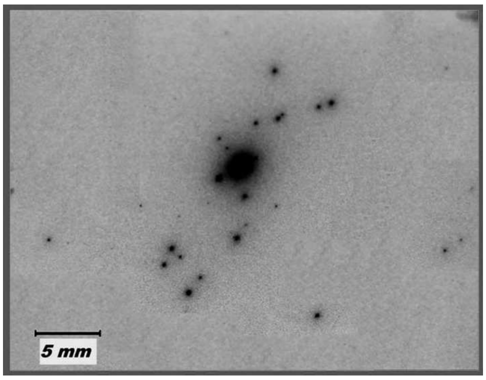


Fig. 1: The general view of the central area of the "STRANA" superfamily in X-ray film.

Fig. 2: The general view of the superfamily JF2af2 (Concord experiment) in emulsion.

## I. INTRODUCTION

The world statistics of experimental data on cosmic rays includes only two stratospheric superfamilies with super high energy $E_0 \approx 10^{16}$ eV. An important property of these superfamilies is the origin from hypothetically single (due to the smallness of the atmospheric layer traversed by the primary CR particle) nuclear interaction, which distinguishes noticeably these superfamilies from the events detected by emulsion chambers in the mountains and from extensive air showers. These examples of nuclear interaction are of special interest in view of the fact that the investigation of interactions with such a high energy is unavailable for modern accelerators yet; therefore, any specific feature of these events yields important information for getting the idea of the picture of nuclear interaction at a superhigh energy ($E_0 > 10^{16}$ eV).

## II. EXPERIMENTS

The unique gamma-hadron superfamily "STRANA" was detected during the flight of the emulsion chamber aboard a balloon in 1975 [1]. The balloon started at the test area of the USSR Ministry of Defense in the town of Klyuchi, Kamchatka, then the route went above the territory of Kamchatka, the Sea of Okhotsk, Far East, Siberia, Ural, and ended in the Volga region. The flight duration of the balloon along this route was about 147 h. The balloon went up to an altitude of 30–33 km during a rather short time of 2–2.5 h, and then flew at that altitude in the route corridor in a completely autonomous way. The average flight altitude corresponded to an air pressure of $\sim 10.2$ g/cm$^2$.

The detecting setup [2] was a multilayer emulsion chamber. The geometric area of the detector amounted 40x50 cm$^2$. The calorimeter was assembled of nine 0.5 cm lead layers with two types of emulsions as intermediate layers: nuclear emulsion R-2T-50 and X-ray film RT-6M. The total thickness of the calorimeter corresponds to 9 c.u., or to 0.26 of the nuclear interaction path. The general view of the central area of the "STRANA" superfamily in X-ray film is shown in Fig. 1.

The superfamily JF2af2 [3] was detected by the X-ray emulsion chamber on board the supersonic aircraft Concord which performed flights along the route Paris—New York. In each flight during more than 2 h the aircraft was at an altitude of about 17 km, which corresponds to an atmosphere depth of about 100 g/cm$^2$. The detector thickness allowed registration of the gamma-component up to 1000 TeV [4], but was insufficient for detecting secondary hadrons. The general view of the superfamily JF2af2 in emulsion is presented in Fig. 2.

## III. General characteristics of "STRANA" and JF2af2 superfamilies

The gamma-hadron superfamily "STRANA", which was reprocessed not long ago [5] with use of modern calculations and modern measuring devices, contains only 107 particles: 30 hadrons and 70 gamma-quanta (plus the leading jet of the hadronic origin at the center of the event). The zenith angle of incidence of the family $\theta = 30^o$. The energy determined by darkened X-ray films was $\Sigma E_\gamma$ = 1670 TeV for the gamma component and $\Sigma E_h^{(\gamma)}$ = 807 TeV for hadrons. The detection threshold was $E_{thr} \approx 3$ TeV. After introducing the corrections to cutting by the film edge, to $< k_\gamma > \approx 1/3$, and the hadron detection efficiency $K_{eff} \approx 40\%$, $\Sigma E_\gamma + (\Sigma E_h^{(\gamma)} / < k_\gamma >)/K_{eff} \approx 0.92 \cdot 10^{16}$ eV [5]. The leading particle adds (1–2)$\cdot 10^{15}$ eV. Finally, $E_0 = (1.0 - 1.1) \cdot 10^{16}$ eV.

The gamma-family JF2af2 (Concord) with the zenith angle of incidence $\theta = 52^o$ contains only 211 particles, all gamma-quanta are above the threshold $E_{thr} \approx 0.2$ TeV. According to estimates in [6], $\Sigma E_\gamma \approx 1600$ TeV, the estimated $E_0 \approx (0.5 - 1) \cdot 10^{16}$ eV.

## IV. Alignment effect in the superfamilies

The alignment is the particle arrangement in the plane of the target diagram along the straight line which corresponds to the coplanar generation of most energetic particles in the interaction event. For alignment analysis always most energetic objects in a family are considered, beginning from the highest one and further in the order of decreasing energy.

For quantitative description of the alignment phenomenon the parameter $\lambda$ is the most appropriate [5]:

$$\lambda_m = \frac{\sum\limits_{i \neq j \neq k}^{m} cos(2\varphi_{ijk})}{m(m-1)(m-2)} \ ,$$

where $\varphi_{ijk}$ is the angle between the vectors $\overrightarrow{ki}$ and $\overrightarrow{kj}$ and m is the number of points. The parameter varies from 1 (for m points situated along the straight line) to $-1/(m-1)$ (in isotropic cases). The event is assumed to be definitely aligned for $\lambda \geq 0.8$.

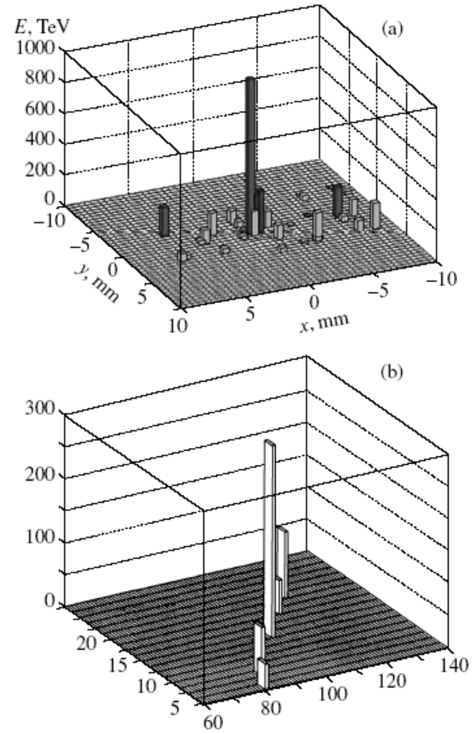


Fig. 3: 1. Alignment of 5 most energetic particles in the superfamilies: (a) "STRANA", 5 most energetic hadrons (dark bars) and all particles of the central region, and (b) JF2af2 (Concord experiment [6]), 5 most energetic gamma-quanta.

The linear correlation coefficient r determined by the least square root method, if the straight line is plotted through the ensemble of points, can also characterize the alignment [6],

$$r_m = \frac{\sum\limits_{i=1}^{m}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum\limits_{i=1}^{m}(x_i - \overline{x})^2}\sqrt{\sum\limits_{i=1}^{m}(y_i - \overline{y})^2}}$$

where m is the number of considered particles, $x_i, y_i$ are their coordinates, and $\overline{x}$, $\overline{y}$ are the means. For r = 0, the ensemble is isotropic; for r = 1, it is aligned along a straight line. The value $\lambda = 0.8$ corresponds to approximately r = 0.94.

Figure 3 shows the diagrams of particle positions in the normal plane in the superfamilies "STRANA" (Fig. 3a) and JF2af2 (Fig. 3b).

The values of the alignment parameter in the family "STRANA" $\lambda_3$ = 0.98, $\lambda_4$ = 0.99, $\lambda_5$ = 0.90. The probability of such random configuration (by simulations using the QGSJET model [5] without any special alignment mechanism) is 0.01% in simulated families from a primary proton and 0.03% in simulated events from a primary iron nucleus.

The values of the alignment parameter in JF2af2 [6] $r_4$ = 0.9993 or $\lambda_4$ = 0.9972 for four most energetic particles and r = 0.993 for 38 energetic gamma-quanta with total energy 808 TeV (51% of $\Sigma E_\gamma$). Thus, both superfamilies possess high degree of alignment of most energetic particles.

It was shown for the event JF2af2 [4] that the large part of comprising particles (38 of 211) with 51% of the energy is situated anisotropically along the alignment direction. In the superfamily "STRANA" the particles in the central area (33 hadrons and gamma-quanta) display also obvious anisotropy of disposition. Whole this configuration is not distorted due to cutting by the film edge. The results of analysis for the whole ensemble with respect to several anisotropy parameters were given in [7]. The experimental values of all parameters exceed significantly the calculated values in artificial events and go far beyond the limits of possible random fluctuations, which is in favor of the pronounced anisotropy in the position of all particles in the central region of the family "STRANA". The stretching direction of anisotropically located particles coincides with the alignment direction of 5 most highly energetic hadrons (i.e., at emission these secondary particles were distributed near the coplanar generation plane).

## V. Interaction height above the chamber and particle momenta in superfamilies

In the superfamily "STRANA" the interaction height above the chamber was estimated using three methods [8]. The height value estimated using pairs of gamma-quanta from $\pi^0$-meson decay was H = 1180 $\pm$ 340 m. The estimation on the base of the particle pseudorapidity distribution in the superfamily gave H = 300 $\pm$ 100 m. The triangulation method with use of many emulsion layers estimated the height as H = 50 $\pm\, ^{310}_{40}$ m.

The corresponding average momentum estimates (over 30 hadrons of the family) obtained using the first method ($\pi^0$-meson decay) yielded $< p_t >= 2.5 \ \pm\ ^{1.1}_{0.7}$ GeV/c; using the particle pseudorapidity distribution in the family, $< p_t >= 10 \ \pm\ ^{5}_{2.5}$ GeV/c; and using the triangulation method, $< p_t >= 60 \ \pm\ ^{250}_{52}$ GeV/c. This allows one to state that $< p_t >$ in this nuclear act is certainly larger than 2.5 GeV/c, and is most likely around 10 GeV/c [8].

In the superfamily JF2af2 the distribution over invariant masses was constructed, and the factor $< ER >$ was estimated; thus the evaluated height of main $\pi^0$-mesons production above the chamber appeared to be smaller than 100 m in the first method, or 65—325 m, when the second method was used. Then the estimates for the momenta $p_t$ for pions responsible for the production of main gamma-clusters of the superfamily are given in [4], [6] as $< p_t >= 3 - 10$ GeV/c. Under the assumption of the mechanism of coplanar generation via the quarkgluon string rupture, the maximal tension of this string formed via a diquark, according to estimate in [6], is 20—30 GeV fm$^{-1}$ instead of 1 GeV fm$^{-1}$.

## VI. Conclusions

Thus, in both events available in the world statistics ("pure" interactions) with $E_0 \approx 10^{16}$ eV the common features are observed in the nuclear interaction. Those are the pronounced effect of coplanar secondary particle generation and large average transverse momenta $< p_t >$ exceeding standard values by a factor of 5–20 (and maybe larger). An unambiguous theoretical explanation of these facts has not been developed yet.

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