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Measuring the ionization energy loss of EAS in the atmosphere

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Abstract: Ionization loss of electrons in the atmosphere, as a corresponding fraction of extensive air shower (EAS) energy dissipated along cascading, amounts to a major part of the primary particle energy. It has been shown that there is a relation between the loss and the total flux of air Cherenkov light induced by relativistic electrons where the model dependence is parameterized by the shower maximum position. We have analyzed the Yakutsk array data using the total flux as a measure of EAS energy loss for ionization in the atmosphere; and furthermore, as the robust estimator of cosmic ray (CR) energy with supplementary data from scintillators. Particularly, the energy spectrum of CRs is considered above 10^{18} eV which is derived from air Cherenkov light measurements.

Introduction

In this paper we are focusing on the experimental data obtained in Yakutsk with Cherenkov light detectors aiming at the energy spectrum of ultra-high energy cosmic rays (UHECRs), particularly in the region where an 'ankle' feature is observed. Although the Cherenkov light data from the Yakutsk array are reliable at CR energies below 10^{19} eV due to Cherenkov detector subset acceptance area, an indication was found of the ankle in the spectrum at $E \leq 10^{19}$ eV in consistency with the data of other giant EAS arrays.

According to UHECR propagation simulations [1, 2, 3] there should be two signatures of extragalactic protons in the spectrum below 10^{19} eV: dip and bump. The dip is produced due to $p + \gamma_{\rm CMB} \rightarrow p + e^+ + e^-$ interaction at energy centered by $E \approx 8 \times 10^{18}$ eV. The bump is produced by pile-up protons which loose energy in the GZK cutoff. The alternative origin of the dip in the spectrum follows from the two-component model as a transition from galactic to extragalactic cosmic rays [2, 3]. These features are clearly seen (as ankle) in the spectra observed by AGASA [4], HiRes [5] and Yakutsk [6] arrays. Furthermore, they say, it can be considered as the confirmed signature of interactions of extragalactic UHE protons with CMB [1].

Air Cherenkov light detectors of the Yakutsk array and the dataset

A description of the Yakutsk array detectors and the data processing methods are given in [6, 7]. We have used in this paper the data of the Yakutsk array observed by naked photomultipliers - air Cherenkov light detectors. Only $\sim 10\%$ of the showers are accompanied by the light detected in moonless&cloudless nights when the Cherenkov signal can be measured and processed properly. A total of 1062 events have been collected above 10^{18} eV (=1 EeV) along EAS selection criteria we have chosen.

An observation period is 1995 - 2007 including 5716 hours of exposition of the Cherenkov light detectors. The showers are selected by the main array trigger system in coincidence with Cherenkov signal; EAS events with axes outside the array area and zenith angles more than 45^0 are rejected. More details concerning EAS event selection methods are given in [8, 9].

Estimation of EAS primary particle energy

The method of energy estimation is based on the ionization integral measurement in EAS. Relativistic electrons of the shower induce Cherenkov light in the atmosphere. The total flux of light, Q_{tot}, is related to the electromagnetic component energy, E_{em}; the relation is largely independent of the model [6, 10]. The energy fraction dissipated in the ground can be estimated using the tail of the cascade curve measured in inclined showers.

Another method of the ionization integral measurement is realized in HiRes [5] and Pierre Auger [11] experiments. In this case the fluorescence light emitted by wounded nitrogen molecules along the trajectory of the shower is collected by mirrors and received by photomultiplier pixels.

The light intensity is proportional to the number of shower electrons, so the cascade curve, $N_e(t)$, is scanned by fired pixels, and ionization in the atmosphere (ionization integral) can be estimated:

$$E_i^{t_{s.l.}} = \frac{\epsilon_0}{t_0} \int_0^{t_{s.l.}} N_e(t) dt,$$

where t is a slant depth along the shower axis; $t_0 = 36.7$ g/cm^2 is a radiation length; $t_{s.l.}$ is a thickness of the atmosphere; $\epsilon_0 = 86$ MeV is the critical energy. It was shown in the cascade theory, that the electromagnetic component energy is equal to the ionization integral $E_{em} = E_i^{\infty}$; this is why the energy E_{em} is actually evaluated in these experiments.

The main distinctive feature of the Yakutsk array is the measurement of the total flux of Cherenkov light emitted in the atmosphere, Q_{tot}, which is the main estimator of the primary particle energy. Using the classic Frank and Tamm formula for the number of Cherenkov photons emitted by relativistic electrons in the atmosphere, the relation between Q_{tot} and ionization integral has been derived [7] (in eV/photon):

$$\frac{E_i^{t_{s.l.}}}{Q_{tot}} \approx (3.01 \pm 0.36) \times 10^4 (1 - \frac{X_{max}}{1700 \pm 270}), \tag{1}$$

where $X_{max} \in (500, 1000)$ g/cm^2; $\overline{T} = -30^0$ C, $\overline{P} = 754$ mm.merc.

The data of Cherenkov light detectors are parameterized by the intensity at 150 m from the shower core, Q_{150}, the only core distance really present in the shifting range of measurements when the primary energy is rising considerably. Detector arrangement of the Yakutsk array is appropriate to estimate Q_{tot} in the range above about $Q_{150} = 10^7$ m^{-2}, as it is seen from Table 1, while charged particles are concentrated near the shower core. In each Q_{150} bin the lateral distribution function is extrapolated in order to calculate the total flux.

Table 1: Fractions of the Cherenkov light (Δ_Q,), charged particles (Δ_S) and muons (Δ_μ) at sea level measurable at the Yakutsk array.

Q_{150}, $^{-2}$	10^6	10^7	10^8	10^9
$\Delta_Q, \%$	50	70	90	85
$\Delta_S, \%$	-	-	14	13
$\Delta_\mu, \%$	-	-	65	65

Other fractions of the primary energy carried out by electromagnetic, muonic and other shower components beyond sea level are evaluated using:

i) the total number of electrons

$$E_g = \epsilon_0 N_e \lambda_e / t_0,$$

where the attenuation length λ_e is derived from zenith angle dependence of N_e;

ii) the number of muons measured on the ground

$$E_\mu = N_\mu(E > 1\, GeV)\overline{E_\mu},$$

where the average energy of muons $\overline{E_\mu} = 10$ GeV is taken from the MSU array data;

iii) residuary energy fractions transferred to neutrinos E_ν, nucleons E_h, etc., unmeasurable with this array, are estimated using model simulations.

The resulting apportioning of the primary energy 10^{18} eV is given in Table 2. The final relation between Q_{150} and the primary energy is taken along suggestion in [7].

Experimental uncertainties of EAS component energies estimated using the Yakutsk array data are summarized in the last column of Table 2. The main contribution arises from δE_i which is formed by uncertainties in the atmospheric transparency (15%), detector calibration (21%) and the total light flux measurement (15%). Errors in estimation of $N_e, \lambda_e, N_\mu + N_\nu$ determine the next two items. Resultant energy estimation uncertainty ($\sim 32\%$) is the sum of all errors weighed with the energy fractions of EAS components.

Table 2: The primary energy fractions carried out by different EAS components. $E = 10^{18}$ eV. $\theta = 0^0$. $E_i^{t_{s.l.}}$ is the ionization loss of electrons in the atmosphere; E_g is the ionization loss of electrons in the ground; E_μ is energy of muons on the ground; E_{unobs} is the energy carried by hadrons, neutrinos, etc.

Energy deposit channel	The fraction of energy, %	Experimental uncertainty, %
$E_i^{t_{s.l.}}$	80	30
E_g	9	60
E_μ	6	10
E_{unobs}	5	20

The energy spectrum of cosmic rays as derived from air Cherenkov light measurements in EAS

Cherenkov light detectors of the Yakutsk array give the possibility to reconstruct the energy spectrum of primary cosmic radiation in the energy range from $E \sim 10^{15}$ to 6×10^{19} eV basing on the Cherenkov light data only [8]. Total numbers of electrons and muons measured on the ground are used to estimate the energy fractions of EAS components in this case but the final relation between the energy of the primary particle and Q_{150} comprises the light intensity alone.

In this paper the intensity of CRs has been evaluated above $E = 10^{18}$ eV using EAS event number detected with Cherenkov light detectors, and aperture $S_{eff}T\Omega$ of the array subset in a particular energy interval, where the area bounded by the perimeter S_{eff} depends on the primary energy and zenith angle, Ω is an acceptance solid angle, and T is a sum of observational periods.

The resulting differential spectrum of cosmic rays is given in Fig. 1; a comparison with the data from other experiments is given in Fig. 2 after normalizing of the energy estimates.

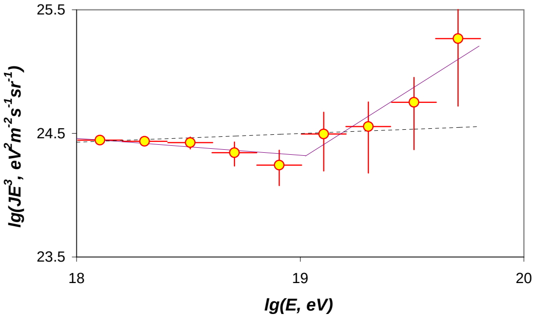

Figure 1: Cosmic ray flux (multiplied by E^3 to exhibit an ankle feature of the spectrum) derived from Cherenkov light data of the Yakutsk array. Experimental data (circles) are given with statistical errors (vertical bars) in energy bins indicated by the horizontal bars. Solid lines are power functions with (integral) exponents $\gamma = -2.14/-0.85$ below/ above $E = 10$ EeV. The dotted line is for $\gamma = -1.93$ in the whole range.

Is there an ankle in the energy spectrum of CRs detected with the Yakutsk array?

While apparently, the best fit to the data (e.g. Fig 1) is given by the power function with different exponents above and below $E \sim 10$ EeV, one cannot exclude a single exponent in the whole energy range. We have checked up with our Q_{tot} measurements a null hypothesis that the CR energy spectrum is $J(>E) = N_{tot}(E/E_{thr})^\gamma$, where N_{tot} is the number of EAS events detected above the threshold energy $E_{thr} = 1$ EeV; $\gamma = -1.93$ in the interval $E \in (1, 100)$ EeV. The actual number of events detected in a particular energy bin is not applicable when calculating a goodness-of-fit statistic due to the array aperture, $ST\Omega$, dependent on energy. Instead, we have used the normalized intensity $n(E_i)ST\Omega(E = 100)/ST\Omega(E_i)$ as the event number in i-th bin.

Pearson's test gives $\chi^2 = 12.1$ for 8 degrees of freedom, so we cannot reject the power law fit of the spectrum without an ankle. The reason behind is the insufficient number of air showers detected with Cherenkov light detectors of the array at energies $E > 10$ EeV. These data yield an indication of the ankle in the energy spectrum of CRs. In the energy range above 10 EeV the charged par-

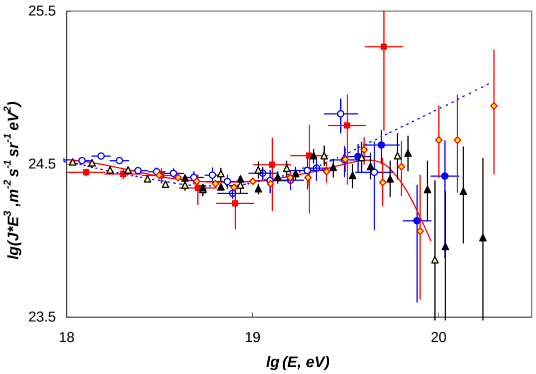

Figure 2: Differential energy spectrum of cosmic rays measured by giant arrays. Experimental data: AGASA (rhombuses), HiRes (triangles), Yakutsk array charged particles data (circles) and Cherenkov light data (squares). All energy estimates are scaled to meet Q_{tot} data. Model simulations: Berezinsky et al. (solid curve), Wibig and Wolfendale (dotted curve).

ticle detectors of the Yakutsk array provide more events. It will be productive to analyze these two sets of data in conjunction.

Discussion and conclusion

The data of giant arrays which have observed the ankle of the CR spectrum are shown in Figure 2. Open and (semi)filled signs refer to different subsets or triggers of the arrays. Due to the variety of methods used to estimate the primary energy of EAS in these experiments resulted in systematic errors of the data, the position of ankle and intensity of the CR flux ($\times E^3$) are different. In order to compare the results we have scaled the primary energies estimated so that the intensities are uniformly close to each other around $E = 10^{19}$ eV. Factors used to scale energies are: 0.89 for AGASA data, 1.21 for HiRes data, 0.77 for the charged particle detectors data of the Yakutsk array. Cherenkov light data are not scaled; an arbitrary primary flux in models is adjusted to match the experimental intensity at 10^{19} eV.

The overall conclusion is that while our Cherenkov light data only are not sufficient to give up the power function fit of the spectrum without any ankle, the multitude of experimental data observed including those from charged particle detectors of the Yakutsk array insist on the existence of the ankle feature of the spectrum in the vicinity of $E = 10^{19}$ eV. The observed ankle (in coincidence by all arrays) is in accordance with theoretical predictions and can be treated in favour of extragalactic origin of cosmic rays above $10^{18} - 10^{19}$ eV.

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