Analysis of the energy estimation algorithm of UHECRs detected with the Yakutsk array

A.A. Ivanov and S.P. Knurenko
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, Yakutsk 677891, Russia

Abstract

The primary energy estimation method is one of the clue features to deal with using extensive air shower (EAS) technique of ultra-high energy cosmic ray (UHECR) measurements. In this paper we discuss the present status of algorithms used to assign the primary energy to showers detected with the Yakutsk array. Special attention is paid to the total flux measurement of the Cherenkov light on the ground which is a basis of the model-independent approach to the energy evaluation of EAS original particle. The uncertainty limits of the energy estimation method are analyzed.

1. Introduction

The main distinctive feature of the Yakutsk array is the air Cherenkov light measurement. The total flux of the light emitted in atmosphere is used as the main estimator of the primary particle energy. Here we discuss the shower parameters governing the energy fractions transferred to EAS components.

2. Energy balance of EAS components

The energy of EAS primary particle, E_0, transferred to the shower components can be described on the basis of cascade kinetic equations [2,3]. If $E_k, (k = N, \pi, \mu\nu, e\gamma)$ is the energy transferred to nucleons, charged pions, muons+neutrinos, electrons+photons, then we are going to demonstrate in this section, with simple arguments, that a few cascade parameters determine the ratios between E_k - the energy balance in the shower. For instance, the kinetic equation for charged pion density $\pi(x, E)$ at depth x:

$$\begin{aligned}\frac{\partial\pi(x,E)}{\partial x} = -(\frac{1}{\lambda_\pi}+\frac{B_\pi}{xE})\pi(x,E) + \frac{2}{3\lambda_\pi}\int_E^{E_0}\pi(x,U)w_{\pi\pi}(E,U)dU \\ +\frac{2}{3\lambda_N}\int_E^{E_0}N(x,U)w_{\pi N}(E,U)dU, \qquad (1)\end{aligned}$$

where interaction mean free paths λ_π, λ_N are assumed constant; $w_{\pi\pi}(E,U), w_{\pi N}(E,U)$ are the spectra of charged pions produced in pion-air and nucleon-air

---

pp. 385–388

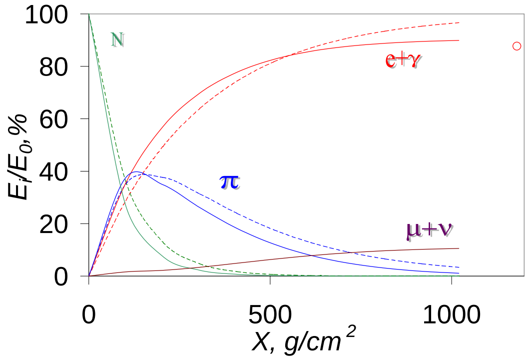

Fig. 1. The energy carried by the cascade nucleons (N), charged pions (π), muons and neutrinos ($\mu + \nu$), electrons and photons ($e + \gamma$). Dashed curves show analytic expressions with $\lambda_i, K_N = const, B_\pi = 0$: $E_N = E_0 exp(-K_N x/\lambda_N)$; $E_\pi = 2/3E_0(1 - exp(-K_N x/\lambda_N))exp(-x/\lambda_\pi/3)$; $E_{e\gamma} = E_0 - E_N - E_\pi$. Solid curves are δ-model results: mean free paths are supposed rising $\propto 0.08 lnE$; $B_\pi = 120GeV$; $K_N = 0.5$; $n_s \propto E^{1/4}$; $E_0 = 10^{18}$ eV.

interactions, can be transformed (integrating $\int EdE$) to:

$$\frac{dE_\pi}{dx} = -\frac{E_\pi}{\lambda_\pi} - \frac{B_\pi \pi(x, E > 0)}{x} + \frac{2}{3\lambda_\pi} E_\pi + \frac{2K_N}{3\lambda_N} E_N, \tag{2}$$

where $E_\pi(x) = \int_0^{E_0} \pi(x, E)EdE$; $\pi(x, E > 0) = \int_0^{E_0} \pi(x, E)dE$; K_N is nucleon inelasticity supposed to be constant; $E_N = E_0 exp(-K_N x/\lambda_N)$.

In the energy range $E >> B_\pi$ the only parameters to define the quantity E_π are K_N/λ_N and λ_π. It means that the energy transferred to charged pions is independent of the spectra of pions produced in nuclear interactions. Hence, in the general case, we can use the simple δ-model with $w_{ik}(E, U) = n_s \delta(E - U/n_s)$, where n_s is the multiplicity of secondaries, to balance the components energy in a shower. Of course, to evaluate the energy of muons and neutrinos we have to use the more realistic model, but the net value of $E_{\mu+\nu}/E_0$ is ~ 0.1, so the uncertainty due to simplified model should be of the second order of magnitude. To summarize, the model parameters to govern the energy balance in the shower are average inelasticity coefficients, mean free paths, multiplicity of secondaries and the fragmentation rate of primary nucleus. Other model characteristics such as 'the form of rapidity distribution of constituent quarks' are redundant.

The resultant energies in the case of constant $\lambda_\pi, \lambda_N, K_N$ and $B_\pi = 0$ are shown in Fig. 1 together with δ-model results. Also shown here (open circle) is an asymptotic ($x = \infty$) estimation of $E_{e\gamma}$ with CORSIKA(+QGSjet) program at $E_0 = 10^{18}$ eV [6].

3. Experimental evaluation of the energy dispensed to EAS components

Energy fractions of the main EAS components can be estimated using the Yakutsk array data. Ionization loss of electrons is measured here detecting the total flux of the Cherenkov light on the ground. A relation between these values is given taking into account model calculation results and detector calibration, k, as far as the atmospheric transparency, τ (see for instance [4] and references therein):

Table 1. The primary energy portions gone with EAS components. $E_0 = 10^{18}$ eV. $\theta = 0^0$.

Energy deposit channel	The portion of energy, %	Experimental uncertainty, %
Ionization loss of electrons in the atmosphere	78	30
Ionization loss of electrons in the ground	9	30
Energy transferred to muons and neutrinos	9	16
Energy carried by the nuclear active component	4	20

$$E_i = \frac{k}{\tau} Q_{tot} = \frac{2.18 \times 10^4 Q_{tot}}{0.37 + 1.1 \times 10^{-3} X_{max}}. \tag{3}$$

Another portion of the energy carried out by electromagnetic and muonic components beyond the sea level is evaluated via the total number of electrons $E_{el} = \epsilon_0 N_e \lambda_e / t_0$ and muons $E_\mu = N_\mu < E_\mu >$ measured on the ground. Residuary energy fractions transferred to neutrinos, nucleons etc., unmeasurable with this array, are estimated using model calculations. The resulting apportioning of the primary energy 10^{18} eV is given in Table 1. The energy fraction carried by electromagnetic component appears to be the basic contribution to the total energy of the shower, and its energy dependence (measured with Cherenkov detectors + electron and muon detectors of the Yakutsk array) is illustrated in Fig. 2, together with δ-model estimation on the superposition assumption for the primary proton and iron nucleus.

Because the air Cherenkov light total flux, and electron and muon number of the shower are experimental values measured on the ground, only about 10% of the primary energy $E_0 = 10^{18}$ eV is calculated using the model assumptions. So we consider the energy estimation algorithm in use in the Yakutsk group to be model-independent in the first approximation.

Moonless nights when air Cherenkov light measurements are possible are $\sim 10\%$ of the observation period. In order to evaluate the primary energy of the bulk of showers, the linear correlation is used between the charged particle density at 600 m from the shower core, S_{600}, and the light intensity at 400 m from the core, Q_{400} (Fig. 3) which, in turn, is related to the total flux of the Cherenkov light on the ground [1,2].

4. Summary of uncertainties in the energy estimation algorithm

Experimental uncertainties in EAS component energies estimated using the Yakutsk array data are summarized in Table 1. The main contribution arise from δE_i which is formed by uncertainties in atmospheric transparency (15%), detector calibration (21%) and the total light flux measurement (15%). Errors

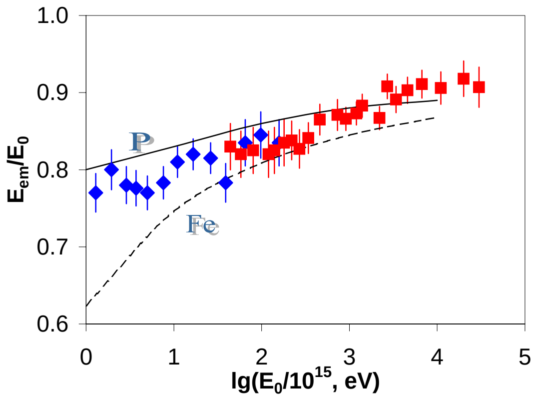

Fig. 2. The electromagnetic component energy estimation from the Yakutsk array data: autonomous subarray (rhombuses), the main array (squares); P, Fe curves are δ-model results.

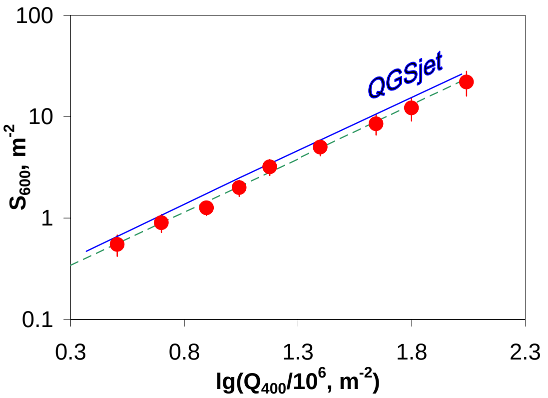

Fig. 3. The correlation between charged particle density at 600 m from the core (S_{600}) and air Cherenkov light intensity at 400 m (Q_{400}) measured in the same showers. The model calculation results (solid line for QGSjet) are from [5].

in estimation of $N_e, \lambda_k, N_\mu + N_\nu$ determine the next two items (for ionization in the ground and $\delta E_{\mu+\nu}$). Resultant energy estimation uncertainty is a product of two columns of the Table 1: $\delta E_0 \sim 30\%$. Extra 20% is added due to $S_{600} - Q_{400}$ conversion uncertainty.

The differences in the energy spectrum of UHECR measured with three arrays: AGASA, HiRes and Yakutsk below $E = 10^{20}$ eV are within 30% uncertainty in the primary energy estimation [4]. It can be considered as a sort of consistency test for the uncertainty limits of the energy estimation algorithm used in Yakutsk.

Acknowledgements. This work is supported in part by RFBR (grants #03-07-90065, #02-02-16380, #00-15-96787) and Russian Ministry of Sciences (grant #01-30).

References

1. Afanasiev B.N. et al. 1993, Proc. Tokyo WorkShop EHECR (ICRR, Tokyo), 35.
2. Dyakonov M. N. et al. 1991, Cosmic Rays of Extremely High Energy (Nauka, Novosibirsk).
3. Erlykin A.D., Wolfendale A.W. 2001, astro-ph/0112553.
4. Ivanov A.A., Knurenko S.P., Sleptsov I.Ye. 2002, Nucl. Phys. B. (Proc. Suppl., submitted).
5. Knurenko S.P. et al. 1999, Proc. 26th ICRC (Salt Lake City), 1, 372.
6. Song C. et al. 2000, ApPh 14, 7.