Cosmic ray primary composition in the energy range 10-1000 TeV obtained by passive balloon-borne detector: re-analysis of the RUNJOB data

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Abstract: We present an alternative analysis of the data reported by the balloon-borne experiment RUNJOB. According to RUNJOB, the average mass number of primary cosmic ray particles is constant up to 1 PeV. Here we show that there is more than one solution, which reproduce the observational data. It is demonstrated that, contrary to the wide-spread opinion, the RUNJOB data are not inconsistent with an increase of the average mass near the knee region of the cosmic ray spectrum. Considering large statistical and systematic errors, especially in the high energy region, none of these two possibilities, heavy dominant composition, or proton dominant composition, can be completely ruled out.

Introduction

The RUNJOB (RUssia-Nippon-JOint-Balloon) experiment aimed at "direct observation of cosmic rays in the knee region" [12]. In $1995-1999$ there have been made 10 successful balloon flights (see Table 1) of traditional calorimeter-type emulsion chambers (see Table 2) with an area of $0.4\,m^2$ and weight $\sim 250\,kg$, on the Trans-Siberian route at an altitude of $\sim\,30\,km$ $(10-12\,g/cm^2)$, each time for about a week. The total accumulated exposure is $\sim 575m^2hrs$. Based on the collected data, RUNJOB presented the experimental results on the composition and the energy spectra of cosmic ray primaries. Early reports[7] based on 20% of the total exposition indicated that the average mass becomes gradually higher as energy gets higher. After 40% of data (exposition 1995-1996) RUNJOB concluded that "the average mass is nearly constant over the wide energy range 20-1000 TeV/particle", and reported that there are no drastic changes at higher energies[7, 1], similarly as observed below the knee. Accumulated data of 1995-1997 (45% of data) stated that "it is difficult to conclude whether the mass increase significantly beyond 100 TeV" [7]. Study of the energy dependence of primary mass based on "all showers with $E_\gamma > 5TeV$ from 1995-1999 expressed the situation as "no drastic change is not indicated here again" [3]. After that, on the basis of the "full data" 1995-1999 [2], the research found that "the RUNJOB data show a constant average mass up to 1 $PeV/particle$". The "constant primary mass" conclusion has caused considerable attention.

The reanalysis of the RUNJOB data was inspired by several comments made by Prof. N.L.Grigorov [6] in 2001. Considering the available data, the RUNJOB "final" interpretation is rather puzzling. We have been motivated to study this. Since RUNJOB 1996, only one interpretation has been favored. We noticed that the RUNJOB data on gamma rays are at variance[10] with the RUNJOB conclusions. In order to construct a consistent view on the RUNJOB experiment $itself$, to search for patterns, we must look at the complete datasets (particle tracks and gamma rays), as they were presented and published. Our present analysis consists of three parts. In this paper we suggest that the actual RUNJOB data are consistent with an increase of the average mass. In the second paper [9] we show that experimental data on gamma rays (the RUNJOB data included) can be an indication of an increase of heavy primaries near the knee region. In the third paper [8], taking into account the reported statistics and methodical procedure, we suggest that the most likely origin of the variation in the RUNJOB conclusions on primary mass composition are the methodical peculiarities. Thus, the RUNJOB experiment provided an important new insight into the observational technique.

Mass composition and average mass

The logarithm of mass number A (see Figure 1) is expressed as $< lnA > (E_p) = \Sigma\Delta J_m(lnA_m)/\Sigma\Delta J_m$, where ΔJ_m is a differential intensity for the element m with mass number A_m in the energy bin $(E_p, E_{p+\Delta_p})$. We can consider two models of primary composition (based on reports from JACEE [13] and RUNJOB [1]): the heavy composition model (HJ) with ($\beta_p : \beta_{He} : \beta_{CNO} : \beta_{NeMgSi} : \beta_{Fe} = 1.8 : 1.68 : 1.5 : 1.5 : 1.5$) and the proton dominant model (PR) with ($\beta_p : \beta_{He} : \beta_{CNO} : \beta_{NeMgSi} : \beta_{Fe} = 1.8 : 1.8 : 1.7 : 1.7 : 1.6$). Both models show an increase of the average mass number. If the spectra behaved as they were reported by RUNJOB (see Table 3 and [8] for details), i.e. that the energy spectrum becomes gradually harder with increasing mass (the PR model), then the average mass would increase. We present data for different charge groups from RUNJOB $1995 - 1996$ [1] and JACEE [13] in Table 4. The RUNJOB 1995-1999 ”final report” [2] did not show raw numbers, except ”1 PeV proton”. It is obvious from Table 3 that RUNJOB does not have enough statistics to separately observe each element in the very high energy region above 100-300 TeV, and the result is quite sensitive to the size of the chosen energy bin $(E_p, E_{p+\Delta_p})$.

Pev proton event

The RUNJOB experiment reported an observation of ”a single proton” with primary energy around 10^{15} eV as an indication of ”the absence of a cut-off region somewhere around 100 TeV” [1]. Taking into account that the observational altitude in the experiment was $10 - 12\,g/cm^2$, and the arrival zenith angle of this particle was determined as $\theta \sim 64.5$ degrees, the slant depth would be around $\sim 30\,g/cm^2$. In fact, the particle itself could be not a primary proton, but a spectator nucleon from an interaction of a heavy primary particle with an air nucleus. Considering an individual shower, it is impossible to determine whether it is originated by a primary proton, or by a nucleon from a heavy primary nucleus. It could indicate the arrival of a cosmic ray family produced by a heavy primary nucleus [11]. In general (not only for 1 PeV event), if secondary nucleons from heavy primaries were accounted as protons, some heavy primaries would be missing. It is not unusual that some families could be detected, but not recognized. The result depends on applied methods.

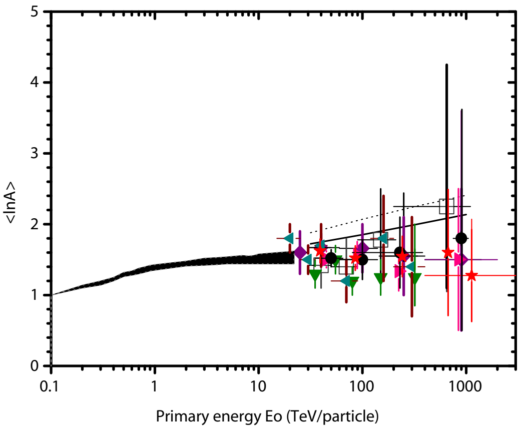

Figure 1: Comparison of the average mass $< lnA >$ evaluated by RUNJOB in different observations (20%-1995 [7] (squares with crosses); 35%-1995-1996 [7] (leftward triangles); 40% 1995-1996 [7] (downward triangles); 40%-1995-1996 [1] (rhombuses); 45%-1995-1997 [7] (solid circles); 1995-1999 [3] (rightward triangles); RUNJOB 1995-1999 [2] (stars)with estimates from the HJ model (dotted line) and the PR model (solid line). The filled area is taken from [1]. The total exposition 1995-1999 is assumed to be (100%).

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Table 1: Basic information[7] on the successful RUNJOB flights. The data show stability and regularity of flights. Balloon positions were measured by perfectly worked ARGOS-GPS system (ISAS/JAXA) and COSPAS system (Russia). One can note some inconsistencies between the flight time used by RUNJOB and the period of time between the launch and the termination of flight. These inconsistencies are not significant for the evaluation of the total exposition ST.

No. flight (hrs)	Year	Chamber (weight)	Launch Termination (m/d-h/m)	No. flight (hours)	Year	Chamber (weight)	Launch Termination (m/d-h/m)
1 (130 h)	1995	$1a-1b$ (230 kg)	$07/15-10^h.57^m$ $07/20-21^h.00^m$	6 (139.5 h)	1997	$6a-6b$ (254 kg)	$07/09-14^h.15^m$ $07/15\sim 9^h.45^m$
2 (167 h)	1995	$2a-2b$ (230 kg)	$07/19-13^h.02^m$ $07/26-11^h.00^m$	8 (141 h)	1999	$8a-8b$ (227 kg)	$07/08-14^h.00^m$ $07/14-11^h.30^m$
3 (134 h)	1996	$3a-3b$ (260 kg)	$07/17-09^h.00^m$ $07/23-01^h.00^m$	9 (145 h)	1999	$9a-9b$ (227 kg)	$07/12-13^h.00^m$ $07/18-14^h.30^m$
4 (147.5 h)	1996	$4a-4b$ (254 kg)	$07/18-13^h.00^m$ $07/24-14^h.50^m$	10 (148 h)	1999	$10a-10b$ (227 kg)	$07/13-13^h.10^m$ $07/19-17^h.10^m$
5 (139.5 h)	1997	$5a-5b$ (260 kg)	$07/09-12^h.15^m$ $07/15-11^h.00^m$	11 (146 h)	1999	$11a-11b$ (227 kg)	$07/14-13^h.15^m$ $07/20-16^h.00^m$

Table 2: Chamber structure in 1995-1999 experiments. UC stands for upper calorimeter. LC stands for lower calorimeter. Data are based on [7]. The target material in the case of 1996 chamber was stainless steel plate [1]. Instead of LC, there is a diffuser(D) module in RUNJOB 1997 and RUNJOB 1999.

Year	Primary	Target	Modules Spacer	UC	LC(D)		UL+LC	Thickness Chamber	Chamber
	mm	mm	mm	mm	mm		c.u.	proton MFP	Fe MFP
1995	4.62	99.82	187.37	57.72	43.41	//	3.60	0.40	2.44
1996	8.85	37.76	53.15	91.00	19.79	//	4.24	0.35	1.51
1997	4.54	47.08	102.72	37.86	37.32	//	4.43	0.37	1.68
1999	1.40	114.00	142.20	43.82	31.20	//	5.17	0.40	2.23

Table 3: Estimation of the raw number of primary tracks in the energy spectra of cosmic ray primaries reported by RUNJOB [7, 1, 5, 4, 3].

Source	Data set	proton	He	CNO	NeMgSi	Fe	All particles
[1]	$1995-1996$	~ 120	~ 40	~ 20	~ 8	~ 6	~ 160
[3]	$1995-1999$	~ 270	~ 70	~ 50	~ 20	~ 7	~ 260

Table 4: Estimation of the number of events for different charge groups from the RUNJOB $1995-1996$ data [1]. The RUNJOB $1995-1996$ data amounts to $231.5m^2hrs$ [1], or 40% of data.

Primary	$140-300$ TeV RUNJOB	$300-500$ TeV RUNJOB	>500 TeV RUNJOB	$116-300$ TeV JACEE	$300-930$ TeV JACEE	>930 TeV JACEE
Protons	2	1	1	14	3	0
Helium	3	0	0	22	7	1
C, N, O	2	0	0	12	9	1
Ne, Mg, Si	1	0	0	9	3	0
SubFe $(Z>17)$	NA	NA	NA	9	3	2
Fe	2	1	0	NA	NA	NA

Toshokan). Members of RUNJOB are appreciated for the realization of experiment.

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