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# All particle spectrum and average mass obtained by RUNJOB experiment

L.G.Sveshnikova[b], V.A.Derbina[a], V.I.Galkin[a], M.Hareyama[c], Y.Hirakawa[d], Y.Horiuchi[e], M.Ichimura[d], N.Inoue[e], E.Kamioka[f], T.Kobayashi[e], V.V.Kopenkin[b], S.Kuramata[d], A.K.Managadze[b], H.Matsutani[g], N.P.Misnikova[h], R.A.Mukhamedshin[h], S.Nagasawa[e], R.Nakano[d], M.Namiki[i], M.Nakazawa[e], H.Nanjo[d], S.N.Nazarov[b], S.Ohata[i], H.Ohtomo[d], V.I.Osedlo[b], D.S.Oshuev[b], P.A.Publichenko[h], I.V.Rakobolskaya[a], T.M.Roganova[b], C.Saito[e], G.P.Sazhina[b], H.Semba[j], T.Shibata[e], D.Shuto[d], H.Sugimoto[k], R.Suzuki[e], V.M.Taran[h], N.Yajima[i], T.Yamagami[i], I.V.Yashin[b], E.A.Zamchalova[b], G.T.Zatsepin[a] and I.S.Zayarnaya[h]
(RUNJOB collaboration, RUssia-Nippon JOint Balloon collaboration)
*(a) Physical Department of Moscow State University, Moscow 119899, Russia*
*(b) D.V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow 119899, Russia*
*(c) Major in Pure and Applied Physics, Science and Engineering, Waseda University, Tokyo 169-8555, apan*
*(d) Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan*
*(e) Department of Physics and Mathematics, Aoyama Gakuin University, Tokyo 157-8572, Japan*
*(f) Multimedia Information Research Division, National Institute of Informatics, The Ministry of Education, Tokyo 101-8430, Japan*
*(g) School of Medicine, Hirosaki University, Hirosaki 036-8562, Japan*
*(h) P.N.\ Lebedev Physical Institute of Russian Academy of Sciences, Moscow 117924, Russia*
*(i) Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara 229-8510, Japan*
*(j) Faculty of Comprehensive Welfare, Urawa University, Urawa 336-0974, Japan*
*(k) Shonan Institute of Technology, Fujisawa 251-8511, Japan*
Presenter: L.G.Sveshnikova (sws@dec1.sinp.msu.ru), rus-sveshnikova-LG-abs1-og11-oral

We report the final results on all particle spectrum and on average mass coming from full data obtained by ten RUNJOB campaigns performed from 1995 up to 1999. We show the all-particle spectrum and the average mass of primary cosmic rays in the energy region 20–1000 TeV/particle. In this report we compare our results to those obtained by other direct measurements and also indirect measurements. The intensity of the RUNJOB all-particle spectrum is 40–50% less than those obtained by JACEE and SOKOL, while the slopes of the spectrum seem to be in agreement in energy range more than 100 TeV/particle. Comparing to indirect measurements, our intensity is similar to lower intensity group such as CASA-MIA, not KASCADE. The average mass remains almost constant up to ~ 1 PeV, whereas the JACEE data suggest a rapid increase with primary energy beyond 100 TeV/particle. In EAS data there is also a considerable disagreement in the indirect data between KASCADE and CASA-MIA, with the former connecting smoothly to the RUNJOB data, and the latter connecting to the JACEE data around 2 PeV.

## 1. Introduction

In the accompanied papers [1, 2] at this conference and in our final paper [3] we present the energy spectra of proton, helium and heavier components of primary cosmic ray obtained by the emulsion chambers on board of ten long duration balloons, launched from Kamchatka between 1995 and 1999 and there we summarize the flight records. In the present paper we report the final results of all particle spectrum and average mass and compare them with those obtained with direct and EAS experiments and also discuss briefly the physical meaning of them. The technical details of the data analysis can be found in [4, 5].

Simultaneous observations of the various cosmic ray (CR) components are essential for understanding sites and mechanism of CRs acceleration in the Galaxy as well as propagation processes. This is particularly important in the high energy region nearby the so-called knee since people believe the origin of this enigmatic phenomenon can directly be connected with the origin of CRs. Many scenarios were proposed for explanation of the knee (see for the references [6], [7]), but in spite of strong efforts it is not possible to confirm surely or reject most of them basing on existing data. Around and above the knee, CRs components have been studied by a number of ground-based extensive air shower (EAS) experiments, but there remain inevitable difficulties in the estimation of the primary energy and its charge. In order to obtain these quantities, it is necessary to rely on simulations of shower phenomena in the atmosphere, which are strongly affected by the choice of nuclear interaction model. One should recall, that there is no experimental basis for simulation codes at such high energies, $10^{15}$–$10^{18}$ eV and beyond, which are much higher than those attainable to particle accelerators. In fact, the indirect data on the all-particle spectrum and the average mass show considerable scatter, in particular the latter, with no consensus imminent in the EAS field, despite many years of observations with increasingly sophisticated techniques. So it is critically important to obtain direct data on the all-particle spectrum as a sum of different nuclear CR species around $10^{14}$–$10^{15}$ eV/particle to see, how the different nuclear CR species "go into" the knee. It is important, even if it is limited with poorer statistics than obtainable from EAS studies, to provide a reference point for the indirect data.

## 2. Results

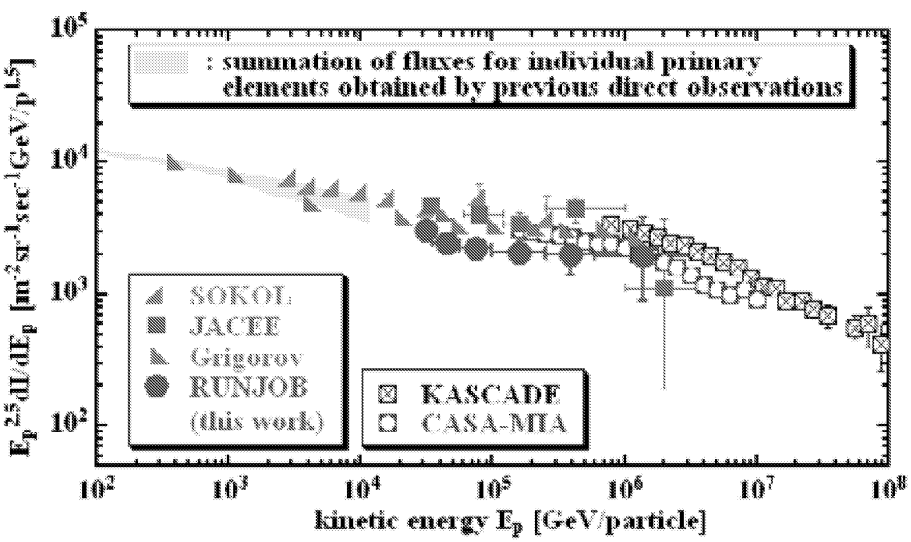


**Figure 1.** All particle spectrum measured in the RUNJOB experiment is presented together with other direct measurements SOKOL [8], JACEE [9], Grigorov [10], and with EAS data KASKADE [11]and CASA-MIA [12].

All particle spectrum is shown in Figure1, which covers the energy range from 50 to 1000 TeV/particle together with other direct data, SOKOL [8], JACEE [9] and Grigorov [10], as well as two indirect data, KASCADE [11] and CASA-MIA [12], where the KASCADE data is a typical one with a higher intensity of the all-particle spectrum in various EAS data nowadays available, while the CASA-MIA with a lower one. We find RUNJOB data in the all-particle spectrum are approximately 40-50% less than those obtained by JACEE and SOKOL. This is as expected, based on the results for light elements given in RUNJOB papers [1] and those for heavy elements in [2], namely the RUNJOB intensities for elements other than protons are significantly less than those given by JACEE and SOKOL. It might appear that the altitude fluctuations at the level ± 4 g/cm$^2$ of balloon flight [1] must result in some uncertainty for the estimation of the absolute CR intensity.

In Figure 2 we plot the average mass in the form of <lnA> (where A is the mass of the primary CR) against primary energy for two direct observations, RUNJOB and JACEE, and two indirect ones, KASCADE and CASA-MIA. The RUNJOB data show a constant average mass up to 1 PeV/particle, whereas the JACEE data indicate a rapid increase with energy beyond 100 TeV/particle. There is considerable disagreement in the indirect data between KASCADE and CASA-MIA, with the former connecting smoothly to the RUNJOB data, and the latter connecting to the JACEE data around 2 PeV. Both EAS data show a common rapid increase of the average primary mass with energy, but the starting energies of the mass increase much differ between two groups. In the present paper and in [1,2] we have presented the final results on the composition and the energy spectra for various CR components based on all ten RUNJOB campaigns performed from 1995 to 1999. While there is consensus on the proton component up to 100 TeV, there still exist many discrepancies, even among the direct observations, aside from those between direct and indirect experiments. It is clear that further direct CR observations with high statistics are required, using new facilities.

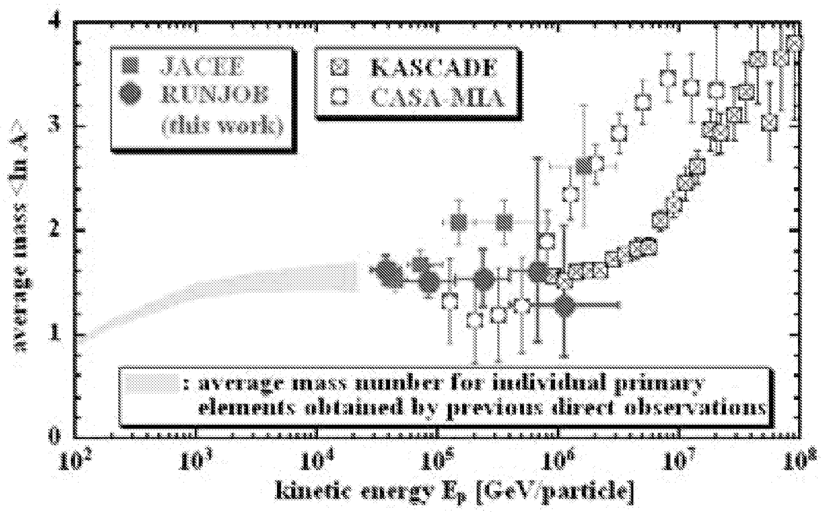


**Figure 2.** Average mass versus primary energy measured in the RUNJOB experiment is presented together with other direct measurements SOKOL [8], JACEE [9] and with EAS data KASCADE [11] and CASA-MIA [12].

## 3. Discussions

The RUNJOB all particle spectrum and the energy dependence of average mass do not show indication of the bend of spectrum in the energy region 50–1000 TэB and do not confirm the decrease of proton content in all particle spectrum toward the knee energy region, while in previous emulsion experiments JACEE, MUBEE [13] it was observed as well as in the pioneering experiments of N.L. Grigorov [10] with the thick calorimeter performed in close energy region on the Soviet "Proton" satellites in 70-years of the last century. Mentioned above experiments giving the different exponents of different nuclear spectra are not be easily explained from our current understanding the shock acceleration process in SNRs and propagation in Galaxy. Vise versa the RUNJOB results obviously confirm standard model of acceleration of the bulk of CRs up to the knee energy region in SNRs and the simple CR propagation model, which depends only on the particle rigidity and predicts the dominating role of the protons in the knee. It is interesting to recall that just in the first our exposition in 1995 we registered the 1 PeV energy proton [4], that was in contradiction with the maximum reachable energy in SNR, expected in that time. But later analyzing the early stage of SNR evolution Bell and Lucek [14] found that the cosmic ray streaming instability in the shock precursor can be so strong that the amplified random magnetic field $\delta B>100$ μG far exceeds the usual interstellar value B=3-5 μG. It allows for to keep the protons around the shock front of SNR up to much higher energy than suggested earlier (up to $E_{max} \sim 10^{17}$ eV as in [14] or $4\times 10^{15}$ eV as in [15]). So the discrepancy between JACEE and RUNJOB is critical for our understanding of the origin of CR and the acceleration mechanism, with these two sets of results leading to quite different alternatives. Recently, the ATIC group have presented two preliminary versions of their proton and helium spectra, the first of which obtained in the test ATIC flight [15] reports helium data more consistent with RUNJOB, and the second of which from the other flight [16] with a result for helium, that is more consistent with JACEE. We eagerly await the final version of the ATIC results, and look forward to AMS , BESS, CREAM experiments in nearest future so that these long-standing questions about the origin of CRs can be resolved.

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