

# Final Results of RUNJOB and Related Topics

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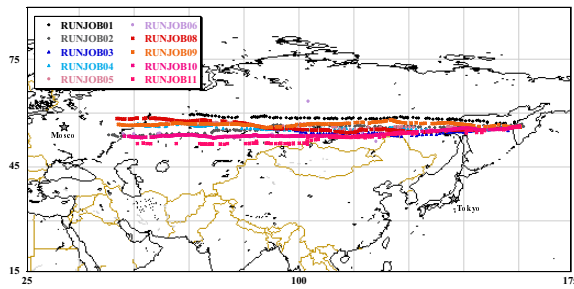
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**Abstract.** This report presents the energy spectra of galactic cosmic rays with the energy ranges between 10 and 1000 TeV/particle based on the full data set obtained by RUNJOB (RUSSIA - NIPPON JOINT BALLOON) experiment. Our proton flux is consistent with the other past observations such as JACEE and SOKOL, but the fluxes of the other components are less than those of the past ones, particularly the RUNJOB helium intensity giving nearly half of those obtained by JACEE and SOKOL. The slope of individual spectra becomes gradually harder as heavier components, in sharp contrast to JACEE and SOKOL data. Comparing the RUNJOB results with the propagation models, it seems to support that the acceleration and the propagation mechanisms of cosmic rays depend simply on particle rigidity.

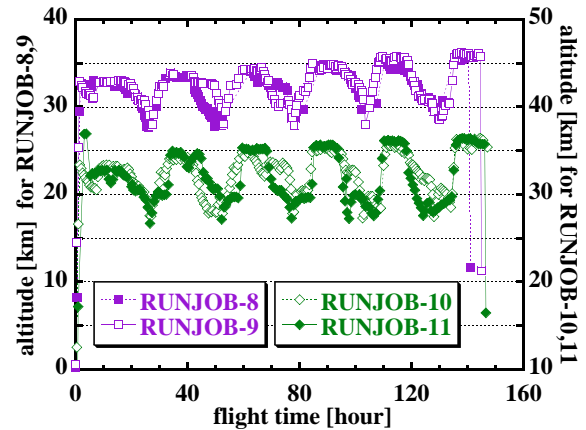
## 1. Introduction

More than a half century have passed since the discovery of the *knee* by Kulikov and Khristiansen[?], showing the bend of the all-particle energy spectrum of cosmic rays (CRs) around  $10^{15}$  eV region. Simultaneous observations of the individual CR components are essential for understanding sites and mechanism of CR acceleration in the Galaxy as well as propagation processes. This is particularly important in the high energy region around the knee, since people believe that the origin of this enigmatic phenomenon can closely connect with the origin of CRs. While many scenarios have been proposed for explanation of the origin of the knee (see for the references [?], [?]), it is still far from the consensus in understanding the knee.

Around and above the knee, CR components have been studied by a number of ground-based extensive air shower (EAS) experiments, but there remain inevitable difficulties in the estimation of its charge. In fact, the indirect data on the average mass show considerable scatter, despite of so many observations with use of increasingly sophisticated techniques. Therefore it is critically important to obtain the direct data on the all-particle spectrum as a sum of different nuclear CR species around  $10^{14}$  –  $10^{15}$  eV/particle, and to see which component is dominant there. It is also important to



**Figure 1.** Trajectories of ten successful RUNJOB flights. The balloon positions were measured by ARGOS-GPS system provided by Japanese balloon team in ISAS/JAXA for RUNJOB -8, -9 and -10 and COSPAS system by Russian balloon team for others.



**Figure 2.** Variations of balloon altitude in 1999 RUNJOB campaign. The left axis shows the level of RUNJOB-8 and -9 flights, and the right one shows those of RUNJOB-10 and -11.

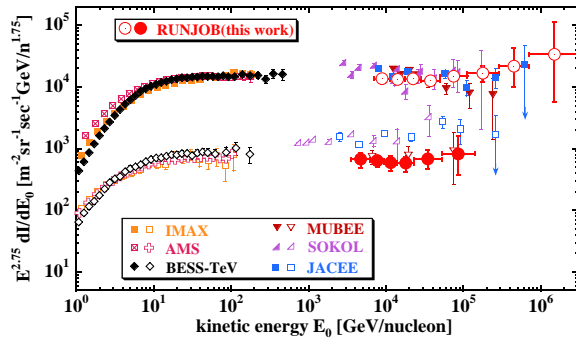
provide a reference point for the indirect data, even if it is limited with poorer statistics than obtainable from EAS studies.

In the present report, we give the final results obtained by the full data of RUNJOB experiment (see also [?]), such as the energy spectra for individual elements, the all-particle spectrum and the average mass, and we also touch the acceleration and propagation problems.

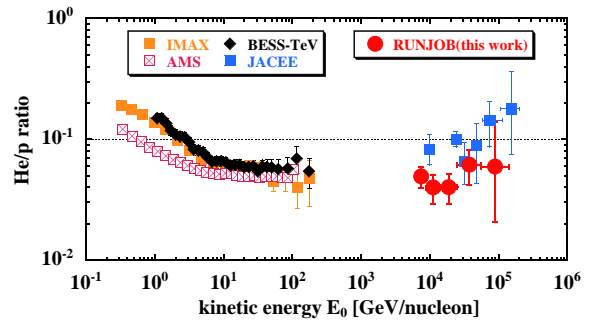
## 2. Observation

The scientific collaboration between Japan and Russia started in 1995 in order to observe CRs in the energy range  $10^{13} - 10^{15}$  eV/particle by means of emulsion chamber on board the long duration balloon. We give the trajectories of ten flights performed between 1995 and 1999 in Fig.??, and the variations of altitude for four flights in 1999 are plotted in Fig.?? as examples. These were obtained independently using two satellite systems, COSPAS system by the Russian side and ARGOS-GPS system by the Japanese side, with both giving consistent results. Eleven balloon flights have been launched from the Kamchatka peninsula and ten of them were successfully recovered near the Volga region after a level flight of  $\sim 150$  hrs, while RUNJOB-7 failed due to the malfunction of the auto-safety system. The total flight time of these campaigns amounts to about 60 days, with an average flight altitude of  $\sim 32$  km corresponding to  $\sim 10$  g/cm<sup>2</sup> of atmospheric depth.

As shown in Fig.??, the ten balloons have flown along latitudes  $50 - 60^\circ\text{N}$  at the level of  $30 - 35$  km, showing quite stable trajectories in the period from the middle to the end of July. The cutoff energy at this latitude corresponds to approximately 1 GeV/nucleon, much higher than that at Antarctic with several tens of MeV/nucleon,



**Figure 3.** Proton and helium spectra obtained by the full data of RUNJOB experiment (open and filled circle) together with other direct observations[?, ?, ?, ?, ?, ?, ?, ?].



**Figure 4.** The ratio of proton to helium fluxes obtained by full data of RUNJOB experiment (filled circle) with other direct measurements as AMS, BESS, IMAX and JACEE[?]. The AMS, BESS and IMAX data points are calculated by one of authors, M.H, from their original papers [?, ?, ?, ?].

which has the great advantage in reducing the noisy low energy CR tracks recorded on the nuclear emulsion plate.

It might appear that the altitude fluctuations at the level of  $\pm 4$  g/cm<sup>2</sup> in Fig.?? result in some uncertainty for the estimation of the absolute CR intensity. In the case of proton and helium, however, these fluctuations are practically negligible, as the attenuation lengths in the atmosphere are of the order of 100 g/cm<sup>2</sup> and 50 g/cm<sup>2</sup> respectively, much larger than the fluctuation level. For heavier components, this problem has been solved by introducing an *effective* altitude instead of using the average one, the details of which are presented in the appendix of the reference [?].

The methodologies of RUNJOB data analysis such as the energy and charge determination, detection efficiency and so on have been reported in the references [?] and [?].

### 3. Results and Discussion

#### 3.1. proton and helium

In Fig.??, we demonstrate the proton and the helium spectra obtained by our ten flights together with the results of other direct measurements such as JACEE[?], SOKOL[?] and MUBEE[?], where the vertical axis is multiplied by  $E_0^{2.75}$  in order to emphasize spectral features. Also shown are the results at lower energy region obtained by AMS[?, ?], BESS[?] and IMAX[?]. Our error bars are statistical only.

Our proton intensity is in good agreement with those obtained by the former groups, JACEE, SOKOL and MUBEE, but our helium intensity is nearly half of those given by JACEE and SOKOL, while consistent with MUBEE. This tendency doesn't change

from our first report [?] based on the data from first two flights in 1995. Focusing upon the data given by RUNJOB covering the high energy region and AMS, BESS and IMAX covering the low energy region, the slopes of the proton and the helium spectra are almost parallel with the indices of about 2.75 in the wide energy range between several 10 GeV/nucleon and several 100 TeV/nucleon. On the other hand, focusing on the JACEE-SOKOL high energy data and the low energy data, the helium component gives much hard spectrum as compared with the proton spectrum.

In order to see the difference of spectral slope more distinctly, we show the energy dependence of the helium-to-proton flux ratio over the very wide energy range a few 100 MeV/nucleon to a few 100 TeV/nucleon in Fig.???. It is clear that the RUNJOB points lie on the extrapolation from those in the lower energy data with a constant value  $\sim 0.05$ , while the JACEE data[?] suggest the ratio increases gradually as the energy gets higher. A discrepancy in the lower energy region,  $\lesssim 10$  GeV/nucleon, is apparent among AMS, BESS and IMAX, but this is simply due to the different period in the solar activity of each experiment.

Seo and Ptuskin[?] and Shibata et al.[?] reported in their propagation model that the value of He/p ratio is almost constant between several 10 GeV/nucleon and several 100 TeV/nucleon, assuming that the source spectrum depends on rigidity with the index  $-\gamma$ ,  $R^{-\gamma}$ , and the diffusion coefficient of CR propagation depends on rigidity,  $R^\alpha$ . Their conclusions are consistent with our result. The change in the ratio at lower energies,  $\lesssim 10$  GeV/nucleon, may be due to the re-acceleration effect, which must be significant for lighter elements such as protons and helium which have much longer collision mean free path than the escape length from the Galaxy, whereas it would not be so important for heavier elements [?].

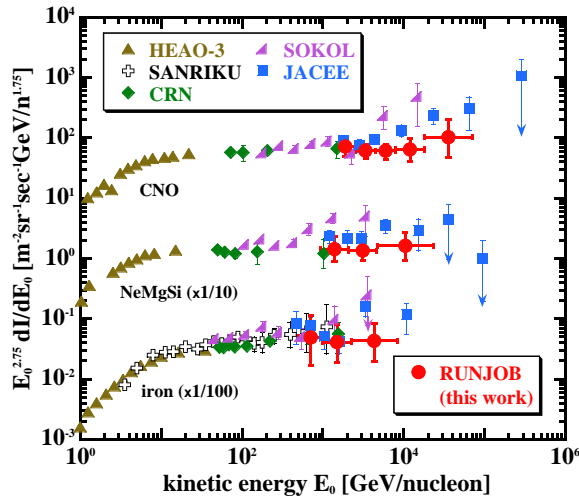
We would like to comment that a PeV-proton was detected in the first 1995 flight[?], but no new proton with PeV energy has been observed in other flights. This proton is the first direct evidence to accelerate a proton to PeV/nucleon energy.

Our proton spectrum indicates no cut-off in the acceleration in this energy region and seems to be harder in several 100 TeV region than that in lower energy region, though the statistics are poor. This may indicate that the spectrum becomes hard just before the limitation of diffusive shock acceleration (for instance, [?]).

### 3.2. Heavy components

We show the energy spectra of three heavy-primary groups, CNO, NeMgSi and Fe, in Fig.???, where the filled red circles denote RUNJOB data, and the other data, HEAO-3[?], SANRIKU[?], CRN[?, ?], SOKOL[?] and JACEE[?] are also plotted together. The vertical axis is multiplied by  $E_0^{2.75}$ . One should note here that the iron data of JACEE and SOKOL include the sub-iron components with  $Z = 17 - 25$ , i.e., not pure iron.

The RUNJOB results for three element groups give the smaller intensities than those obtained by JACEE and SOKOL, while error bars are so large in each group. If we focus on the data given by RUNJOB and CRN alone, the energy spectra



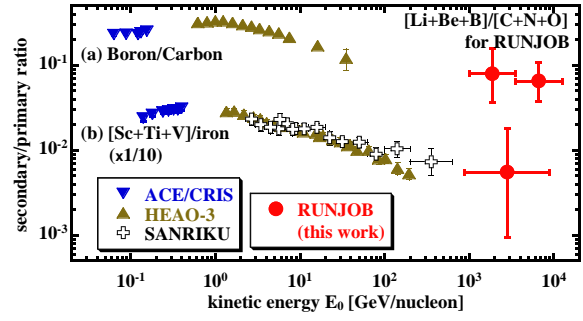
**Figure 5.** Heavy components spectra obtained by RUNJOB (filled red marks) together with other direct measurements. The intensities of NeMgSi-group and iron group are multiplied by 1/10 and 1/100, respectively.

of heavy components decrease monotonically with the energy getting up to several 10 TeV/nucleon. Comparing to the spectra of the light elements, proton and helium, the spectral slopes of heavy components look like almost parallel or a little bit harder than those of proton and helium. This tendency is consistent with the spectra expected from rigidity dependent Galactic phenomena such as the acceleration in the source and the propagation after leaving there[?].

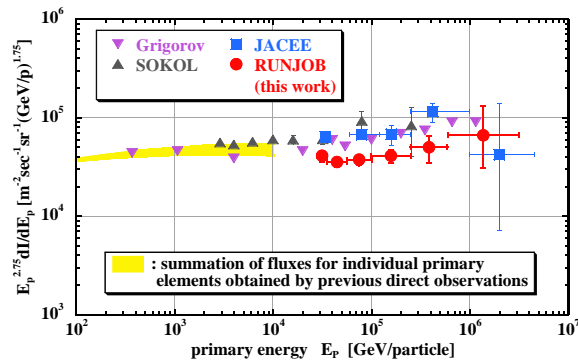
On the other hand, if we focus upon JACEE-SOKOL and CRN, their spectral slopes are clearly harder than that of proton, but similar to that of helium. In particular for CNO component, the slope of the spectrum is quite different between less and more than around 10 TeV/nucleon. This indicates that some new effects may appear, either with the acceleration mechanism or the different origin between proton and the others, if it is the case.

In Fig.??, we show the secondary/primary ratio, boron/carbon and sub-iron/iron, obtained by the present work together with other data, ACE/CRIS[?], HEAO-3[?, ?] and SANRIKU[?], covering the lower energy region. Here RUNJOB points on B/C include Li, Be for the secondary, and N, O for the primary. We have eliminated contaminations of 45% for the sub-Fe components and 67% for the LiBeB group coming from the fragmentation products in the residual atmosphere in Fig.?. The details of these calculations were shown in Ichimura et al.[?].

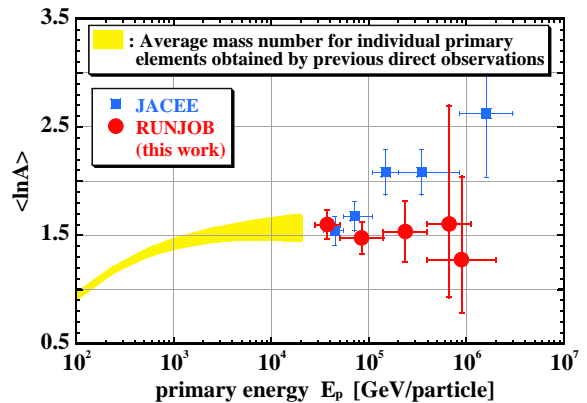
Although RUNJOB data include large uncertainties in the contamination effect in addition to the poor statistics, it seems to support the rigidity dependency of  $R^{-1/3}$  suggested by Seo and Ptuskin[?] and Shibata et al.[?], connecting closely to the



**Figure 6.** The secondary/primary ratio obtained by RUNJOB (circle) with other observations, ACE/CRIS[?], HEAO-3[?, ?] and SANRIKU[?]. (a) : B/C ratio. RUNJOB points denote the LiBeB/CNO ratio in place of B/C. (b) : sub-iron/iron ratio. Here, the sub-iron denotes three elements, Sc, Ti and V, with the charges, 21, 22 and 23 respectively.



**Figure 7.** All-particle spectrum obtained by RUNJOB together with those obtained by other direct and indirect experiments. The intensity is multiplied by  $E_p^{2.75}$ .



**Figure 8.** Average mass versus primary energy obtained by RUNJOB, together with those obtained by other direct and indirect experiments. The two points at the highest two energies for RUNJOB are obtained from the same data with two different choices of bin-width.

CR propagation problem such as the diffusion coefficient and the escape of CR from our galaxy. In order to make it clearer, however, we should observe the ratio in  $\gtrsim 100$  GeV/nucleon region with good statistics.

### 3.3. All-particle spectrum and Average mass

All-particle spectrum obtained by RUNJOB covering the energy range from 50 to 1000 TeV/particle is shown in Fig.??, where we present together with other direct data, SOKOL[?], JACEE[?] and Grigorov[?].

We find RUNJOB data in the all-particle spectrum are approximately 40 – 50% less than those obtained by JACEE and SOKOL. This is reasonable result because our intensities for individual elements are lower than others except for proton as mentioned before. The yellow zone at the lower energy region shows the all-particle intensity summing up the past various direct observations results that was calculated by Ichimura et al. in 1993[?]. They used the data set of Ryan et al.[?] for proton and helium intensities covering around 100 GeV/nucleon – 1 TeV/nucleon. However, the newly proton intensity reported by recent observations such as AMS and BESS is about 20 – 30% less than those obtained by Ryan et al. Considering this fact, RUNJOB points seem to connect smoothly from the yellow zone data in the lower energy region.

It is remarkable that focusing upon the 100 TeV/particle region, all groups seem to show the *flattering* in the slope of the spectrum just before the knee. If it is the case, some new effect may be appeared in this region, for instance some new component, either from our Galaxy or the extra Galaxy, become dominant around the knee and/or

the spectrum changing predicted by the diffusive shock acceleration.

In Fig.??, we plot the average mass in the form of  $\langle \ln A \rangle$  (where  $A$  is the mass of the primary CR) against the primary energy for two direct observations, RUNJOB and JACEE, together with the yellow zone which shows the average mass based on the past direct observations, same as the case of all-particle spectrum. Two points at the highest two energies for RUNJOB are obtained from the same data with two different choices of bin-width, either with or without the PeV-proton event.

The RUNJOB data show a constant average mass up to 1 PeV/particle from the yellow zone. This result is a natural consequence from those appearing in the individual spectra as shown in Figs.?? and ??. On the other hand, the JACEE data indicate a rapid increase with the energy beyond 100 TeV/particle. This is also quite natural from previous discussions, giving the noticeable hard spectra for helium and heavy components as compared with the proton spectrum.

#### 4. Conclusion

This report gives the final results obtained by the full data of RUNJOB experiment performed between 1995 and 1999.

Our proton intensity is consistent with other observation results, but the intensity of the helium component is nearly half of that obtained by JACEE and SOKOL, while it agrees with MUBEE. The slopes of the both spectra in RUNJOB are almost parallel with power index of 2.7 – 2.8 in the energy range 10 – 500 TeV/nucleon.

Heavy components spectra observed by RUNJOB monotonically decrease with energy getting higher and in agreement with the extrapolation lines from those obtained by CRN group at lower energy region. We have observed also secondary components such as the LiBeB group and the sub-Fe group, and present the secondary/primary ratio in the TeV/nucleon region.

The intensity of the RUNJOB all-particle spectrum is 40 – 50% less than those obtained by JACEE and SOKOL, and the RUNJOB average mass remains almost constant up to  $\sim 1$  PeV.

These results are consistent with the propagation models assuming the source spectrum with  $R^{-\beta}$  in rigidity, predicted by the shock acceleration, and the diffusion coefficient with the dependence of rigidity,  $R^\alpha$ .

Finally, we hope to clear the *knee* problem by further direct CR observations with high statistics using new facilities such as the super-long-duration balloon capabilities in the Antarctic, or at mid-latitudes in the Northern or Southern Hemispheres, and/or those under construction for year-long exposures on the international space station and on the moon surface in the far-off future.

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