The Astrophysical Journal, 628:L41–L44, 2005 July 20
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COSMIC-RAY SPECTRA AND COMPOSITION IN THE ENERGY RANGE OF 10–1000 TeV PER PARTICLE OBTAINED BY THE RUNJOB EXPERIMENT

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Received 2005 March 28; accepted 2005 June 15; published 2005 July 7

ABSTRACT

This is a full report on the cosmic-ray spectra and composition obtained by the emulsion chambers on board 10 long-duration balloons, launched from Kamchatka between 1995 and 1999. The total exposure of these campaigns amounts to 575 m^2 hr, with an average flight altitude of ∼32 km. We present final results on the energy spectra of two light elements, protons and helium nuclei, and on those of three heavy-element groups, CNO, NeMgSi, and Fe, covering the very high energy region of 10–1000 TeV particle^{-1}. We additionally present the secondary/primary ratio, the all-particle spectrum, and the average mass of the primary cosmic rays. We find that our proton spectrum is in good agreement with other results, but the intensity of the helium component is nearly half that obtained by JACEE and SOKOL. The slopes of the spectra of these two elements obtained from RUNJOB data are almost parallel, with values of 2.7–2.8 in the energy range of 10–500 TeV nucleon^{-1}. RUNJOB heavy-component spectra are in agreement with the extrapolation from those at lower energies obtained by CRN (Chicago group), monotonically decreasing with energy. We have also observed secondary components, such as the LiBeB group and the sub-Fe group, and present the secondary/primary ratio in the TeV nucleon^{-1} region. We determine the all-particle spectrum and the average mass of the primary cosmic rays in the energy region of 20–1000 TeV particle^{-1}. 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 ∼1 PeV.

Subject headings: acceleration of particles — cosmic rays — shock waves — supernovae: general

1. INTRODUCTION

The simultaneous observations of various cosmic-ray (CR) components, proton to iron, bring us vital clues for the understanding of the origin of cosmic rays, their acceleration mechanism, and the propagation processes in the Galaxy, particularly in the high-energy region, where troublesome effects such as the ionization loss, solar modulation, complicated energy-dependent collision cross sections, and so forth, become negligible.

There remain, however, many open questions. For instance, (1) does the acceleration limit actually appear in the proton spectrum somewhere around 0.1–1 PeV, and subsequently does the helium and heavier components become dominant as the proton spectrum drops off? (2) Does the secondary/primary ratio in the TeV region decrease monotonically with the energy increase in the same way as in the GeV region? (3) Do the indirect ground-based data connect smoothly to those obtained by the direct balloon- or spacecraft-based data on the energy spectra and the mass composition?

It is also noteworthy that measurements of the diffuse TeV γ-ray flux are becoming available (Fleysher et al. 2005) as the capabilities of ground-based telescopes rapidly develop. Most diffuse TeV γ-rays probably result from nuclear interactions between CR protons with $E_0 \gtrsim 10$ TeV and the hydrogen gas in the Galactic disk. So, naturally, one must ask if the intensity of the TeV γ-rays is in agreement with that predicted from the CR proton flux at energies greater than 10 TeV. If not, it might indicate that the TeV γ-rays come from a novel source in the Galaxy, such as the annihilation of supersymmetric particles in dark matter (Bergström & Gondolo 1996; Edsjö & Gondolo 1997), thus addressing a challenging problem in both particle physics and astrophysics.

With this background, we commenced a joint balloon experiment with the use of emulsion chambers in 1995, and we have performed 11 balloon flights from the Kamchatka peninsula, in 10 cases successfully recovering the balloon near the Volga region after a level flight of ∼150 hr.

We have already reported the RUNJOB (RUssia-Nippon JOint Balloon collaboration) results obtained from the first four flights, RUNJOB-1 and -2 in 1995 and RUNJOB-3 and -4 in 1996 (Apanasenko et al. 2001, hereafter Paper I). In Paper I we demonstrated the flight performance, such as the trajectories

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and the altitude variations of RUNJOB balloons (see also Furukawa et al. 2003), gave detailed descriptions of technical details, such as the chamber efficiency, energy determination (see also Hareyama et al. 2003), charge determination, and so on, and presented preliminary results on the energy spectra of various CR components.

For this reason we omit the technical details in this report and focus on the final results based on all RUNJOB experiments, including the remaining six flights, RUNJOB-5 to -11, excluding RUNJOB-7 as its campaign failed due to a malfunction of the auto-safety system.

2. RESULTS AND DISCUSSION

In Figure 1, we show the proton and the helium spectra obtained by our 10 flights, where the vertical axis is multiplied by $E_0^{2.5}$ in order to emphasize spectral features. Also shown are the results of other measurements, including the results at lower energies recently obtained by AMS (Alcaraz et al. 2000a, 2000b) and BESS (Haino et al. 2004). Both groups provide remarkable spectra with excellent energy resolution and high statistics, although the energy region, 0.5–100 GeV nucleon^{-1}, does not extend to the energy region of interest here. Their spectra appear to continue smoothly to energies of $\gtrsim 1$ TeV nucleon^{-1}, although we cannot conclude whether the extrapolation of their helium spectra is more likely to connect to the RUNJOB or JACEE (Asakimori et al. 1998) points.

We note that no new proton with PeV energy has been observed since the PeV-proton event detected in the 1995 campaign. Second, we find that the slopes of the proton and the helium spectra are nearly parallel, with indices of 2.74 ± 0.08 and 2.78 ± 0.20 in the energy range of less than 100 TeV nucleon^{-1}, respectively, where the errors are statistical only. Third, our helium intensity, while consistent with MUBEE (Zatsepin et al. 1994), is nearly half of those given by JACEE and SOKOL (Ivanenko et al. 1993).

The JACEE and SOKOL results are unexpected from our current understanding of the shock acceleration process in supernova remnants, which depends only on the particle rigidity, while the RUNJOB result seems to match these expectations. So the discrepancy between JACEE/SOKOL and RUNJOB/MUBEE is critical for our understanding of the origin of CRs and the acceleration mechanism, with these two sets of results leading to quite different alternatives.

In Figure 2, we give the energy spectra of the three heavy primary groups, CNO, NeMgSi, and Fe, where the filled red symbols denote RUNJOB data, and also plot data from the *HEAO 3* (Engelmann et al. 1990), SANRIKU (Kamioka et al. 1997), CRN (Müller et al. 1991; Swordy et al. 1993), SOKOL (Ivanenko et al. 1993), and JACEE (Asakimori et al. 1997) groups. The vertical axis is multiplied by $E_0^{2.5}$. One should remember here that the JACEE data for iron include the subiron components with $Z = 17$–25, while those from RUNJOB are for pure iron only.

If we focus on data given by RUNJOB and CRN alone, the energy spectra of heavy components decrease monotonically with energy up to ~10 TeV nucleon^{-1}, and the slope of the energy spectrum becomes gradually harder with heavier mass, for instance ~2.7 for the CNO group and ~2.6 for Fe. Recalling from Figure 1 that the slopes of proton and helium spectra are 2.7–2.8, the gradual change in the slope of the energy spectra of the individual elements indicates a rigidity-dependent form. This result is a natural consequence of the different collisional cross sections, with, for instance, ~40 mbarns for p-p and

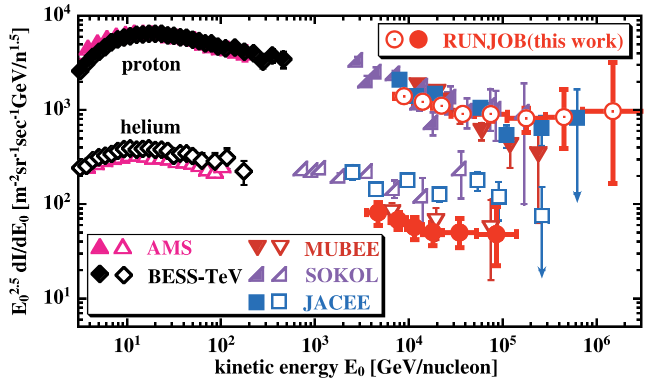

FIG. 1.—Proton and helium spectra obtained by the RUNJOB experiment (*red circles*) together with other direct measurements.

~750 mbarns for Fe-p in the TeV region, coupled with two scenarios: the stochastic shock acceleration at supernova blast waves and the leakage from the Galaxy in the propagation process, both of which depend on the particle rigidity (see, for instance, Shibata et al. 2004).

On the other hand, if the JACEE and SOKOL data are correct, we must find an alternative scenario, in relation to the source and the acceleration mechanism. In fact, as several authors have pointed out, based on JACEE data the source of helium and heavier components must be different from that of protons and could, for example, be produced by supernova shocks expanding into Wolf-Rayet winds (Biermann 1993; Biermann & Strom 1993; Biermann et al. 1995).

In Figure 3, we show the secondary/primary ratio obtained by the present work together with data from *ACE*/CRIS (Davis et al. 2000), *HEAO 3* (Binns et al. 1988; Engelmann et al. 1990), and SANRIKU (Hareyama et al. 1999), covering the lower energy region. One should recall, however, that the balloon altitudes in RUNJOB of ~10 g cm^{-2} result in a considerable contamination effect for these secondary components, coming from the fragmentation products in the atmosphere. In Figure 3, we have eliminated 45% of the contaminations for the sub-Fe components and 67% for the LiBeB group.

While the contamination effect is quite large, the uncertainty in the correction procedure is as large as 15%–25%, coming mainly from the uncertainty of the fragmentation parameter P_{ij} for an i-nucleus fragmenting into a j-nucleus. The details of these calculations appear in the paper of Ichimura et al. (1993), where the simulation procedure and the explicit values of the fragmentation parameter for various projectile nuclei against the atmosphere are summarized. Thus, one should view the RUNJOB data in Figure 3 with these uncertainties, and we reserve a definite conclusion until after further study.

Once we obtain the energy spectra of individual elements from proton to iron, it is straightforward to estimate the all-particle spectrum and the average mass of the primary CRs. In Figure 4, we present the all-particle spectrum together with other direct data, SOKOL (Ivanenko et al. 1993), JACEE (Asakimori et al. 1997), and Grigorov (Grigorov et al. 1971a, 1971b, 1971c), as well as indirect data from KASCADE (Ulrich et al. 2001) and CASA-MIA (Glasmacher et al. 1999), which are representative of recent flux measurements and of a systematically lower flux, respectively.

We find that the RUNJOB data result in a spectrum approximately 40%–50% less than those obtained by JACEE and SOKOL. This is quite natural from the results for light elements

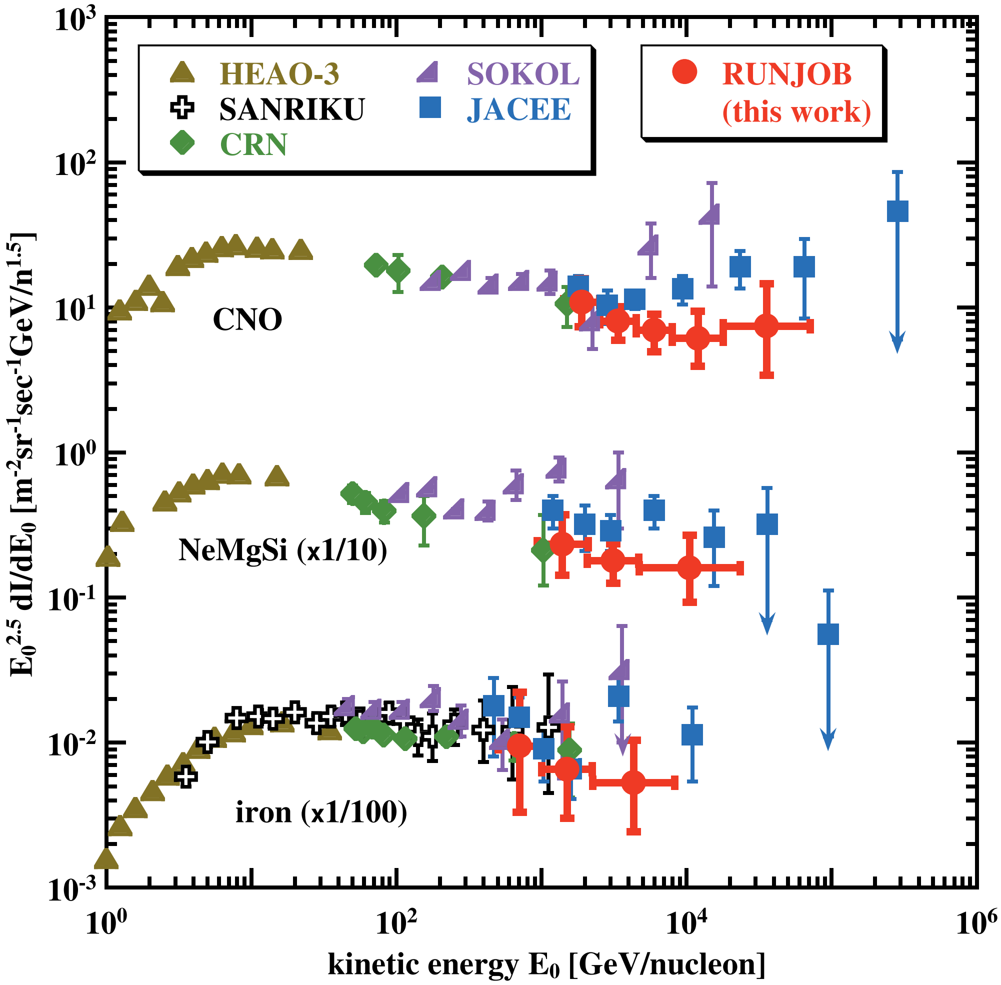

FIG. 2.—Heavy-component spectra obtained by RUNJOB (*red symbols*) together with other direct measurements. The intensities are multiplied by 1/10 for the NeMgSi group and 1/100 for the iron group.

in Figure 1 and those for heavy elements in Figure 2; namely, the RUNJOB intensities of elements other than protons are significantly less than those given by JACEE and SOKOL.

In Figure 5, we plot the average mass in the form of $\langle \ln A \rangle$ (where A is the mass of the primary CR) against primary energy for two direct observations, RUNJOB and JACEE, and two indirect measurements, KASCADE (Ulrich et al. 2001) and CASA-MIA (Glasmacher et al. 1999). The RUNJOB data show a constant average mass of up to ∼1 PeV particle^{-1}, whereas the JACEE data indicate a rapid increase with energy beyond 100 TeV particle^{-1}.

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

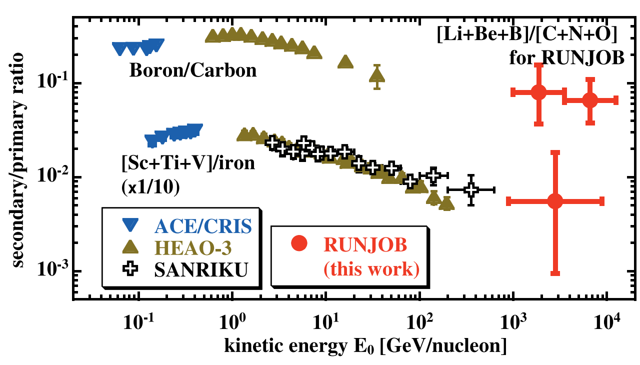

FIG. 3.—Secondary-to-primary ratios for (*a*) B/C and (*b*) sub-Fe/Fe, where RUNJOB data give [LiBeB]/[CNO] in place of B/C, and sub-Fe represents $Z = 21$–23. Contaminations of atmospheric secondary products are eliminated 67% for (*a*) and 45% for (*b*).

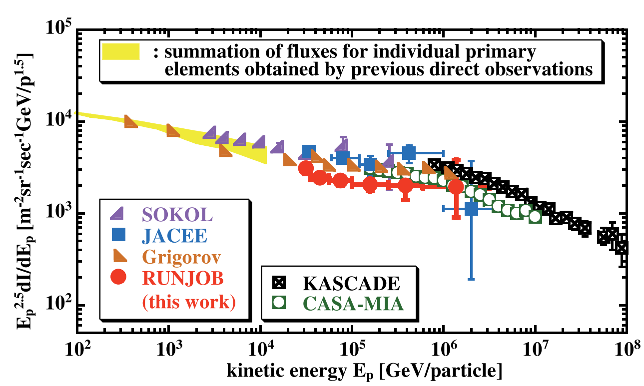

FIG. 4.—All-particle spectrum obtained by RUNJOB together with those obtained by other direct and indirect experiments.

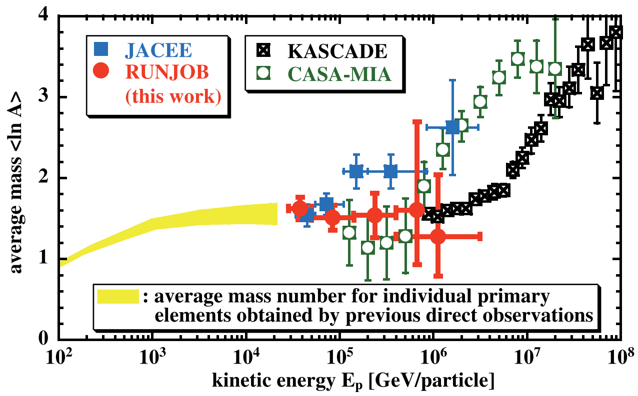

FIG. 5.—Average mass vs. primary energy obtained by RUNJOB, together with those obtained by other direct and indirect experiments. The two points at the highest two energies for RUNJOB are obtained from the same data with two different choices of bin width.

rapid increase of the average primary mass with energy, but the starting energies of the mass increase differ greatly between the two groups. It is worth mentioning, however, that the Cerenkov light measurements of the composition obtained by BLANCA at CASA (Fowler et al. 2001) do not show such a strong shift in the mean mass around the knee region but give no mass increase at least up to 10 PeV particle^{-1}.

While we have focused on the experimental results below the knee, we touch briefly on the difficulties in those above the knee, in connection with the direct experiments. The CR spectrum and composition above the knee have been studied by a number of ground-based extensive air shower (EAS) experiments. There remain, however, inevitable difficulties in the estimation of the primary energy and mass. 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 accessible to particle accelerators. In addition, shower phenomena are essentially governed by the secondaries produced in the *fragmentation* region, which is difficult to observe in the inclusive experiments of high-energy accelerators, even in $Sp\bar{p}S$ experiments at $E_0 \approx 10^{14}$ eV, much lower than those necessary for practical EAS studies.

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 and the average mass at around 10^{14}–10^{15} eV particle^{-1}, even if it is limited to slightly lower energies and with poorer statistics than obtainable from EAS studies, to provide a reference point for the indirect data.

Finally, it is clear that further direct CR observations with high statistics are essential, using new facilities such as the super–long-duration balloon capabilities in the Antarctic or at midlatitudes in the Northern or Southern Hemisphere, and/or those under construction for year-long exposures on the international space station.

This work has been supported by the Institute of Cosmic Ray Research (ICRR), the University of Tokyo, the Institute of Space and Astronautical Science (ISAS), the Japan Aerospace Exploration Agency (JAXA), Grants-in-Aid for Scientific Research and also for International Scientific Research from the Japan Society of Promotion of Sciences (JSPS; grants 08404012, 08045019, and 111695026), the Russian Foundation of Fundamental Research (grant 00-15-96632), the International Projects of the Russian Ministry of Science and Technology, and the Russian Commission of Balloon Research, grants PFFI 99-02-1772, 99-02-31005, and 99-02-18173, and grant "Universiteti Rossii" 990592 in Russia.

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