Adv. Polar Upper Atmos. Res., **20**, 52–62, 2006


*Research note*

# High energy electron observation by Polar Patrol Balloon flight in Antarctica

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(Received January 11, 2006; Accepted March 17, 2006)

***Abstract:*** We accomplished a balloon observation of the high-energy cosmic-ray electrons in 10–1000 GeV to reveal the origin and the acceleration mechanism. The observation was carried out for 13 days at an average altitude of 35 km by the Polar Patrol Balloon (PPB) around Antarctica in January 2004. The detector is an imaging calorimeter composed of scintillating-fiber belts and plastic scintillation counters sandwiched between lead plates. The geometrical factor is about 600 $cm^2sr$, and the total thickness of lead absorber is 9 radiation lengths. The performance of the detector has been confirmed by a test flight at the Sanriku Balloon Center and by an accelerator beam test using the CERN-SPS (Super Proton Synchrotron at CERN). The new telemetry system using the Iridium satellite, the power system supplied by solar panels and the automatic flight level control operated successfully during the flight. We collected $5.7\times10^3$ events over 100 GeV, and selected the electron candidates by a preliminary data analysis of the shower images. We report here an outline of both detector and observation, and the first result of the electron energy spectrum over 100 GeV obtained by an electronic counter.

**key words:** cosmic ray, high energy electron, balloon observation, Antarctica

## 1. Introduction

Several theoretical studies have suggested the importance of cosmic electron observations in the high energy region since these bring us crucial information for the origin and the acceleration mechanism (Nishimura *et al.*, 1980; Atoyan *et al.*, 1995). Especially, by observing the electrons over 100 GeV, it is possible to identify the acceleration sites and to define the propagation properties in the Galaxy (Kobayashi *et al.*, 2004). The electron observations, however, still do not have sufficient accuracy to test the theoretical expectations. The reason is mainly due to the difficulty of observation caused by the copious background protons (more than 100 times in flux) as well as the low absolute intensity of electrons. The detector should, therefore, satisfy two contradicting requirements; large geometrical factor and mass, and a high rejection power against the background protons.

Although several kinds of detectors have been invented to overcome the difficulties during the past ~30 years, only the emulsion chambers (ECC) have achieved the observation of electrons above 100 GeV (Kobayashi *et al.*, 1999). The Balloon Borne Electron Telescope with Scintillating Fibers (BETS) has been developed as an electronic counter which preserves the superior performance to ECC (Tamura *et al.*, 2000; Torii *et al.*, 2000). Namely, it can observe the details of three-dimensional shower development by an imaging technique with timing capability. Our primary aim, to measure the energy spectrum at 10–100 GeV, has already been concluded (Torii *et al.*, 2001). For the observation over 100 GeV, we have successfully developed an advanced BETS detector, PPB-BETS, which could attain a long-duration balloon flight in Antarctica (Torii *et al.*, 1999; Kadokura *et al.*, 2002).

## 2. Instrumentation

The PPB-BETS detector consists of 36 scintillating fiber (SciFi) belts, 9 plastic scintillation counters and 14 lead plates with 9 radiation lengths (r.l.) in total. Each SciFi belt is composed of 280 scintillating fibers of $1\times1$ mm in cross-section and 280 mm in length, putting side by side in parallel, shaped like as flat cable. A schematic side view of the detector is shown in Fig. 1. The basic structure is similar to that of the BETS detector, but several improvements has been made to observe high energy electrons up to 1 TeV (=1000 GeV). The incident area of the detector is $28\times28$ cm and the total thickness is 22.6 cm, including spacers shown in Fig. 1 with blank layers. The SciFi belts detect one dimensional distribution of shower particles produced in the lead plate just above each SciFi belt. The SciFi belts are set alternately orthogonally to observe projected shower particle distribution in $X$ and $Y$ axis direction, respectively. Plastic scintillation counters are used to generate event trigger signals by taking coincidence among the counters and to measure the shower energy. The top three scintillation counters are of 1 cm thickness in each in order to detect small number of simultaneously incident particles. The thickness of another 6 scintillation counters is 0.5 cm to measure large number of shower particles without saturation of signal, which are placed at a depth of around shower maximum. The instrument's geometrical factor is nearly 600 $cm^2sr$ for observation of electrons above 100 GeV.

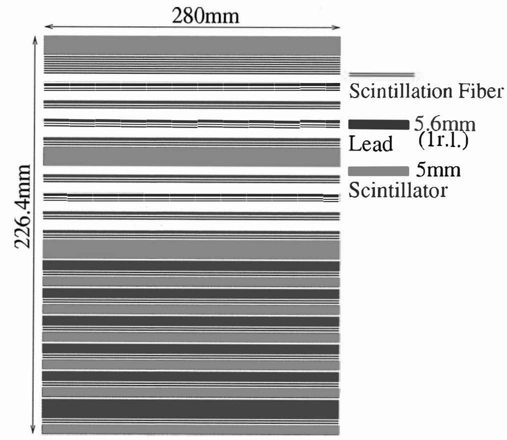


*Fig. 1. Schematic side view of the PPB-BETS detector. This figure shows the layout of lead plates, plastic scintillation counters, and SciFi belts.*

One end of each SciFi is connected to light guide made of optical fiber. The optical fibers are bundled for each $X$ and $Y$ axis direction, respectively, and the other end of the optical fiber bundles are coupled optically onto photocathode of an image intensifier (I.I.). The intensified image is read out by a CCD camera of $1024 \times 1024$ pixels. The signal from each pixel is digitized into 12 bits data by 40 MHz sampling rate. The spatial resolution and dynamic range of the image-intensifier CCD system has been improved from those of the BETS detector.

By tight limitation on weight of the payload, we did not use pressurized gondola. All the instruments were tested in same environmental condition as that at balloon altitude. Long term operation test of the detector system and balloon control system were conducted for about 10 days in thermal vacuum chamber. New instruments developed for balloon flight in Antarctica were, 1) power supply system by solar cells, 2) down and up link system by the Iridium satellite phone system, and 3) automatic flight level control system, and so on. Thermal design of the system was one of the most difficult issue. Basic physical quantities of the detector and balloon system are given in Table 1.

*Table 1. Basic parameters of PPB-BETS.*

| Parameter | Number | Comment |
|---|---|---|
| Energy range | 10–1000 GeV | by two modes of trigger |
| Geometrical factor | 550–600 $cm^2sr$ | in the energy region over 100 GeV |
| Energy resolution | 12–18% | in r.m.s. |
| Detector weight | 200 kg | including un-pressurized container |
| Power consumption | 70 W | supplied by solar panels |
| Observation altitude | ~35 km | controlled by Auto-Level system |
| Down-link rate | 2.4 kbps | *via* the Iridium satellite system |
| (Line-of sight | 64 kbps | by telemetry to the ground stations) |

## 3. Detector performance

We carried out a beam test of the flight model with electrons from 10 GeV to 200 GeV and protons from 150 GeV to 350 GeV, using the Super Proton Synchrotron (SPS) at European Organization for Nuclear Research (CERN) in October 2001. We confirmed both the performance of the data taking system and the detector response. The data size of CCD images were carefully investigated since it should not be over a limit imposed by an actual telemetry rate of 2.0 kbps in the Iridium system. Since the trigger rate was expected to be nearly one event per minute, the event data should keep a size of 20 kB (or less) on average. This kind of control is very difficult without beam tests using the same particles with similar energy. We could adjust the data size of images, after a compression to 14 kB on average, for the 100 GeV electron showers and much less for the proton showers.

### *3.1. Energy resolution*

The energy of the electromagnetic shower was first estimated by the pulse height at the bottom scintillation counter, which corresponds to the number of shower particles

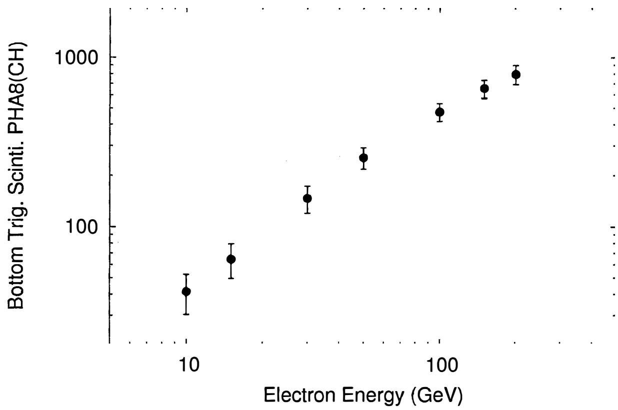


*Fig. 2. Relation between the electron energy and the pulse height (in ADC count) in the bottom scintillation counter.*

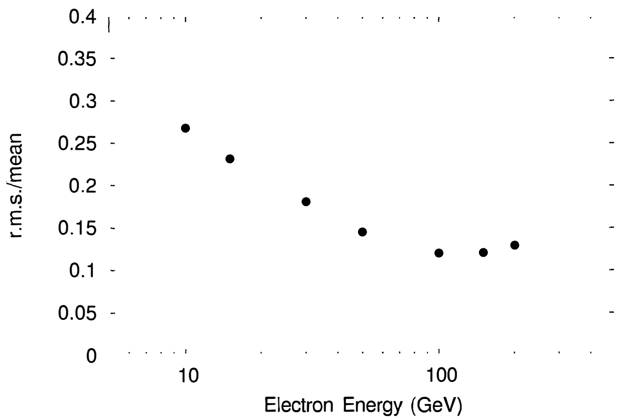


*Fig. 3. Energy dependence of the energy resolution for electrons.*

around the maximum development. As shown in Fig. 2, the relation between the average pulse heights and the electron energies shows a good linearity. The energy resolution was obtained by a Gaussian fit of the pulse height distribution for the electrons with an energy from 10 GeV to 200 GeV. The energy resolution presented by the ratio of r.m.s. value to average, is shown in Fig. 3 as a function of the energy. The resolution becomes better as the energy increases, and keeps mostly constant of nearly 12%, above 100 GeV.

### 3.2. *Imaging analysis and electron selection*

The development of showers in the detector was finely observed by the image intensified CCD cameras as presented in Fig. 4. To reduce the image size, the CCD images are recorded after binning $4\times4$ pixels and are presented on a log scale. After the position calibration of SciFi's in the raw CCD image, the relative light yield in each SciFi was measured, and the shower image was reconstructed in detector space as also shown in Fig. 4.

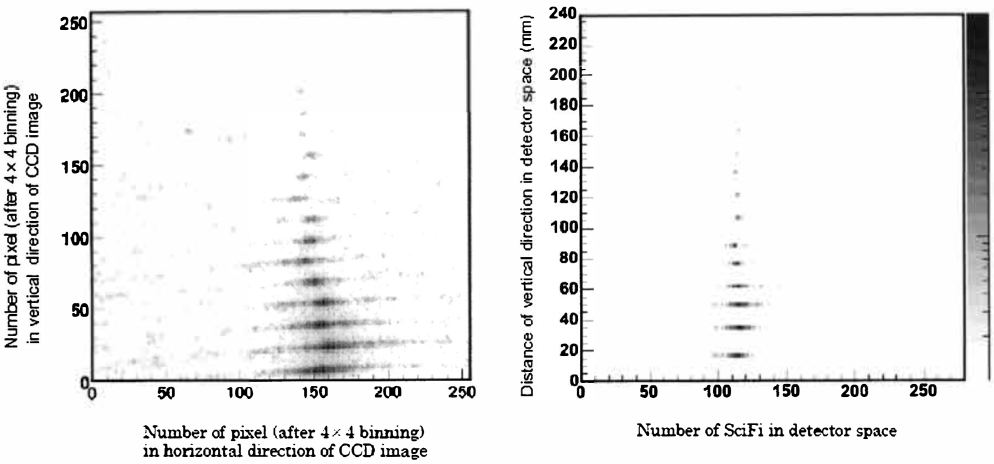


*Fig. 4. An example of image of a cascade shower induced by a 200 GeV electron at CERN-SPS. The left is a raw CCD image; the right is a reconstructed shower development in detector space. In the CCD image, the signal intensity in each pixel is represented by light and shade. The reconstructed image is drawn for each fiber.*

It is important to determine accurately the shower axis since the accuracy is crucial to determine the shower energy and to separate the electrons from the background protons by using shower images. We determined the shower axis from the energy weighted center of lateral spreads of a shower, which are observed with the SciFi belts at each depth. The angular resolution obtained by the reconstruction of the shower axis is better than $0.6^\circ$ for the electrons from 10 GeV to 200 GeV, which are incident perpendicularly to the detector top. The resolutions is considerably better than that of the BETS detector ($>1.0^\circ$) by avoiding the saturation effects of signals around the shower axis. For rejection of the background protons, we adopted the *RE* parameter

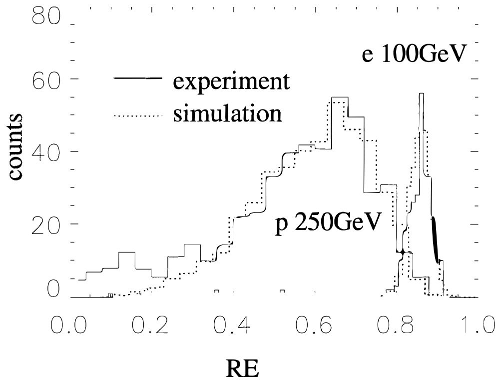


*Fig. 5. RE distributions of 100 GeV electrons and 250 GeV protons. The number of simulation events and observed events are normalized in number to compare with the experiment.*

defined by the ratio of energy deposit within 5 mm from shower axis to the total. Proton-induced showers usually have wider lateral spread comparing to electron-induced showers due to the effects of secondary hadronic nuclear interactions. Figure 5 shows the $RE$ distribution for the beam experiments of 100 GeV electrons and 250 GeV protons compared to the simulations. The experiment data are consistent with the simulation results for both electrons and protons. By a selection with the $RE$ parameter ($>0.8$), the protons are reduced to 5% keeping most of the electrons, 95%. Since a large fraction of the protons, 99.5%, is previously rejected by both the on-board trigger and the one-dimensional analysis, the total rejection power of protons could attain to $2.5\times10^{-4}$ ($=0.005\times0.05$) using the shower image analysis. Then, we have confirmed that the electrons could reliably be selected up to the TeV region in which the flux ratio of protons to electrons would be nearly $10^3$.

## 4. Balloon observation

The balloon was launched at the Syowa Station (39.60°E, 69.01°S) at 15:57 UTC on January 4, 2004. Figure 6 shows the PPB-BETS instrument just before launching. The level flight started at two hours after the launch and continued till 01:46 on January 17, 2004 at an altitude between 33 and 37 km (34.6 km, time averaged). The total exposure time was 296 hours. The balloon traveled around Antarctica at ~65° south latitude in a counter-clockwise direction with a speed of 30–35 km/h. The trajectory of the balloon is presented in Fig. 7. Power consumption of 70 W for the instrument was normally supplied by the solar cells. The automatic level control system operated successfully as demonstrated in Fig. 8.

The event trigger was executed with two modes, the high-energy (HE) mode and the low-energy (LE) mode. The LE mode is available for observing electrons over 10 GeV and was assigned for the observation during 10 hours just after the launch. The data acquired by this mode were directly transmitted to the Syowa Station with a bit rate of 64 kbps. The HE mode was adopted throughout the flight duration to observe

*Fig. 6. PPB-BETS ready for launch.*

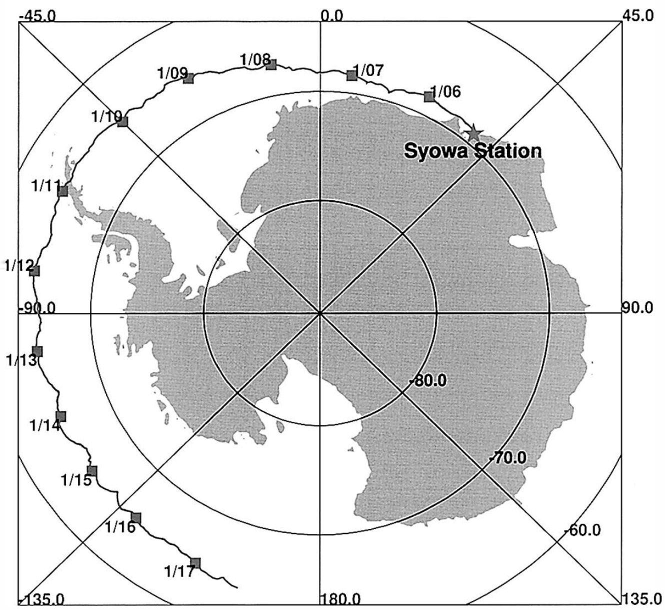


*Fig. 7. Trajectory of the PPB-BETS flight.*

electrons over 100 GeV. The triggered events were further selected by a software trigger (the 2nd trigger) using on-board software. The remaining event data was transferred to the operation room at the National Institute of Polar Research in Japan *via* a receiving station in the US. The command signals were also sent from the NIPR operation room *via* the US station. The trigger rate in the LE-mode during the level flight was ~$1\times10^4$ events per hour (~3 Hz). For the HE-mode, the average rate was ~70 events per hour (~0.02 Hz). Since the data size per one CCD image depends on the environmental temperature, the trigger rate was adjusted several times by commands

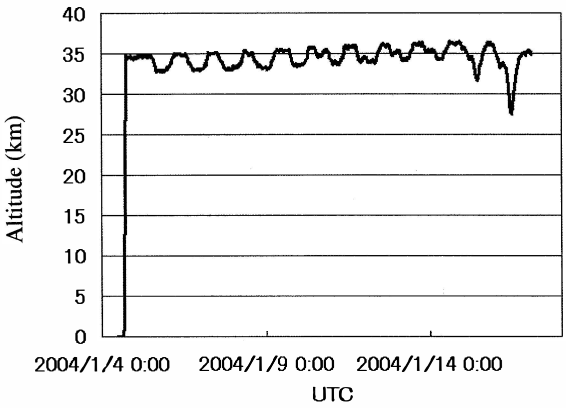


*Fig. 8. Time profile of the balloon altitude.*

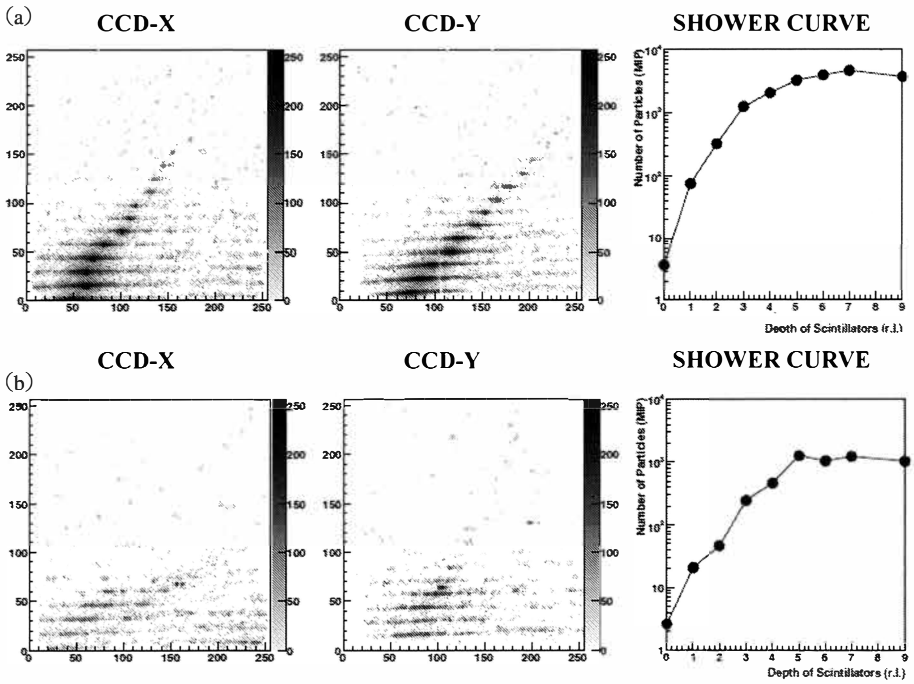


*Fig. 9. Examples of the CCD images (x and y) and the one-dimensional development of an observed shower. The upper example is a typical electron-induced shower and the lower is a proton-induced shower. See Fig. 4 for horizontal and vertical axis in CCD image.*

to keep the data rate nearly constant.

Examples of the observed CCD projected images ($x$ and $y$) and the shower development are presented in Fig. 9. A typical event of electron-induced shower presents a narrower lateral spread concentrated along the shower axis and a regular shape of shower curve, as presented in the upper panel of the figure. On the contrary, that of proton-induced shower in the lower panel usually shows a wider lateral spread and an irregular development.

## 5. Data analysis

We adopted, mainly, two sets of discrimination levels of pulse heights in all scintillation counters for the triggering in the HE-mode. The one set corresponds to the threshold energy of 100 GeV and the other to 150 GeV. Figure 10 shows the pulse height (converted to the number of Minimum Ionizing Particle, MIP) distribution of the scintillation counter at the depth of 7 r.l. for these thresholds. The trigger system worked normally because the observable minimum energy is shifted properly depending on each threshold. The spectra in high energy region are compared to a power law with an index of $-2.7$. It is consistent with the cosmic-ray proton spectrum since the events triggered on board are dominated by protons which are much more abundant than electrons. The number of triggered events in the HE-mode and the LE-mode was 5700 and 22000, respectively.

We applied an imaging analysis to select the electrons from the background protons as used in the analysis of the beam test data. The positions of each SciFi on the CCD image were obtained before flight by observing cosmic-ray muon tracks at ground level. The relative displacement of the SciFi positions during flight was calibrated by using the LED-illuminated fibers. The electron candidates were selected by the *RE* distribution under the condition that the *RE* values are greater that 0.8. The number of selected events was 84. A preliminary electron energy spectrum was obtained above 100 GeV, as presented in Fig. 11, after several further corrections; gamma-rays, secondary electrons, protons in $RE > 0.8$ and so on, which will be explained elsewhere Our spectrum

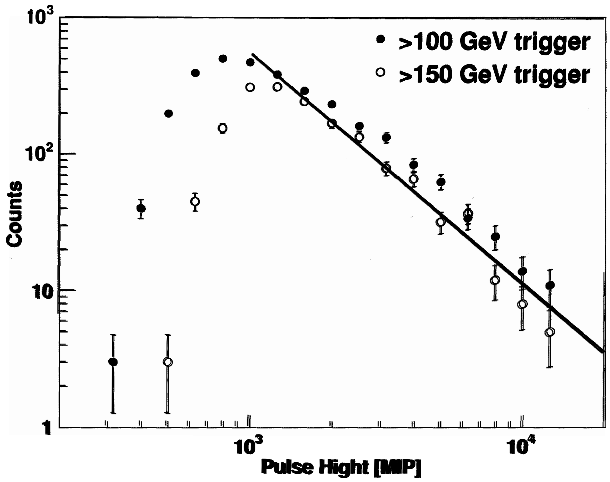


*Fig. 10. Pulse height distributions observed by the scintillation counter placed at depth of 7 r.l. for the 100 GeV threshold (black dots) and for the 150 GeV threshold (open circles). The solid line shows a power law spectrum with an index of −2.7.*

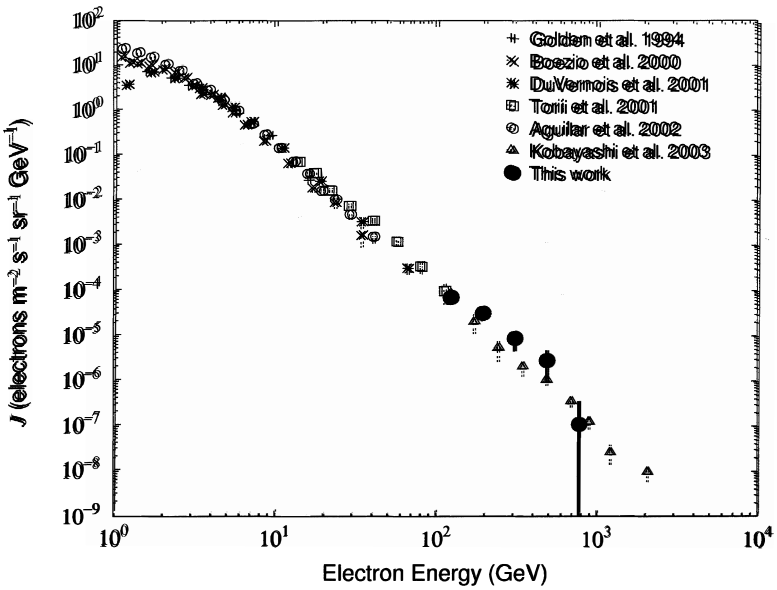


*Fig. 11. Preliminary electron energy spectrum observed in this experiment, compared to previous data.*

is consistent with previous observations within statistical errors above 100 GeV.

## 6. Summary and conclusion

We carried out a successful observation of cosmic-ray electrons over 100 GeV by long duration ballooning in January 2004. The balloon flight lasted for 13 days at a ceiling altitude of ~35 km. About 5700 events were triggered in the HE-mode during the flight. We have selected 84 events as electron candidates by a data analysis using the shower images. A preliminary energy spectrum is obtained after applying several corrections which are necessary to know the electron flux at the top of atmosphere. This is the first report by an electronic counter experiment for the electron observation over 100 GeV. The data analysis will be improved further, and the energy spectrum of cosmic ray electrons will be concluded soon in future paper. By the success of the long duration balloon experiment, we could get a future prospect of the electron observation in the TeV region, which will bring us conclusive results on the origin of electrons and the propagation mechanism in the Galaxy.

We demonstrated successful use of Iridium satellite telephone-system for telemetry and command, solar cell power system and flight level control system. These technology will be useful for future balloon experiment in Antarctica.

## Acknowledgments

We sincerely thank the 45th Japanese Antarctic Research Expedition team at Syowa Station of National Institute of Polar Research for the successful balloon launching. We also thank the staff of the H4 beam-line at CERN-SPS for their helpful support. This work was partly supported by Grant-in-Aid for Scientific Research on Priority Areas A (Grant No. 14039212) and Scientific Research C (Grant No. 16540268).

The editor thanks Dr. J.P. Wefel and another referee for their help in evaluating this paper.

## References

Atoyan, A.M., Aharanian, F.A. and Volk, H.J. (1995): Electrons and positrons in the galactic cosmic rays. Phys. Rev. D, **52**, 3265–3275.

Kadokura, A., Yamagishi, H., Sato, N., Ejiri, M., Hirosawa, H., Yamagami, T., Torii, S., Tohyama, F., Nakagawa, M., Okada, T. and Bering, E.A. (2002): Polar patrol balloon experiment in Antarctica during 2002–2003. Adv. Polar Upper Atmos. Res., **16**, 157–172.

Kobayashi, T., Komori, Y., Nishimura, J., *et al.* (1999): High energy cosmic ray electrons beyond 100 GeV. Proc. of the 26th International Cosmic Ray Conference, **3**, 62–65.

Kobayashi, T., Komori, Y., Yoshida, K. and Nishimura, J. (2004): The most likely sources of high-energy cosmic-ray electrons in supernova remnants. Astrophys. J., **601**, 340–351.

Nishimura, J., Fujii, M., Taira, T. *et al.* (1980): Emulsion chamber observations of primary cosmic-ray electrons in the energy range 30–1000 GeV. Astrophys. J., **238**, 394–409.

Tamura, T., Torii, S., Yoshida, K., Yamagami, T., Murakami, H. *et al.* (2000): Performance of the BETS detector for cosmic ray electrons. Adv. Space Res., **26**, 1397–1400.

Torii, S., Yamagami, T., Yuda, T. and Kasahara, K. (1999): Measurement of high-energy cosmic-ray electrons with a Polar Patrol Balloon. Adv. Polar Upper Atmos. Res., **13**, 176–181.

Torii, S., Yamagami, T., Tamura, T., Yoshida, K., Murakami, H. *et al.* (2000): The balloon-borne electron telescope with scintillating fibers (BETS). Nucl. Instrum. Meth. Phys. Res., **457**, 499–508.

Torii, S., Tamura, T., Yoshida, K., Nishimura, J., Yamagami, T. *et al.* (2001): The energy spectrum of cosmic-ray electrons from 10 to 100 GeV observed with a highly granulated imaging calorimeter. Astrophys. J., **559**, 973–984.