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Energy spectrum and arrival directions of high-energy electrons over 100 GeV observed with PPB-BETS

K.YOSHIDA[1], S.TORII[2], T.TAMURA[3], H.KITAMURA[4], T.YAMAGAMI[5], J.CHANG[6], I.IIJIMA[5], A.KADOKURA[7], K.KASAHARA[2], Y.KATAYOSE[8], T.KOBAYASHI[9], Y.KOMORI[10], Y.MATSUZAKA[5], K.MIZUTANI[11], H.MURAKAMI[12], M.NAMIKI[5], J.NISHIMURA[5], S.OHTA[5], Y.SAITO[5], M.SHIBATA[8], N.TATEYAMA[3], H.YAMAGISHI[7], T.YUDA[13]

[1] *Department of Electronic Information Systems, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi 337-8570, Japan*

[2] *Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan*

[3] *Institute of Physics, Kanagawa University, 3-27-1 Rokkakubashi, Kanagawa-ku, Yokohama 221-8686, Japan*

[4] *National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-shi 263-8555, Japan*

[5] *Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara 229-8510, Japan*

[6] *Purple Mountain Observatory, Chinese Academy of Sciences, 2 West Beijing Road, Nanjing 210008, China*

[7] *National Institute of Polar Research, 1-9-10 Kaga, Itabashi-ku, Tokyo 173-8515, Japan*

[8] *Department of Physics, Yokohama National University, 79-1 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan*

[9] *Department of Physics and Mathematics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara 229-8558, Japan*

[10] *Kanagawa University of Human Services, 1-10-1 Heiseicho, Yokosuka 238-8522, Japan*

[11] *Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama-shi 338-8570, Japan*

[12] *Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan*

[13] *Institute for Cosmic Ray Research, University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa 277-8582, Japan*

yoshida@shibaura-it.ac.jp

Abstract: We have observed cosmic-ray electrons from 10 GeV to 1 TeV with PPB-BETS by a long duration balloon flight using Polar Patrol Balloon (PPB) in Antarctica. The observation was carried out for 13 days at an altitude of 35 km in January 2004. The detector is an imaging calorimeter composed of scintillating-fiber belts and plastic scintillators inserted between lead plates. The geometrical factor of detector is about 600 cm^2sr and the total thickness of lead absorber is 9 radiation lengths. We have collected 5.7×10^3 events over 100 GeV including nearly 100 candidates of primary electrons. During the flight, sun aspect sensors and geomagnetic aspect sensors operated to determine the attitude of the instrument. The arrival directions of high-energy electrons over 100 GeV, together with the energy spectrum, are suggested to be a powerful probe to identify nearby cosmic- ray electron sources. In this paper, we present the energy spectrum and arrival directions of cosmic-ray electrons from 100 GeV to 1 TeV observed with PPB-BETS.

Introduction

Compared to cosmic-ray nuclei, high-energy electrons lose energy rapidly by the synchrotron and inverse Compton processes during propagation in the Galaxy. Because of these radiative losses, the high-energy electrons from the distant sources cannot reach the solar system. Hence, it has been suggested that the energy spectrum of cosmic-ray electrons might have a structure in the energy region above several 100 GeV due to the discrete effect of nearby supernova remnants (SNRs) [1]. This means that we can identify cosmic-ray electron sources from the electron spectrum above several 100 GeV together with the anisotropy in arrival directions.

In order to observe the higher-energy electrons above 100 GeV, we have developed an advanced BETS detector [2] and observed cosmic-ray electrons by using Polar Patrol Balloon (PPB), which has a capability to achieve a long duration balloon flight for ~ 4 weeks at an altitude of ~ 35 km in Antarctica [3].

Instrument and observations

Since the PPB-BETS instrument and observations in Antarctica are described in detail in a previous paper [2], we will briefly summarize the PPB-BETS detector and the observations.

The PPB-BETS detector consists of 36 scintillating fiber belts, 9 plastic scintillation counters, and 14 lead plates with a total thickness of 9 radiation lengths (r.l.). Each fiber belt is composed of 280 fibers with a 1 mm square cross section and the number of fibers is 10,080 in total. The basic structure is similar to that of the BETS detector [4], but several improvements have been adopted to observe high-energy electrons up to 1 TeV.

The balloon was launched at the Syowa Station (39.60°E, 69.01°S) in Antarctica at 15:57 on January 4, 2004 (UTC). The level flight was started at two hours after the launch and continued till 1:46 on January 17, 2004 at an average altitude of ∼35 km. The total exposure time was 296 hr. During the observations, power supply system by solar panels, telemetry system by the Iridium satellite phone line, and auto-level control system by CPU operated successfully. In order to determine the attitude of the instrument, sun aspect sensors and geomagnetic aspect sensors also operated during the flight.

The number of acquired events was 2.2×10^4 above 10 GeV with a trigger rate of ∼3 Hz, and 5.7×10^3 above 100 GeV with a trigger rate of ∼0.02 Hz.

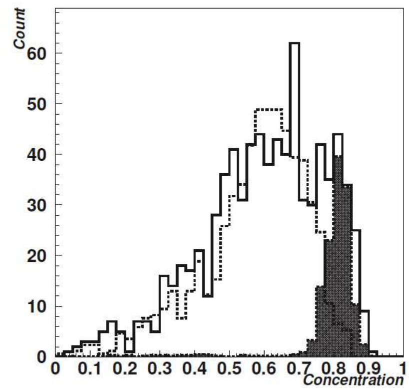

Figure 1: RE distributions of the observed events (solid line) with 100 GeV electrons (hatched region) and 250 GeV protons (dashed line) of the CERN SPS beam tests.

Data analysis

Electron selection

For the acquired events, we reconstructed the raw CCD images of showers to the fiber positions in detector space by using the positions of each fiber on the CCD image. From the reconstructed shower image, we determine the shower axis that is crucial to determine the energy, incident direction, and selection of electrons. The accuracy of angular determination of shower axis ranges from 0.35 to 0.60 degree with electron energies in 10 GeV – 200 GeV from the CERN-SPS beam tests [2].

A typical event of electron-induced shower presents a narrower lateral spread concentrated along the shower axis. On the contrary, that of proton-induced shower shows a wider lateral spread [2]. We characterize this physical property by the RE parameter, the ratio of energy deposition within 5 mm from the shower axis to the total, as described in Torii et al. (2001) [4]. Figure 1 shows the RE distributions of the observed events compared with the distribution of 100 GeV electron and 250 GeV proton beams at CERN-SPS. The electron candidates were selected by the RE distribution under the condition that the RE values are greater than 0.75.

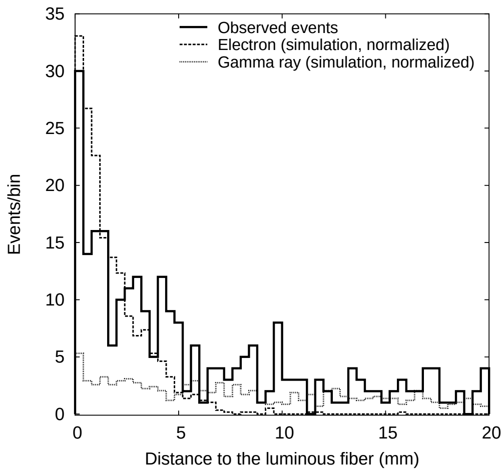

Figure 2: Observed distribution of the nearest hit fiber positions from the shower axis (solid line) compared with the simulated distributions of electrons and gamma rays.

As for the separation between electrons and gamma rays, electrons could be identified by the presence of hits in the scintillating fibers at 0 r.l. along the shower axis. Figure 2 presents the observed and simulated distributions of the distances of the nearest hit fiber position from the shower axis at the top layer. As incident electrons leave signals on the fibers along the shower axis, the distribution of electrons is concentrated around the incident point. On the other hand, as incident gamma rays leave no signals except for the back-scattered particles, the distribution by gamma rays becomes much broader. We judged electrons as the events whose distances are less than or equal to 5 mm. Gamma-ray events are rejected by 90 %. As a result, the number of the electron candidates above 100 GeV is 84 events among the 4.7×10^3 analyzed events.

Energy spectrum of electrons

Since the number of shower particles at the shower maximum is nearly proportional to the energy of incident electrons, we determined the electron energies by using the number of particles at the shower maximum in the transition curve with plastic scintillators. The energy resolution is 12 % at 100 GeV for the CERN-SPS electron beams that is consistent with the simulations [2].

From the electron events, with the above selection and energy determination, we derived the cosmic-ray electron spectrum by using the following formula:

$$J_{\rm e}(E) = (\frac{N_{\rm e} C_{\rm RE} C_{\rm eg}}{S\Omega T \Delta E} C_{\rm enh} - C_{\rm 2nd}) C_{\rm atm}, \quad (1)$$

where $N_{\rm e}$ is the number of electron candidates, $S\Omega$ the effective geometrical factor, T the observed live time, ΔE the energy interval, $C_{\rm RE}$ the correction factor of the proton contamination in the RE-cut with energy dependence, $C_{\rm eg}$ the correction factor of the gamma-ray contamination in the gamma-ray rejection with energy dependence, $C_{\rm enh}$ the correction of enhancement of flux due to the energy resolution, $C_{\rm 2nd}$ the flux of secondary (atmospheric) electrons at the observation level, and $C_{\rm atm}$ the correction factor of energy loss of primary electrons in the overlying atmosphere.

Figure 3 presents the electron energy spectrum multiplied by the cube of energy, in comparison with other electron observations. The PPB-BETS spectrum represented by a single power-law function is given by

$$J_e = (1.83 \pm 0.65) \times 10^{-4} (\frac{E}{100 \rm GeV})^{-3.09 \pm 0.35} \quad (2)$$
$$({\rm m}^{-2} {\rm s}^{-1} {\rm sr}^{-1} {\rm GeV}^{-1}).$$

The energy spectrum is consistent with the extrapolated spectrum of the BETS [4] at 100 GeV and that of ATIC-2 [5] within statistical errors in the 100 GeV – 1 TeV region.

Arrival directions of electrons

Incident directions of electrons on the PPB-BETS detector are determined by using the shower axis with an accuracy of around 0.5 degree. Since the attitudes of PPB-BETS instrument are determined with sun sensors and geomagnetic sensors, we can determine arrival directions of cosmic-ray electrons. For the determination of attitudes with geomagnetic sensors, we referred to the International Geomagnetic Reference Field (IGRF) model. The difference of the attitudes between sun sensors and geomagnetic sensors is $\sim$6 degree in r.m.s. Figure 4 presents a ratio of the observed distribution

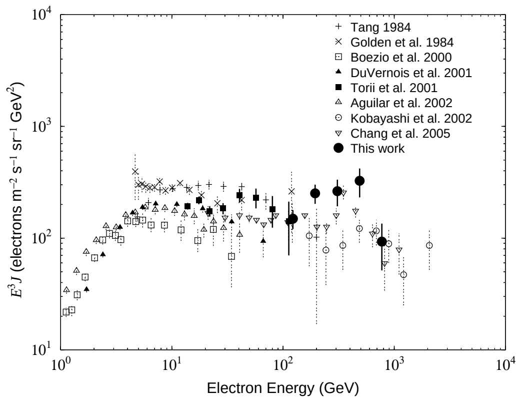

Figure 3: Electron energy spectrum observed by the PPB-BETS (solid circles) in comparison with the energy spectra of other observations.

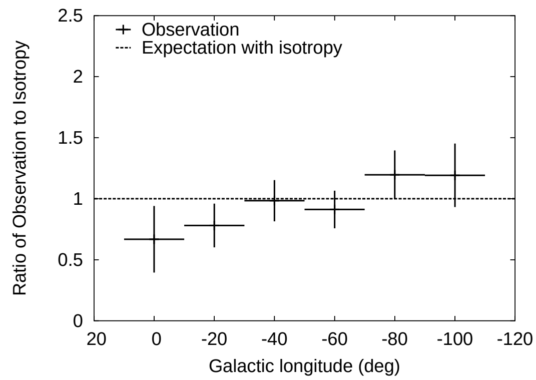

Figure 4: A ratio of the observed flux to the isotropic flux along the Galactic longitude.

above ~100 GeV to the isotropic distribution along the Galactic longitude. As shown in Fig. 4, the arrival directions of electrons are consistent with the isotropic distribution.

Summary and discussions

We observed cosmic-ray electrons above 100 GeV with PPB-BETS in Antarctica and derived the energy spectrum of cosmic-ray electrons. We also derived the arrival directions of electrons above ~100 GeV.

Electron energy spectrum and anisotropy above 100 GeV is crucial to detect the nearby SNRs as discussed by Kobayashi et al. (2004) [1]. The data statistics of our results, however, are insufficient to discuss the details of the contribution of nearby SNRs. For the future observations, we are planning to increase greatly our statistics by experiments such as CALET on International Space Station [6].

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