Proceedings of ICRC 2001: 4027 © Copernicus Gesellschaft 2001

ICRC 2001

Particle acceleration in thunderstorms

T. Takami[1], Y. Muraki[1], Y. Matsubara[1], K. Masuda[1], T. Sako[1], S. Sakakibara[1], T. Murata[1], H. Tsuchiya[1], D. Yamamoto[1], W. I. Axford[1], S. Shibata[2], Y. Munakata[2], K. Munakata[3], S. Yasue[3], T. Sakai[4], K. Mitsui[5], and E. O. Flückiger[6]

[1]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, 464-8601, Japan
[2]College of Engineering, Chubu University, Kasugai, 487-8501, Japan
[3]Department of Physics, Shinshu University, Matsumoto, 390-8621, Japan
[4]College of Industrial Technologies, Nihon University, Narashino, 275-0005, Japan
[5]Department of Management Information, Yamanashi Gakuin University, Kofu, 400-8575, Japan 6
[6]Physikalisches Institut, Universit at Bern, CH-3012 Bern, Switzerland

Abstract. Evidence for particle acceleration by the electric field in a thundercloud was first reported by Baksan group in 1985 and recently by the EAS-TOP group at the Utah ICRC (1999). In this paper, we will present further evidence for particle acceleration in thunderheads, using the large area (64 m^2) proportional counter and scintillator array located at Mount Norikura Cosmic Ray Observatory at an altitude of 2770m.

Atmospheric conditions at Mount Norikura in the Japanese Alps during the 4 - 8 August 2000, were very unstable in the afternoon. Thunderstorms developed, followed by rainfall lasting several hours. We obtained evidence that, in association with these thunderstorms, particles (probably electrons) were accelerated to energies higher than 40 MeV (perhaps higher than 100 MeV) in the atmosphere somewhere above the detector. We propose that the effect is the result of the acceleration of high energy knock-on electrons or decay electrons of muons.

1 Introduction

We tend mostly to be interested in particle acceleration only in interstellar or interplanetary space, in magnetospheres of various kinds and in solar and stellar flares. The possibility of acceleration of particles in a region closer to home, namely the earth's atmosphere, is something that we easily overlook. However it has been shown by ground-based measurements, designed mainly to investigate air showers, that particle acceleration in the atmosphere occurs, at least in the special circumstances pertaining to thunderstorms (Alexeenko et al., 1987; Aglietta et al., 1999). The results of particle acceleration in the upper atmosphere has also been observed by satellites with gamma ray detectors (Fishman et al., 1994). Once again thunderstorms appear to be involved but in this case it is cloud-ionosphere lightning discharges that are the direct cause of X-day generation (Suszcynsky et al., 1996, Eack et al., 1996; for earlier references, see the paper by Aglietta et al., 1999).

Correspondence to: Muraki (muraki@stelab.nagoya-u.ac.jp)

The various kinds of ground-based detectors in use may respond to variations in the fluxes of protons, electrons, muons, neutrons and even possibly to electrical disturbances associated with thunderstorms. Alexeenko et al., have shown that the effects observed are indeed of atmospheric origin but argue that they result from modulation of the muon intensity by the vertical electric field associated with thunderstorms. Aglietta et al., have found that there are long-lived (duration ∼hours) and short-lived (duration ∼10 minutes) events that have different origins. The long-lived events appear to be associated with the rainout of atmospheric radon daughter products since the gamma ray lines expected from these products are clearly observed. They suggest, on the basis of an analysis by Dorman and Dorman (1995), that the short-lived events are possibly the result of electric fields acting on the cosmic ray secondaries, including muons, or possibly on the electrons, which might be accelerated beyond 25 MeV, thereby modifying the air shower count rate.

In this paper we will show that the increases are not due to protons, neutrons or muons, but that they are likely to be the result of electrons being accelerated to more than 40 MeV and probably even more than 100 MeV.

2 Experimental Results

2.1 Long-lived events:

The EAS-TOP group showed that for these events there was an increase in the low energy component (E > 0.1 MeV) in the NaI detector that was associated with the decay of radon daughter products. An investigation in Nepal showed that the radon was drawn upwards by ascending air currents during the day and precipitated in the evening in association with rainfall (M. Brunetti et al, 1999).

2.2 The Norikura events:

We have observed several examples of such long-lived events during the summer of 2000. Weather conditions in the Japanese Alps became very unstable, especially during the afternoons of 4-8 of August when thunderstorms developed followed by rainfall which lasted several hours. A typical example is shown in Fig. 1a: During the period of rainfall the large area (64 m^2) proportional counters of our system showed an increase which must be caused by low energy gamma rays (presumably from the radon family, e.g. Bi-214, 609 keV. Total amount of the rainfall was 38 mm). Photons with energy higher than 100 keV can penetrate the 2.3mm thick steel wall. As the rainfall decreased the count rate decreased gradually.

2.3 Short-lived events:

The plastic detectors in our system showed a quite different pattern of behavior during this period. As shown in Fig. 1b and 1c, there were sharp and short lived ($\sim$10 min) enhancements at $\sim$1400 JST and $\sim$1900 JST corresponding to the start and end of the rainfall respectively. The data shown in Fig. 1b was taken from the 64 $m^2 \times$ 20 cm thick plastic scintillator (Tsuchiya et al., 2001) and that shown in Fig. 1c from a 36 $m^2 \times$ 5cm thick plastic detector having a double layer structure (Nagashima et al., 1989). Coincidences between signals in the double layer structure of the latter detector are shown in Fig. 1d and the neutron monitor data is shown in Fig. 1e.

It is evident from these results that short-lived events were not produced by protons (the anti-coincidence circuit worked), nor by muons (which would easily penetrate two layers of the 36 m^2 detector), nor by neutrons/hadrons (there is no increase in the 10 NM64 neutron monitor). Furthermore, since a 1m^2 neutron telescope did not show any increase, we can also rule out electrical disturbances in the laboratory due to the thunderstorm as a cause of the effects observed. We conclude that the signal must be caused by gamma rays with energies exceeding 40 MeV, since the scintillator threshold for charged particles (electron-positron pairs) was set at over 20 MeV. The energy of electrons that produced the gamma rays must have been $>$ 100 MeV, slightly higher than the critical energy.

Unfortunately, we did not install an electric field mill at Mt. Norikura during this period, and so we cannot provide values for the vertical electric field and polarity at the site. Therefore we must guess the electric field from other data. Geophysicists have published the results of their measurements of the electric field in several scientific papers (for example, Suszcynsky et al., 1996). Observations made for events similar to these considered here (Domoto, 1998) indicate that the electric field typically has the double ('M'-type) structure observed by the field mill (see Fig. 2).

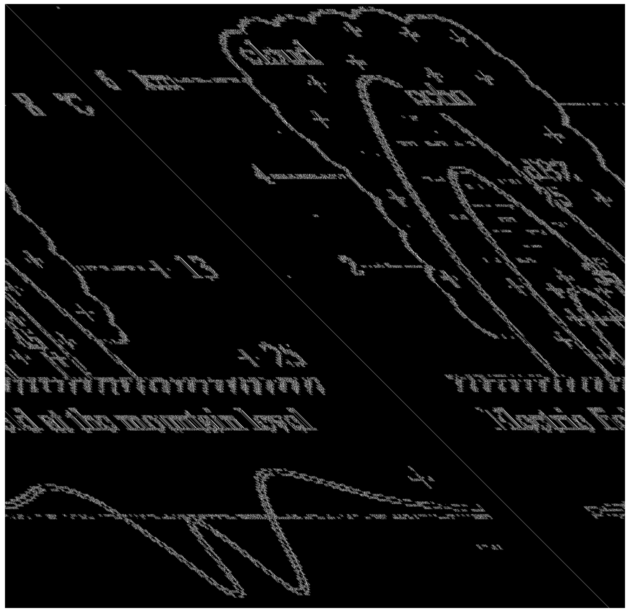

Fig. 2. Thunder cloud and the electric field at the mountain level

3 Interpretation of the events

Although they are not shown in this paper, we observed 4 similar events during the same week. All of them have more or less the same shape and two increases of the counting rate were observed.

The results of the measurements by Domoto encourage us to believe that the electric field variations during August 4-8th, 2000 must be also M-type shape (two peak structure) and that when the strongest electric field passed over the laboratory two times, electron pairs converted from photons were detected in the plastic scintillator twice.

Measurements of the electric field in the thunderstorm have shown the strength to exceed 100 kV/m. Hence within a short distance ($\sim$1,000 m), electrons can be accelerated to quite high energies ($\sim$100 MeV). To produce a photon by the bremsstrahlung process, an accelerated electrons pass through 400 m on average at the altitude of Norikura (760g). So on average the accelerated electron has a chance to produce about one photon by the bremsstrahlung process.

- An acceleration hypothesis -

We shall present a hypothesis in this section in order to clarify the problem of the short-lived events. We first assume here that the enhancement of the counting rate resulted from the acceleration of secondary electrons which were formed at $\sim$1.5 km above Mount Norikura observatory (2,770m). Secondary electrons produced by standard cosmic rays must be accelerated, from an altitude of $\sim$4 km down to the cosmic ray observatory, a total distance of about 1 km. The ground (2,770m) must be charged positively and the electric field strength must be 100 kV/m, or 100 MV/km. Only very few high energy knock-on electrons are sufficient for acceleration. Both electrons and muons can be effective in this process. The electrons produce photons with an energy about 40 MeV by the bremsstrahlung process. The photons pass through the large area anti-counters and enter into the large area plastic scintillator array. These photons are then converted into electron pairs inside the scintillator. The scintillator has an equivalent thickness of a half radiation length ($\sim$0.5).

The increase of the counting rate was only about 1%. This gives us important information on how much the electrons were accelerated without collisions in the air. Suppose the electrons start this acceleration from the 4 km level. The equivalent atmospheric thickness is about 600 g/cm^2. At this altitude the main component of cosmic rays are electrons and muons (about 1:1). These charged particles can deposit their initial energy into knock-on electrons when they run 60 g/cm^2 and lose $\sim$120 MeV of their initial energy. The W-value of the air is 34 eV. Hence 120 MeV/34 eV $\approx 3 \times 10^6$ ion pairs will be produced in the 1 km distance of the air. Almost 3 million seed electrons are available as the candidates for acceleration in the strong electric field. We suggest one survived and underwent continuous acceleration over a distance of 1 km before entering the detector as a photon.

- A numerical check -

It has been estimated in this paper that electrons with energies higher than 84 MeV (critical energy), are continuously accelerated. They are "collision free" electrons. Otherwise by the collisions with atomic electrons, they lose energy which is used to ionize or liberate the atomic electrons.

Three million electrons should be prepared at the start line for the candidates of acceleration. Of these only a few survive to produce the observed increase. Can we realize this ? The answer is 'Yes'. The spectrum of knock-on electrons can be expressed by $(1/E^2)dE$, where E represents the energy of secondary electrons (see Rossi, 1952). Integrating this equation, the number of electrons with the energy higher than E is 1/E. The ratio of (W/E) turns out as 4×10^{-7}. Here W represents 34 eV and E=84 MeV. There is a small possibility that very few electrons are produced by the knock-on process with E$>$ 84 MeV. Then multiplying this factor to the total number of seed electrons (3×10^6) produced by one high energy cosmic ray, (electrons and muons), we obtain the survival probability of electrons. The number should be around one electron.

At the acceleration region, the atmospheric pressure must be a half of that at the ground. We assume here that the electric field strength is 100 MV/1 km, therefore the energy of the electrons near critical energy will be increased to 184 MeV. However as a result of ionization loss ($\sim$120 MeV), they lose energy and are reduced to 64 MeV above the detector. On passing 1 km of air they have a chance to produce a photon of about 40 MeV. These photons are observed in our detector.

Of course this is just one of the possible interpretations of the high energy electrons produced in thunderstorm.

- Another possibility -

Here we must mention another possibility. Low energy electrons and muons are re-accelerated by the electric field. However this hypothesis introduces a new effect. When electrons and negative muons are accelerated, positrons and positive muons will be decelerated and vice versa. The energy spectrum of muons at 600 g/cm^2 has a peak around 2 GeV, while the decay electrons have a peak around 84 MeV. To judge which idea is working, we need a measurement of the polarity of the electric field. In the former case, the event will be detected only in the case of positively charged mountain surface, since the knock-on process only produces negative electrons. While in the latter case, the event must be observed whatever the polarity of the surface charge.

There might be a process, proposed by the EAS-TOP group, in which the increase of the counting rate in association with the thunderstorm is produced by the acceleration of the shower electrons and positrons. However here we would like to point out another possibility that they are produced by the knock-on electrons produced by the normal low energy comic rays.

References

Aglietta, M., et al., Proc. 26th ICRC, 3, p. 351, 1999.
Alexeenko, V. V., et al., Proc. 20th ICRC, 4, p. 272, 1987.
Brunetti, M., et al., Proc. 26th ICRC, 3, P. 355, 1999.
Domoto, M., Winter Lighting, Corona Publishing Co., 1998. (http://www.coronasha.co.jp)
Dorman, L. I., and Dorman, I. V., Proc. 24th ICRC, 4, p. 1160, 1995.
Eack, K. B., et al., J. Geophys. Res., 101, p. 29,637, 1996.
Fishman, G. J., et al., Science 264, p. 1313, 1994.
Nagashimai, K., et al., Nuovo Cimento, 12C, p. 695, 1989.
Rossi, B., High Energy Interactions, Prentice-Hall Inc., 1952.
Suszcynsky, D. M., et al., J. Geophys. Res., 101, p. 23,505, 1996.
Tsuchiya, H., et al., Nucl. Inst. Meth., A463, p. 183, 2001.

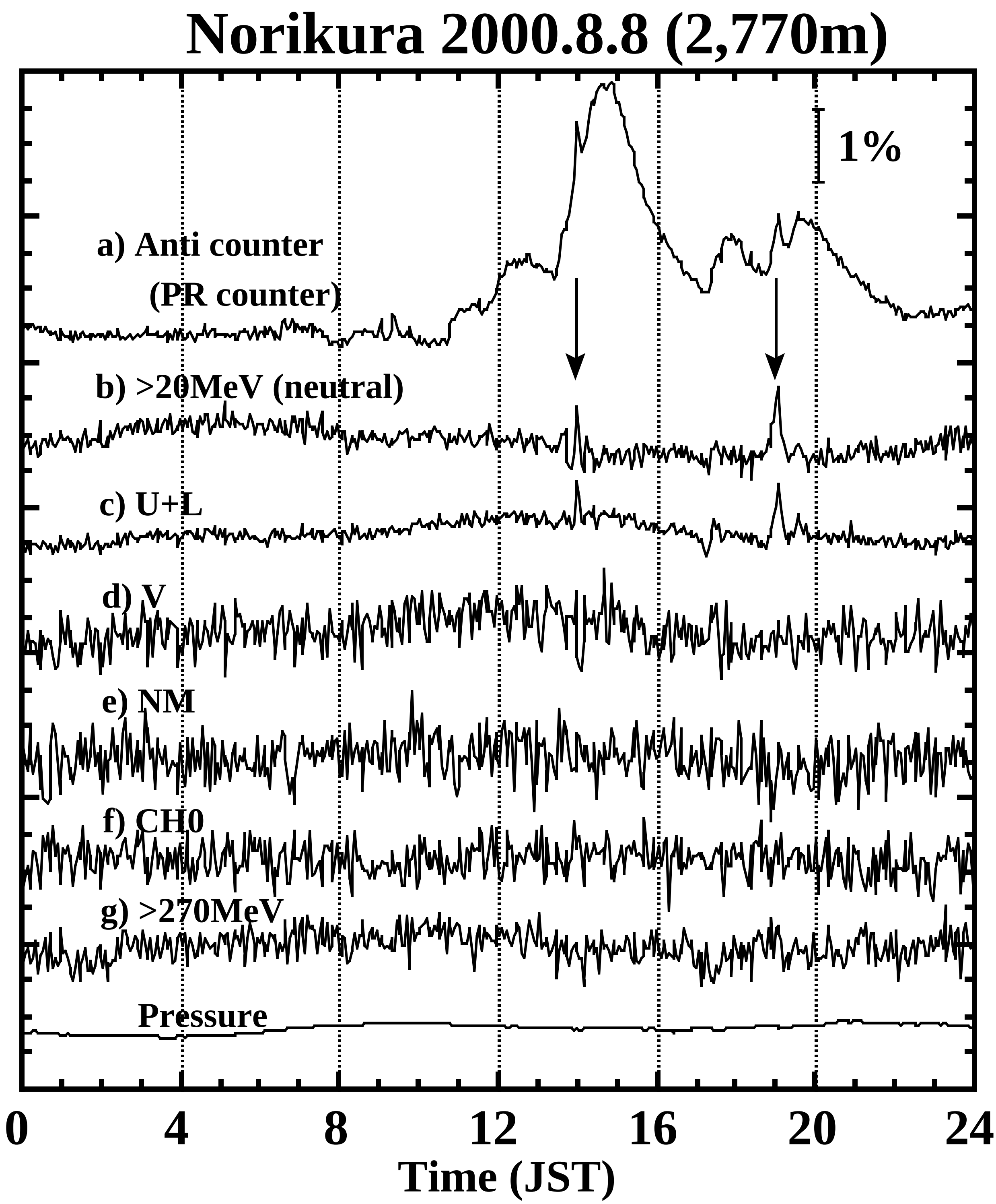

Fig. 1. The time profile of the counting rate on August 8th 2000 at Mount Norikura : (a) 64 m^2 proportioncal counter, (b) 64 m^2 scintillation counter with anti-counters, (c) 36m^2 scintillation counter without anti-counter, (d) the same detector but for the coincidence channel, (e) the neutron monitor 10NM64, (f) 1 m^2 $\times$ 50 cm plastic scintillation detector, (g) the $>$270 MeV channel of the 64 m^2 detector. As shown by the arrow, at $\sim$ 14 JST and $\sim$ 19 JST, two spikes can be seen, which we discuss here as an evidence for electrons produced by the thunderstorm run down mechanism. The excess could not be seen at higher channel of which deposit energy is higher than 270 MeV. The incidence particle must be less than 270 MeV. The data show 3 minutes value. The scale is indicated by the barred line indicating 1%.