Proceedings of ICRC 2001: 1733 © Copernicus Gesellschaft 2001

ICRC 2001

Origin of large albedo positron ratio

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Abstract. Atmospheric secondary positrons and electrons had been observed by many balloon experiments. The positron flux is approximately equal to the electron flux. However, the secondary positron electron flux ratio measured by the Alpha Magnetic Spectrometer were found to be depend on the magnetic latitude. They can be as high as 4 near the magnetic equator and as low as 1 at high latitude. This new finding can be explained by an old phenomenon, the east-west effect. A model combining the secondary particles production and the east-west effect was proposed. An analytical formula was also derived to explain the latitude dependence of the albedo positron electron ratio.

1 Introduction

Cosmic positron plays a major part in the search for dark matter and study of cosmic ray transportation. Many balloon experiments measured the cosmic positrons and electrons at approximately 40 km altitude. The major difficulty is the correction of the secondary particles produced in the residual atmosphere. The vertical depth of the residual atmosphere is approximately $5\mathrm{gm/cm}^2$, compared to the $\sim 15\mathrm{gm/cm}^2$ the mean matter that cosmic rays traversed inside the galaxy (Shapiro , 1991). These secondary positron and electron flux are modeled and corrected according to some particle interaction and decay models. A collection of atmospheric secondary positron and electron fluxes can be found in Barwick et al. (1998a). The atmospheric secondary positron electron ratio is approximately 1.

It is hoped that moving the detector to space could avoid the contamination from residual atmosphere. However, a recent space borne experiment, the Alpha Magnetic Spectrometer (AMS), observed many particles below the geomagnetic rigidity cutoff (Alcaraz et al. , 2000a,b) during the test flight in June, 1998. These below cutoff particles are found to originate from the atmosphere and rebound to space (Huang et al. , 2001). A large amount of positrons were observed all over the areas covered by the AMS. The most possible mechanism behind the global production of positrons is the interaction of primary cosmic rays with atmospheric nucleus, i.e., the same mechanism accounting for the atmospheric secondary particles observed by balloon experiments.

The albedo particles observed by the AMS can be divided into two groups, short flight-time (SFT) and long flight-time (LFT) particles. They exhibit different distributions of source position and spatial coverage (Huang , 2000b; Huang et al. , 2001). The most interesting result is the albedo positron electron flux ratio, which is found to be around 4 near the equator and varies with latitude. These ratios are different for SFT and LFT particles. The excess of positrons arouses questions concerning the potential contamination for cosmic positrons measurement and the correction factor of the balloon experiments.

This paper use the east-west effect to derived an analytical formula, which explained the latitude dependence of the positron electron ratio.

2 Albedo positron electron ratio

Albedo positrons and electrons are produced from the interaction between primary cosmic rays and atmospheric nuclei. The hadronic interactions produce π^+, π^-, π° and they decay through $\pi^\pm \to \mu^\pm \to e^\pm$ and $\pi^\circ \to \gamma \to e^+ + e^-$ At GeV range, the multiplicity of π^+ is slightly higher than that of π^- (Honda , 1995). Near the equator, the rigidity cutoff is above 10GeV, the contribution from the over-production of e^+ is small, less than 10%, and cannot account for the large positron electron ratio $\simeq 4$.

Owing to the geomagnetic rigidity cutoff and because the

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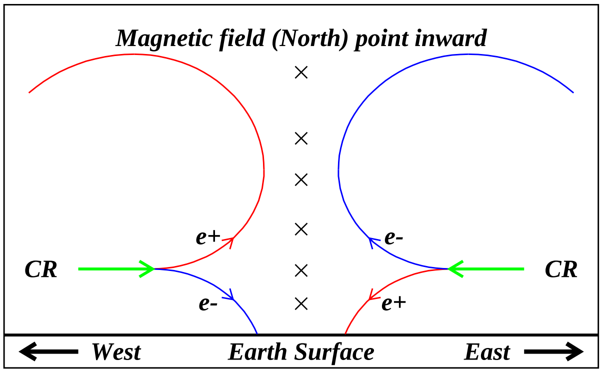

Fig. 1. Illustration of the albedo positrons and electrons produced by cosmic rays from the west and the east. Positrons from the west and electrons form the east have higher chance to move upward and become albedo particles.

majority of cosmic rays are positively charged particles, there are more cosmic rays coming from the west than from the east (Alvarez & Compton , 1933; Johnson , 1933). For the same reason, the Lorentz force moves the positrons coming from the west and electrons coming from the east upward, as shown in Fig. 1. Since the primary cosmic ray flux from the west is larger than that from the east, the secondary positrons from the west are more abundant than the electrons from the east. The difference in rigidity cutoff decreases with increasing magnetic latitude, so does the flux ratio.

To avoid the complexity, a simplified model which simulates the secondary particle flux by three parts (source, production, and transportation) is proposed (Huang , 2000a, 2001).

$$\psi(\lambda_d) = \int_{E_{\Re}}^{\infty} \frac{d\phi(E,\lambda_p)}{dE} P(E) dE \times \mathbf{T}(\lambda_p,\lambda_d) \qquad (1)$$

$\psi(\lambda_d)$:	Secondary particle flux at detection position λ_d
$E_{\Re}$:	Energy corresponding to rigidity cut-off, which depends on λ_p.
Source $d\phi(E,\lambda_p)/dE$:	Primary cosmic ray flux of energy E at production position λ_p
Production $P(E)$:	Probability for secondary particles to be produced from primary cosmic rays of E
Transportation $\mathbf{T}(\lambda_p,\lambda_d)$:	Probability for particles to be transported from position λ_p to λ_d.

2.1 Source

The primary cosmic rays are simplified as a power law spectrum. At production sites, they are

$$\frac{d\phi(E,\lambda_p)}{dE} = \begin{cases} c \times E^{-\kappa} & E \geq E_{\Re} \\ 0 & E < E_{\Re} \end{cases}$$

where c is a normalization constant and κ is the power law index.

The rigidity cutoff in the realistic geomagnetic field cannot be expressed in analytical form. To simplify the calculation, the Strömer cutoff (Strömer , 1930) is assumed.

$$\Re_c(\gamma,\lambda) = \frac{\cos^4\lambda \times 59.6(\mathrm{GV/c})}{(r/R_E)^2(1+\sqrt{1-\cos\gamma\cos^3\lambda})^2}$$

where γ is the angle between particle velocity and magnetic west, λ is the magnetic latitude, and R_E=6371.2 km is the mean Earth radius.

2.2 Production

The atmospheric nuclei are almost stationary compared with the relativistic primary cosmic rays. Only the center of mass energy contributes to the production of secondary particles. Assume the multiplicity to be proportional to E^δ where $\delta \sim 0.45$ in the range $10\mathrm{GeV} < E < 1\mathrm{TeV}$ (Kasahara , 2001),

$$P(E) \propto E^\delta \qquad (2)$$

The secondary particle flux ψ can be expressed as

$$\psi(\lambda) = \int_{E_{\Re}} c' E^\delta E^{-\kappa} dE \simeq \frac{c'}{-\kappa'+1} E_{\Re}^{-\kappa'+1} \qquad (3)$$

where $\kappa' = \kappa - \delta$, and c' is a new constant. So the flux ratio at production altitude h can be approximated as

$$e^+/e^-(\lambda_h) = \frac{\psi(e^+)}{\psi(e^-)} = \left(\frac{E_{\Re +}}{E_{\Re -}}\right)^{-\kappa'+1} \qquad (4)$$

When $E_{\Re} \gg$ mass of proton, this ratio can be further simplified as

$$e^+/e^-(\lambda_h) = \left(\frac{1+\sqrt{1-\cos(\gamma_-)\cos^3\lambda_p}}{1+\sqrt{1-\cos(\gamma_+)\cos^3\lambda_p}}\right)^{2(-\kappa'+1.)} \qquad (5)$$

2.3 Transportation

Because of the second adiabatic invariant(Walt , 1994), the trajectories of particles trapped inside the geomagnetic field follow the guiding center magnetic field line, which can be specified by the L shell. L-shell is a magnetic field line and is defined as the radial distance at the magnetic equator in unit of R_E. Therefore, the particles are transported from the production site at altitude h to the AMS altitude (380 km) by the same L-shell.

$$L = \frac{R_d}{\cos^2(\lambda_d)} = \frac{R_p}{\cos^2(\lambda_p)} \qquad (6)$$

$$R_d = (380 + R_E)/R_E \qquad R_p = (h + R_E)/R_E$$

3 Results

In Huang (2000a), it is assumed that positrons come from the west ($\gamma_+ = 0°$) and electrons come from the east ($\gamma_- = 180°$). With $\kappa' = 2.75$, Eq. 5 predicts a result consistent with the LFT e^+/e^-.

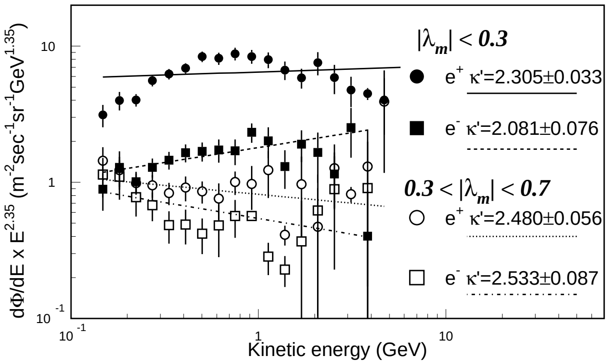

Fig. 2. The differential spectra of upward-going positrons and electrons are multiplied with $E^{2.35}$ where E is the kinetic energy. The spectrum index κ' and the denotations of symbols are shown on the figure. λ_m is the magnetic latitude in radian.

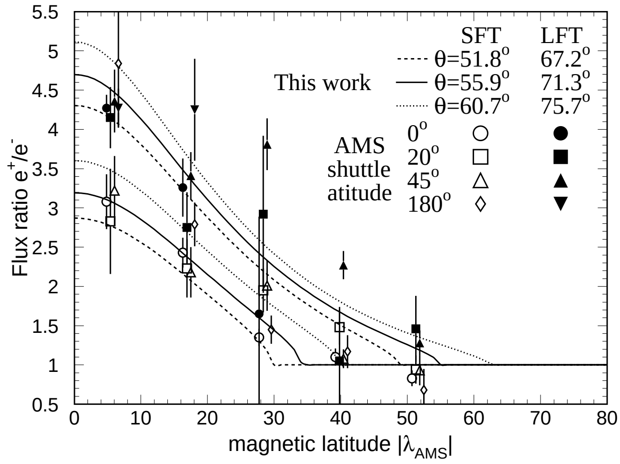

Fig. 3. The e^+/e^- at the AMS altitude are fitted to obtain the angle θ. The data points are artificially separated by a small difference in latitude for clearness. The solid line corresponds to the minimum χ^2 fit, and the dotted/dash lines correspond to the upper/lower limit of θ at $\chi_{\nu}{}^2_{min} + 1$.

In this study, the AMS flux ratios are used to derive the arrival directions of the primary cosmic rays that produced the albedo particles. The AMS spectra (Alcaraz et al. , 2000b) at $|\lambda_m| < 0.7$ rad. are used to verify κ'. Figure 2 shows the spectra of upward-going electrons and positrons (Alcaraz et al. , 2000b), which consist of albedo particles only. The mean value of the fitted power law spectrum indexes is 2.35, consistent with the assumed value $\kappa' = 2.78 - 0.45 = 2.33$ using the AMS proton spectrum, $\kappa \simeq 2.78$ (Alcaraz et al. , 2000c). This consistency confirms the assumptions in Eq. 2. $\kappa' = 2.33$ is used in the subsequent analysis. The large fluctuation of κ' may be due to the combined effects of the rigidity cutoff and the spectrum shape at $E < 10$GeV, where the spectrum shape changes due to the solar modulation effect.

Equation 4 is less dependent on production altitude h. Assuming $\gamma_+ = 0°$ and $\gamma_- = 180°$, the e^+/e^- at magnetic equator are 4.83 and 5.29 for production altitudes of 0 km and 100 km respectively. The difference is only 0.46 or 9%. The production altitude of 40 km is chosen in order to be consistent with the definition of flight time.

The west angle $\gamma(\lambda)$ dominates the e^+/e^-. In order to stay above the atmosphere most of the time, the mirror points of LFT particles must be around the top of the atmosphere at the production site. This implies that the velocities of LFT particles are almost perpendicular to the magnetic field lines. With this condition, the $\gamma(\lambda)$ distribution can be derived as

$$\cos\gamma = \sqrt{\sin^2\theta - 4\tan^2\lambda\cos^2\theta} \quad (7)$$

The angle θ is the only free parameter. By using Eqs. 4 and 7, and $\kappa' = 2.33$, the AMS e^+/e^- can be fitted to obtain the θ, giving $\gamma(\lambda)$. With minimum χ^2 fit, shown in Fig. 3, θ is $71.3^{+4.5}_{-4.1}$ degree for the LFT particles and $55.9^{+4.8}_{-4.0}$ for the SFT particles.

Figure 4 shows the distribution of the expected γ angles as a function of latitude. The SFT particles have γ close to $90°$, while the LFT particles have γ close to $0°$ (electrons) or $180°$ (positron). Owing to non-negative constraint of Eq. 7, there is an artificial truncation $\gamma \simeq 90°$ at $\lambda > 50°$. In reality, γ could cross over the boundary at $90°$, therefore $e^+/e^- \simeq 1$ at $|\lambda| > 45°$ as shown in Fig. 3.

The $\gamma(\lambda)$ distribution can be employed to derive the particle direction. The arrival directions are taken as the reverse directions of albedo particles, assuming that secondary particles are mostly in the forward direction. In the reaction chain $p + ... \to \pi^{\pm} + ... \to \mu^{\pm} + ... \to e^{\pm} + ...$, the secondary $e^{\pm}$ velocity direction can deviate from the primary p velocity direction up to approximately $10°$ in laboratory frame. For cosmic rays with zenith angles $\theta > 80°$, or elevation angle $0°$ to $10°$, the secondary particles can have elevation angle $\pm 10°$ and become albedo particles. Figure 5 shows an example at latitude $15°$. The arrival directions of cosmic rays con-

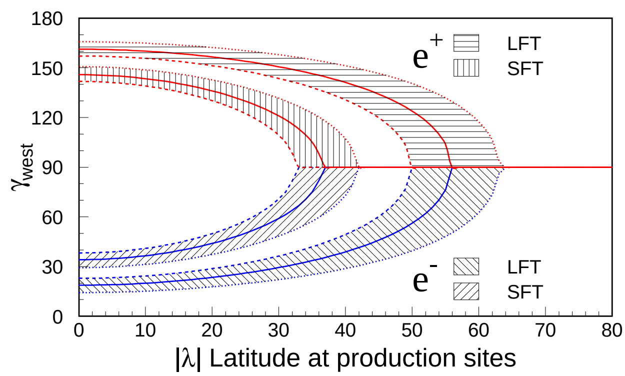

Fig. 4. The west angles γ are shown as a function of latitude at production sites. The notations of lines are the same as those in Fig. 3.

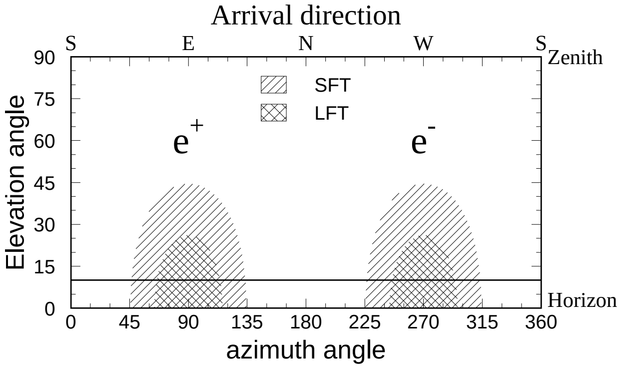

Fig. 5. The parameter space for LFT and SFT particles at magnetic latitude $15°$. The elevation angle is $90° - \theta$ and the arrival direction is the reverse direction of velocity. The solid line shows the upper limit for upward-going secondary particles produced by horizontal shower. The allowed regions of LFT (SFT) particles are the hatched (shaded) areas under the solid line. Particles outside these regions can be regarded as SFT particles.

centrate in East $\pm 23°$ for those that produced LFT positrons and in West $\pm 23°$ for those that produce LFT electrons. This indicates that the LFT e^+/e^- are mainly caused by the east-west effect, while the SFT e^+/e^- are due to cosmic rays coming from other directions.

4 Disscusion

A model based on secondary particles production and the east-west effect is proposed to explain the large albedo e^+/e^- ratio observed by the AMS. The albedo particles spectra are consistent with the assumption of secondary particles production from cosmic rays air shower. This model derived an analytical formula of $e^+/e^-(\lambda)$. One important parameter, the west angle γ, is derived by confining the particle velocity to be perpendicular to the magnetic field. A free parameter can be found by fitting the AMS e^+/e^-. Then the arrival direction can be obtained from the γ distribution. The results suggest that LFT particles come from air showers produced by near-horizon cosmic rays near the East and the West. Detail simulations (Kasahara and Huang , 2001) based on the simulation code **COSMOS** (Kasahara , 1999) are presented in this conference.

The excess of albedo positrons can be explained by the east-west effect. On the global scale, the positron flux and the electron flux are equal. It is not necessary to add extra sources of positrons in the corrections of atmospheric secondary particles. The corrections of the atmospheric secondary particles by balloon experiments are still valid.

Figure 4 shows that LFT particles could be produced in $|\lambda_m| > 50°$, contradict to what Alcaraz et al. (2000b) stated that LFT particles concentrate in low latitude regions only. The LFT particles should also exist in high latitude regions, $|\lambda_m| > 50°$, where the rigidity cutoff is close to the secondary particle rigidity $\sim 2GV/c$. Many of the secondary particles have rigidity in the penumbra, where cutoffs are broadened to intermittent bands. Some particles could be trapped and some particles could escaped to space. For those trapped particles, their trajectories are irregular and some could drift across the Earth several times and become LFT particles. These events are excluded in Alcaraz et al. (2000b) but included in discussion of Huang (2000b).

When the rigidity is in the penumbra, the re-entrant albedo particles and cosmic rays could mix together and it is very difficult to separate them individually. For AMS positron measurements near cutoff, the albedo positrons could be a significant source of contamination. Detailed study of penumbra is necessary for achieving a better separation of cosmic and albedo positrons. Measuring both upward and downward fluxes also helps to reduce the contamination of albedo positrons.

Acknowledgements. The author wishes to thank the AMS collaboration for providing the data used in Fig. 2 and Drs. L.C. Lee, S.C. Lee, K. Kasahara, and S.A. Stephens for their valuable comments. This study was supported by the National Science Council, Taiwan, ROC under grant NSC89-2811-M-001-0076.

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