Atmospheric Secondary Particles
In Near Earth Space

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The Alpha Magnetic Spectrometer detects a large amount of particles below rigidity cutoff. Those high energy particles create questions related to radiation belts and atmospheric neutrinos. To understand the origin of these particles, we use a trajectory tracing program to simulate particle trajectories in realistic geomagnetic field. The complex behaviors and large $e^+/e^-$ are explained here.

1 Introduction

In June 1998, the Alpha magnetic spectrometer AMS had a test flight on board space shuttle and recorded some $10^8$ events. The AMS proton and leptons spectrum have a magnetic latitude dependence. The spectral shape of primary cosmic rays can be explained by the geomagnetic rigidity cutoff. However, below the rigidity cutoff, a second spectrum was clearly seen. The energy of this second spectrum is as high as 6 GeV, 10 times higher than previous measured energy in the radiation belts! Beside this apparent difference, these second spectrum particles have similar trajectories as particles in trapped radiation, however, the fate are quite different. The discovery of these GeV sub-rigidity particles create new questions about the radiation belts and the atmospheric neutrinos flux. In this article, the trajectories of these particles are simulated in the same condition as AMS. They are shown to explain the complex behaviors of these secondary particles.

2 Trajectory Tracing

A trajectory tracing program are used to trace particle trajectory forward and backward in time. The interactions between particles and atmosphere are ignored. The particles are defined as cosmic rays if their radial distance greater than $10R_E$ ($R_E$ mean Earth radius 6371.2km) when traced backward. The particle hit the ground in backward tracing is defined as atmospheric secondary. Physically, it is impossible to hit the ground at these energy regions. A limit of 40-km altitude was set as the top of atmosphere (TOA). The position where particle originates (traced backward) at 40 km altitude is defined as the “source”. The position where particle re-enter atmosphere (traced forward) at 40 km altitude is defined as the “sink”. The total time from the source to the sink, i.e. from creation to absorption by atmosphere, is called the

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“lifetime”. Two groups of events are found, the Short-Lived Particles (SLP) which have lifetime in the order of bouncing period and the Long-Lived Particles (LLP) which have lifetime much longer than bounce period and less than drift period.

3 The Short-Lived Particles

The SLP are absorbed by atmosphere in several bouncing motions between southern and northern hemisphere after their creation. Their motions can be categorized by the number of magnetic equator crossing times. This number corresponds to the ratio of lifetime to the half of bouncing period. The most common crossing times are 1 and 2. Figure 1 show the trajectories of those two cases. The bouncing period is inverse proportional to particle velocity \([\beta]\). At GeV range, the electron and positron move at \(\beta \sim 1\). Therefore, the lifetime is independent of energy.

![Image of trajectories showing 1 and 2 equatorial crossings](image)

Figure 1: Two examples of short-lived particle trajectories. The horizontal axis is the equatorial component and the vertical axis is the Earth rotational axial component. The left/right figures show an event which cross the magnetic equator once/twice. The lifetime from source (dot) to sink (triangle) is shown on the upper right corner.

Since SLP are created and absorbed by atmosphere in very short time, their source and sink positions must follow the magnetic field line to TOA and ground. Therefore the distribution of sources and sinks have a pattern similar to the flight path of detector. The SLP are detected all over the AMS covered area, latitude \(-51.5^\circ\) to \(+51.5^\circ\). In the equatorial region, there is a gap in the source/sink of SLP. Inside this gap, the local magnetic field line can not reach AMS altitude, particles within this gap could not fly up to AMS altitude and be detected as SLP.

4 The Long-Lived Particles

Particles produced inside the gap need to drift to higher altitude to be detected. This drift motion increase the lifetime. Figure 3 show the summary of trajectories of two LLP events. The source and sink of the LLP are separated to two regions. The main reason is the offset of the center of geomagnetic dipole from the center of the Earth. Along the magnetic equator, one
Figure 2: The equatorial gap and space covered by short lived particles are shown in a slice along the dipole plane. Notice the short lived particles can cover space up to $4 - 6R_E$ in AMS covered region. Traditionally, radiation zone covers from $1.2R_E$ to $\sim 7R_E$.

side (magnetic longitude $180^\circ$) the magnetic field are stronger, so the particle move to higher altitude; on the opposite side (magnetic longitude $0^\circ$), the magnetic field are weaker and particles move to lower altitude and could hit the TOA, shown in figure 4. Positive LLP are generated in magnetic longitude $-180^\circ$ to $0^\circ$ and sink to magnetic longitude $0^\circ$ to $180^\circ$. Negative particles reverse this direction. For particles coming directly from top of magnetic longitude $0^\circ$, they fly to AMS altitude not far from their source or sink. These regions are excluded in the AMS analysis. Therefore, the source and sink are separated in east and west of the magnetic longitude $0^\circ$.

The mean lifetime of LLP is approximately half of drift period which is proportional to $\sim 1/\gamma \beta^2$ [5]. Therefore the lifetime and energy have an approximately inverse proportional relation.

These LLP create a partial ring current, their trajectories cover altitude from $1R_E$ to $1.2R_E$, the mirroring magnetic latitudes are within $\pm 25^\circ$. This non-uniform (not anisotropic as AMS claimed), distribution of LLP is result of multi-pole moment of geomagnetic filed. In a centered dipole field, there will be no LLP.

The source(sink) of positive(negative) LLP are separated to two groups, north and south of magnetic equator. This is the effect of asymmetry of geomagnetic field in magnetic latitude. The magnetic equator is not always the position where the magnetic field is minimum. At magnetic longitude $-60^\circ$ $\sim 130^\circ$, the positions of minium magnetic field are south of magnetic equator, particles reach lower altitude in area south of magnetic equator and have chance to hit TOA. For magnetic longitude $> 130^\circ$ or $< -60^\circ$, particles will hit TOA in area north of magnetic equator.
Figure 3: Two examples of long-lived particles trajectories projected on the equatorial plane, viewing from North Pole. The circle is the Earth. Only the northern/southern mirroring points (those points closer to earth) and point of highest altitude (those points away from earth) are plotted. The total lifetime is also printed in the center of each figure.

Figure 4: The source and sink of long-lived particles are distributed at the east and west side of weakest magnetic field along the magnetic equator. The long-lived particles are created near magnetic longitude 0°, drift along the same L shell, pass the highest altitude near magnetic longitude 180°, then descend and enter atmosphere.
5 Position Electron Ratio

The secondary positron and electron ratio can be higher than 4 and have a latitude dependence. This effect is dominated by rigidity cutoff. Secondary positrons from west and electrons from east have chance to move to space. However, the rigidity cutoff from west is lower than from east, so there are more positrons than electrons. The difference of rigidity cutoff between east and west decrease at higher latitude, therefore the $e^+/e^-$ decreases too. Base on the following assumptions:

1. Positrons all come from west and electrons all come from east.
2. Dipole field and Stromer rigidity cutoff.
3. Primary cosmic rays flux follows power law spectrum $\Phi(E) \propto E^{-\gamma}$.
4. At interesting energy region $10\text{GeV}/c^2 < E < 1\text{TeV}/c^2$, the multiplicity of total secondary particles are simplified as proportional to power law of primary cosmic ray energy $M(E) \propto E^\eta$.

This simple model predict

$$e^+/e^- = \frac{\Phi(e^+)}{\Phi(e^-)} = \left(\frac{1 + \sqrt{1 - \cos^4 \lambda}}{1 + \sqrt{1 + \cos^4 \lambda}}\right)^{2(-\gamma+\eta+1)}$$

The particles are produced in 40Km altitude and transported to 380Km by the same L shell. Using $\gamma = 2.75$ and $\eta = 0.5$, the predicted $e^+/e^-$, shown in figure 5, are consistent with the AMS results.

For different incident angles, the difference in rigidity cutoff decrease, so does $e^+/e^-$. However, the conservation of isospin make the positron multiplicity higher than electron multiplicity at primary energy below $10\text{GeV}/c^2$. This effect will increase $e^+/e^-$. A Monte-Carlo simulation which include realistic geomagnetic field and particle interactions is in progress.

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References

[1] S. Ahlen. et al, Nucl. Instrum. Methods A 350, 351, (1994).
[2] AMS collaboration, J. Alcaraz, et al, Phys. Lett. B 472, 215, (2000)
[3] AMS collaboration, J. Alcaraz, et al, Phys. Lett. B 484, 10, (2000)
[4] M.A. Huang, et al, submitted to Chinese J. of Phys. 38, , (2000)
[5] Martin Walt Introduction to Geomagnetically Trapped Radiation, (Cambridge Univ. Press, 1994).
[6] J. Benecke, et al, Nucl. Phys. B 76, 29, (1976); W.M. Morse, et al, Phys. Rev. D 15, 66, (1977); A. Breakstone, et al, Phys. Rev. D 30, 528, (1984);
Figure 5: The ratio of positron over electron from this work is consistent with the AMS long-lived measurements [3]. This ratio drop to 1 at high latitude region where balloon experiment measure secondary $e^+/e^- \simeq 1$. 