Proceedings of ICRC 2001: 4200 © Copernicus Gesellschaft 2001

ICRC 2001

Primary cosmic rays and trapped radiation as the sources of the positron fluxes in the Earth's vicinity

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Abstract. The production of positron and electron fluxes due to nuclear reactions of cosmic rays and trapped particles in the Earth's magnetosphere, is considered. It is supposed that positrons as well as electrons are mainly produced in the decay of charged pions, which are born in nuclear collisions of trapped relativistic inner zone protons with the residual atmosphere constituents. These positrons and electrons are captured in the magnetosphere and create positron and electron radiation belts of nuclear reaction origin. We simulated the positron and electron trapped magnetospheric fluxes as due to the radiation belt proton source modeled by AP-8 through reactions and decay schemes and obtained the e^+/e^- flux ratios dependent on positron energy and close to ~ 4. However, this excess is absent when we considered the primary and secondary cosmic ray proton fluxes observed in equatorial region as a positron flux source in our simulations. Interestingly, the Alpha Magnetic Spectrometer (AMS) on board the space shuttle, in the equatorial region at altitudes of » 400 km (The AMS collaboration, 2000), registered quasi-trapped positron fluxes with intensities about 4 times higher than the electron fluxes at energies above 200 MeV and with e^+/e^- flux ratio dependent on positron energy. This agreement between the e^+/e^- flux ratio and its energy dependence calculated on the basis of AP-8 model and the AMS observations is good.

1 Introduction

The likely existence of significant fluxes of geomagnetically trapped anti-particles in the innermost magnetosphere of the Earth has been demonstrated in recent papers (Gusev et al., 1996; Pugacheva et al., 1997). These anti-particles (positrons and antiprotons) are not of primordial or direct extraterrestrial origin, but are expected as the natural products of nuclear reactions of high energy trapped protons (TP) confined in the terrestrial radiation belt and primary cosmic rays (CR) with the ambient neutral atoms of the terrestrial atmosphere residing at several hundred kilometers altitudes. The subsequent trapping and storage of these charged anti-particles within the magnetosphere results in the formation of radiation belts similar to those of protons, electrons and anomalous CR nuclei. From the computations presented herein, we expect the presence of trapped energetic multi-MeV positron fluxes in a narrow L-shell range in the innermost magnetosphere, low enough for heavy neutrals to be abundant and high enough for radiation belt protons to have appreciable fluxes to induce the anti-particle generation effects.

Since the 1960s, attempts have been made to un- ambiguously detect the presence of positrons in the Earth's vicinity. In balloon experiments carrying instruments with magnets, De Shong et al., (1964) and Hartman et al., (1965) made the first attempts to observe interplanetary positrons in the energy range of 50 MeV to several GeV. Through the detection of 0.511 MeV annihilation quanta, Cline and Hones, (1968), identified the presence of low energy positrons (0-3 MeV) of interplanetary origin in experiments carried on the OGO-1 and OGO-III spacecraft.

Measurements of cosmic ray positrons with energies above 0.3 GeV, with sophisticated experimental technique using standard and super conductive magnets, have been carried out over a number of years (Boezio et al., 2000, and references therein). The aim of these high energy experiments is to detect primary CR positrons. However, until now the observed positron CR flux attests the origin to be purely of secondary nature, i.e. positrons are generated in nuclear reactions of primary cosmic rays with interstellar matter well beyond the Earth.

The hypothesis that high energy positron/electron radiation belt of nuclear origin could be locally generated in the Earth's uppermost atmosphere was first considered by Basilova et al., (1982). Recently, the Alpha Magnetic Spectrometer (AMS) on board the space shuttle "Discovery" detected a surprisingly large excess of positrons over electrons at energies >150 MeV in the equatorial region of the inner magnetosphere at altitudes of around 400 km (The AMS collaboration, 2000). Experiments on board the Russian COSMOS-1669 satellite and on the MIR space station provided measurements of magnetospheric positron and electron fluxes with energies from 20 to 150 MeV. The results showed higher positron fluxes within the Brazilian Magnetic Anomaly (BMA) region compared to the fluxes outside of this region (Voronov et al., 1987), and indicated an excess of electrons over positrons in the BMA region itself (Galper et al., 1997).

Freden & White (1960) have pointed out that the trapped high energy protons could locally produce a variety of isotopes of the lighter elements, such as deuterium (D), tritium (T), and ^{3}He in nuclear interactions with heavy atoms of the residual atmosphere. Instrumentation on board the SAMPEX and CRRES satellites recently confirmed this expectation, reporting the presence of D and ^{3}He isotope radiation belts in the Earth's inner radiation zone (Selesnick and Mewaldt, 1996*; Chen et al.*, 1996). In summary, these recent observations all support the hypothesis that the rarefied upper atmosphere at altitudes of 300-1000 km, is the locus for the generation of noticeable fluxes of trapped energetic electrons, positrons and various daughter-nuclei ionic species.

In our modeling, we consider the resulting values of the e^+/e^- flux ratio that is expected from the nuclear reaction source mechanism outlined above. This ratio is an important characteristic of the positron flux source function, and it could be used as an indicator in the analysis of experimental data concerning magnetospheric positrons.

2 Nuclear reaction source of magnetospheric positrons

Unlike the production of D, T, and ^{3}He isotopes in nuclear spallations, the positrons and electrons considered here are not generated as direct products of inelastic nuclear reactions in the Earth's exosphere. They are predominantly formed in the decay of short-lived charged pions and kaons ($\pi^\pm \to \mu^\pm + \nu$; $\mu^\pm \to e^\pm + \nu + \tilde{\nu}$) that are generated in the nuclear collisions. The minimum proton energy threshold for π-meson production is ≈290 MeV. Due to the short lifetimes of pions and muons, the resulting positrons and electrons are effectively produced in the same region where the parent pions and muons are born and will be essentially confined to the same L-shells of their parent TP.

In the chain of unstable particle decays, the mean fractions of energy carried away by a muon in the pion decay and by an electron in the muon decay are q_μ=0.8 and q_e=0.33 respectively. The production spectrum of electrons, $P_{e\pm}(E_e)$ (i.e. the number of particles generated by a unit incident proton flux in 1 g/cm^2), is related to that of the pion spectrum $P_{\pi\pm}(E_\pi)$ as: $P_{e\pm}(E_e) = P_{\pi\pm}(E_e/q_\mu q_e)/q_\mu q_e$. This means that the ratio of e^+/e^- in the production spectra at energy E_e is the same as the ratio in the production spectra of the parent-pions at the corresponding pion energy $E_\pi = E_e/q_\mu q_e$. The differential electron flux, $F_e(E_e)$, at the point of observation is determined by the particle conservation law: $F_e(E_e)=P_e(>E_e)/(dE/dx)$, where $P_e(>E_e)$ is the integral electron production spectrum and dE/dx is the energy loss.

Accordingly, the ratio of the resulting differential fluxes of e^+ and e^- is equal to the ratio of the integral production spectra of positrons to electrons at the same energy, and is also equal to the ratio of the integral production spectra of the pions with energies corresponding to $1/q_e q_\mu$ times the positron/electron energy:

$$F_{e+}(E_e)/F_{e-}(E_e)=P_{e+}(>E_e)/P_{e-}(>E_e)=P_{\pi+}(>E_e/q_\mu q_e)/P_{\pi-}(>E_e/q_\mu q_e)$$

It permits us to substitute the rather complicated modeling of the absolute fluxes of positrons and electrons by the much simpler computation of the pion production spectra for the various incident proton energies.

Qualitatively, the excess of positrons over electrons is a natural consequence of the A(p,π) nuclear reactions, in which D+π^+, p+π^+ and p+n+π^+ products predominate near the proton reaction threshold energy (Machner and Hidenbauer, 1999) (here A is a target atomic number). The trapped component has comparatively greater fluxes of protons at energies near the reaction threshold than the CR protons to provide a substantial positron excess.

To estimate $F_{e+}(E_e)/F_{e-}(E_e)$ flux ratios in the region of L=1.2±0.1 where intense TP fluxes are present, we have computed the production spectra of pions produced by protons with energies from 300 MeV to 2 GeV, and by the CR protons (>8 GeV). In the equatorial region, at L=1.2, the TP are predominantly located in a narrow pitch-angle range of 90±10°. Thus in this modeling, we took into consideration only the pions born with velocity vectors parallel to those of the parent protons, because only they produce positrons and electrons that can be trapped. The others, generated with angles beyond this range, after decay, produce quasi-trapped particle fluxes with about the same e^+/e^- flux ratio.

As thermal He is an essential constituent of the Earth's upper atmosphere at altitudes of about 800 km (the minimum altitude of the L=1.2 geomagnetic field lines at the geomagnetic equator), the modeling utilized the He(p,π) reactions. Besides, the charged pion production has a weak dependence on the target atomic number A.

To obtain the pion production output we run a version of the Monte Carlo code SHIELD for the intra-nuclear cascade simulations (Dementyev & Sobolevsky, 1999).

In Fig. 1, the results of Monte Carlo simulations of the He(p,π) pion production are presented. The ratio of the intgral production spectra of π^+ and π^- mesons at energies of about 40 MeV, produced by the protons in the energy range 0.3 - 2.0 GeV, lies between 2 and 5 and increases with the pion energy. This positron excess is a direct consequence of the charge conservation law which tends to favor positive pion production when only a few pions are born. Thus, nuclear reactions of the 0.3 - 2 GeV energy trapped protons substantially favor the production of positrons over electrons in the energy range of 20 MeV to several hundreds of MeV.

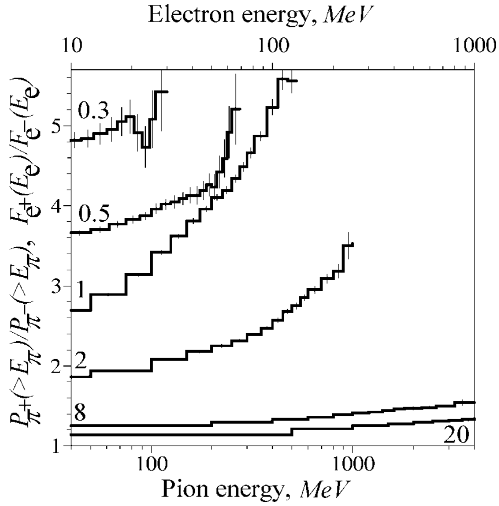

Fig. 1. The dependence of e+/e- differential flux ratio on electron energy and pion integral production spectra ratio on the pion energy for various parent proton energies. The error bars mark the statistical errors of the simulation. The numbers near the curves mark the parent proton energies in GeV.

The estimates of the e^+/e^- flux ratio, obtained in these nuclear reactions, both with the energetic TP spectrum from AP-8 model (Vette, 1991) and the CR spectrum in the equatorial region are presented in Fig. 2. In the L=1.2±0.1 region, in the energy range of E_e=20-1500 MeV, the TP source produces more positrons than electrons by factors of ~ 4. At higher positron/electron energies, this ratio essentially decreases to ≈1.25 characteristic of the CR source.

3 Discussion

We attempt to compare the estimates obtained above with the recent results from space shuttle AMS experiment and with the observations on board the COSMOS-1669 satellite and the MIR space station.

The possible existence of the positron radiation belt theoretically considered is essentially supported by the observation of the AMS experiment recently carried out on board the space shuttle "Discovery" at an orbit altitude of ~ 400 km (The AMS collaboration, 2000). This experiment detected a strong presence of quasi-trapped positrons (called by authors as "long-lived" particles) with energies of 150 to 3000 MeV in the equatorial region at L < 1.3 and observed a mean flux ratio of positrons to electrons of 4.27±0.17. The energy dependence of the e^+/e^- flux ratio observed in the experiment is also shown in Fig. 2. These ratios are found to be in good agreement with the results of our numerical modeling for the e^+/e^- flux ratio at E_e>150 MeV. At higher geomagnetic latitudes corresponding to L >1.3, the observed positron excess decreased to

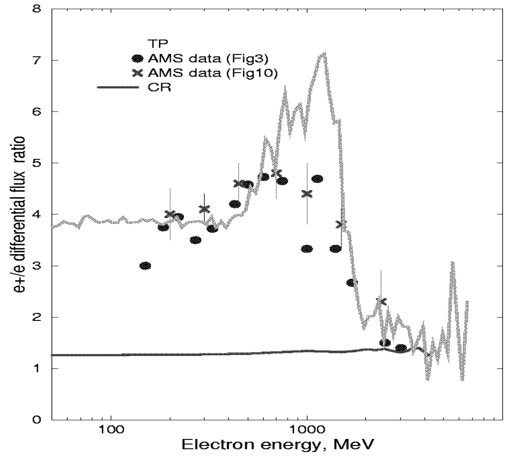

Fig.2. The computed *e+/e-* differential flux ratio from trapped proton spectrum (TP) at L=1.2 and from CR spectrum at the geo magnetic equatorial region; the *e+/e-* differential flux ratio observed by the AMS collaboration, (2000) at low latitudes.

1.28±0.16, values characteristic of a CR source. From this agreement we conclude that the positron excess observed in the AMS experiment at L ~ 1.2 is related to the local pion production by the low energy TP in this region.

The positron fluxes observed by AMS at L<1.3 demonstrate the "inverse" latitude dependence (i.e. a positron flux decrease with latitude) opposite to that expected for the albedo fluxes of CR origin. This "inverse" dependence is also an evidence of a presence of an additional local positron source, different from the CR source.

The AMS instrument also looked at the distribution of hundreds MeV helium nuclei, but only the ^{3}He isotope was observed. This is possible to understand in terms of quasi-elastic knock outs of secondary nuclei caused by protons of TP energies (Komarov, 1974). In these specific reactions, the secondaries of hundreds of MeV energies have greater yield for the lighter ion species. The relative yield of D: ^{3}He: ^{4}He is expected to be 4100:33:1 with overwhelming ^{3}He ion flux compared with the ^{4}He ion flux. Thus, the results of the ^{3}He observations also demonstrate that the nuclear interactions of TP with the residual atmosphere can generate significant, detectable charged particle fluxes. This indirectly supports the hypothesis of positron radiation belt production in the local nuclear reactions of TP.

The Cosmos 1669 and the MIR experiments recorded trapped particles in the (BMA) region and atmospheric albedo particles below the main radiation belt at the altitudes of ~400 km. The experiment on Cosmos-1669 observed a greater positron flux in the 20-150 MeV energy range within the BMA region (≈250 /m^2 s sr) compared to the fluxes detected outside the radiation belt in the equatorial region (≈86 /m^2 s sr) by a factor of ≈3. It means that an additional source of positrons has to exist in BMA, because the CR source provides the same positron fluxes both within and outside BMA (Gusev & Pugacheva, 1982). This supports the hypothesis of a viable local nuclear source for the positron radiation belt from energetic TP

The MIR space station experiment revealed the excess of electrons over positrons by factor ~3 in a confinement region within L=1.25 to 1.8 with the maximum in flux around L=1.5. This experimental result comprised data obtained over extensive L shell range, unlike the simulation results presented here for L = 1.2 ± 0.1. As we showed in our recent work (Pugacheva et al., 1997) a spatial distribution of energetic trapped positron and electron fluxes of nuclear reaction origin is restricted within L < 1.3 due to narrow confinement of the source energetic trapped proton fluxes and due to the synchrotron radiation (SR) energy losses with a maximum around L=1.2. Therefore, the MIR station result is not directly related to the simulation results obtained here.

For electrons of energies <100 MeV and at L=1.2, it may be of interest to evaluate the contribution from the radial diffusion mechanism as it could decrease the $F_{e+}(E_e)/F_{e-}(E_e)$ ratio considered from the nuclear collision source mechanism alone. It is rather unreasonable to expect the existence of both trapped positrons and electrons of hundreds of MeV of pure radial diffusive origin in the innermost part of the Earth's magnetosphere. Recently, Pugacheva et al., (1998) showed that hundreds of MeV electrons cannot steadily diffuse down to L≈1.2 from the outer boundary of the magnetosphere without large energy losses. This potential radial influx is largely prohibited (or at least strongly discriminated against) due to synchrotron radiation energy losses, since the cross-field transport time scales are much too long at very low L-shells. We therefore conclude that in the hundreds of MeV energy range, in the innermost radiation belt, we expect the flux ratio, $F_{e+}(E_e)/F_{e-}(E_e)$, to be governed by the nuclear collision reactions.

4 Conclusion

Nuclear interactions of trapped protons of energies >300 MeV with upper atmosphere constituents are considered for the production of positrons excess over electrons in the innermost magnetosphere. The numerical simulations performed in this work, predict the existence of a positron belt in a narrow region at L=1.2. The flux ratio of e^+/e^- is estimated to be ≈4 for energies of 20 to 1500 MeV. On the other hand, cosmic ray protons, in the same spatial region, provide e^+/e^- ratio near unity.

The AMS experiment carried out on board the space shuttle reported an excess of positrons over electrons by factor of ≈4 at energies > 150 MeV, with energy dependence similar to the one obtained by the simulation in the equatorial region of L < 1.3. This offers strong to support to the hypothesis of positron excess over electrons due to nuclear reactions of trapped protons with atmospheric constituents presented herein.

Acknowledgments: The Brazilian group was sponsored by grants FAPESP-SP (93/4978-0), CNPq (300015/99-2), FAEP (Unicamp).

References

Basilova, R. N., A. A. Gusev, G. I. Pugacheva, A. F. Titenkov, High energy trapped electrons in the inner radiation belt, Geom. and Aeronom.*, 22*, 671-673, 1982.

Boezio, M., P. Carlson, T. Francke, N. Weber, M. Suffert, M. Hof, W. Menn, et al., Astrophys. J., 532(1), 653-669, 2000.

Cline, T.L., and E.W. Hones, Jr., Canadian J. of Phys., 46, 527-530, 1968.

Chen, J., T. G. Guzik, J. P. Wefel, K. R. Pyle, and J. F. Cooper, J. Geophys. Res., 101, 24787 - 24801, 1996.

Dementyev, A. V., N. M. Sobolevsky, SHIELD - universal Monte Carlo hadron transport code: scope and applications, Radiation Measurements, 30, 553-562, 1999.

De Shong, J. A., R. H. Hildebrand and P. Meyer, Phys. Rev. Lett., 12(1), 3-6, 1964.

Freden, S. C. and R. S. White, Particle fluxes in the inner radiation belt, J. Geophys. Res., 65(5), 1377 - 1383, 1960.

Galper, A. M., S. V. Koldashev, L. V. Maslennikov, V. V. Mikhailov, N. I. Shvetz, S. A. Voronov, Energy spectra of stationary and unstable electron radiation belts, 25th Int. Cosmic Ray Conference, 2, SH6.1.1, 333-336, 1997.

Gusev, A. A., and G. I. Pugacheva, Geom. and Aeronom., 22, 912-918, 1982.

Gusev, A. A., I. M. Martin, G. I. Pugacheva, A. Turtelli Jr., and W. N. Spjeldvik, Energetic positron population in the inner zone, Il Nuovo Cimento, C, 19(4), 461-468, 1996.

Hartman, R. C., P. Meyer, and R. H. Hildebrand, J. Geophys. Res., 70(11), 2713-2715, 1965.

Komarov, V. I., Direct reaction of fast-fragment knock-out by high-energy protons, Soviet J. of Particles and Nuclei, 5(2), 168 - 191, 1974.

Machner, H. and J. Hidenbauer, Meson Production close to Threshold, J. of Phys. G: Nucl. and Particle Physics, 25(10), 231-271, 1999.

Pugacheva, G. I., W. N. Spjeldvik, A. A. Gusev, and I. M. Martin, On the natural energetic positron population in the inner zone of the Earth, J. Atm. Sol.-Terr. Phys., 59, 363-369, 1997.

Pugacheva, G., D. M. Boscher, A.Gusev, I. Martin, and W. N. Spjeldvik, J. Atm. Sol.-Terr. Phys, 60,1159-1162, 1998.

Selesnick, R. S. and R. A. Mewaldt, J. Geophys. Res., 101, A9, 19745-19759, 1996.

The AMS collaboration, Leptons in Near Earth orbit, Phys. Lett. B, 10, 484, 2000.

Voronov, S., Galper A., V. Kirillov-Ugryumov, S. Koldashev, Popov A., Geom. and Aeron., 27(3), 424-427, 1987.