Leptons with E>200 MeV trapped in the Earth’s radiation belts

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Abstract

For the first time accurate measurements of electron and positron fluxes in the energy range 0.2÷10 GeV have been performed with the Alpha Magnetic Spectrometer (AMS) instrument at altitudes of 370÷390 Km in the geographic latitude interval ±51.7°. We present an original analysis of the AMS data, focused on the study of the under-cutoff component of these fluxes, outside the region of the South Atlantic Anomaly (SAA). A separation in quasi-trapped, long lifetime (O(10 s)), and albedo, short life time (O(100 ms)), components is found. The flux maps as a function of the canonical adiabatic variables L, αo are determined in the interval 0.95 < L < 3, 0° < αo < 90° for electrons with E<10 GeV, and positrons with E<3 GeV. The results are compared with existing data at lower energies and in similar L, αo range. The properties of the observed under-cutoff particles are also investigated in terms of their residence times and geographical origin. The resulting distributions are discussed and related to the characteristics of the drift shells observed by AMS.
1 Introduction

Evidence for high energy (up to few hundreds of MeV) electrons and positrons spiralizing beneath the Inner Van Allen Belts has been published during last 20 years. The major source of experimental data in the energy range 0.04-200 MeV comes from satellites covering a large range of adiabatic variables. Further information comes from balloon-borne experiments [[19],[4]] which detect relatively higher energies, however with limited spatial coverage and uncertainties related to the limited measurement times and presence of background from atmospheric showers.

Although the trapping mechanism is well understood, we still lack a complete description of the interplay of the mechanisms filling and depleting the populations in the belts as well as those determining their energy spectra. This is particularly true at energies above few hundreds of MeV where the experimental information is very sparse. At very low energy, indeed, models are available for leptons and protons [[20],[9]] based on satellite campaigns and continuously updated [25].

At higher energies, up to $\sim$ hundreds of MeV and low altitude (300÷1000 km), data come from the missions carried out at the Moscow Engineering Physics Institute. Data were taken with many instruments onboard of several satellite campaigns and Mir station [[22], [7], [1]]. These missions proved the existence of O(100 MeV) trapped leptons both in the Inner Van Allen Belts (stably trapped) and in the region underneath (quasi-trapped), measuring also their charge composition [[3], [8]]. At these heights, the shell structure is strongly distorted by SAA and therefore different regions are crossed: Inner Van Allen belts over the SAA and quasi-trapping belts outside of the SAA. In Fig.1 is shown a shell surface for typical quasi-trapping belts: it develops mostly out of the atmosphere intercepting it only around the SAA. Russian mission concentrate mostly studies over SAA and few results are available outside.

From these data the ratio between $e^+$ and $e^-$ is found to strongly depend on the type of the observed belts. In the SAA, electrons dominate over positrons by a factor $\sim 10$, a ratio similar to what is observed in the cosmic flux, while outside the SAA the two populations are at the same level which turns out to be similar to the $e^+$ flux inside the SAA [8]. It should be noted, however, that the situation is far from being clear, since other groups reported a lower $e^-$ excess ($\sim 2$) over SAA [11]. In the following, we use the high statistics collected by the AMS experiment in 1998 to present a detailed study of under cutoff lepton fluxes in the O(1 GeV) energy region. They are analyzed in terms of the canonical invariant coordinates of the particles motion, the L parameter, the equatorial pitch angle with $\vec{B}$ field, $\alpha_0$, and the mirror field $B_m$ [[15], [10]].

2 AMS and the STS-91 flight.

The Alpha Magnetic Spectrometer (AMS) is equipped with a double-side silicon microstrip tracker, with an analyzing power $BL^2=0.14 T m^2$. A time of flight system measuring the particle velocity and an Aerogel Threshold Cerenkov detector to better discriminate between proton and $e^+$ complete the detector. For this analysis, a fiducial cone
with a 28° opening half-angle was defined to select the leptons, resulting in an average acceptance of $\sim 700 \text{ cm}^2\text{sr}$. More details on the detector performances, lepton selection and background estimation can be found in [2], and references therein.

The apparatus was flown for 184 h, starting on June 2nd 1998, in the cargo bay of the shuttle Discovery during STS-91 mission. The detector was not magnetically stabilized, but spent 17, 6, 7, 14 hours pointing consecutively at 0°, 20°, 45°, 180° off local zenith. Data analyzed refer to these periods. The orbital inclination was of 51.7° in GTOD coordinates at a geodesic altitude of 370-390 Km. Trigger rates were varying between 100 and 700 Hz. The SAA region is excluded in this analysis.

At all the times, the shuttle position and the AMS orientation in GTOD coordinates were known from the telemetry data. The values of $L$, $\alpha_0$ and $B_m$ of detected leptons were calculated using the UNILIB package [25] with a realistic magnetic field model, including both the internal and the external contributions [13], [17].

The AMS Field of View (FoV) in the ($L, \alpha_0$) coordinate space is determined both by the orbit parameters (geographic locations and flying attitude) and the finite acceptance of the detector.

A stand alone simulation was used to determine the AMS FoV along the orbit and to evaluate the effects due to the finite detector acceptance. The result is shown in Fig.2.

The ($\alpha_0, L$) coverage is similar for the different attitudes, the finite acceptance of the detector playing a role only in the definition of the lower contour. Since the particles which are mirroring above AMS altitude cannot be observed, particles with large equatorial pitch angles can only be observed at very low $L$ values ($L \leq 1.2$). At larger $L$, only

\[ \sin \alpha_0 = \sqrt{0.311/L^3 B_m} \]

[1] The upper limit is imposed by the orbit altitude and is described by the relation $\sin \alpha_0 = \sqrt{0.311/L^3 B_m}$ where $B_m = 0.225 G$ is the minimum mirror field encountered along the AMS orbit.
Figure 2: Comparison among field of view of AMS, balloons and satellite data in \((L, \alpha_o)\). In the small plot, the AMS coverage in \(\beta_0\) vs \(\alpha_o\) is shown.

particles with a smaller \(\alpha_0\) can be observed. Because of the fixed flight attitudes, the azimuthal \(\beta_0\) coverage in the local magnetic reference frame \((\hat{z}=\hat{B}, \hat{x}=(\vec{\nabla}B)_\perp, \hat{y}=\hat{z} \times \hat{x})\) was not complete, as shown in the small plot in Fig.2.

3 Data Analysis

To reject the cosmic component of the measured lepton fluxes, a tracing of lepton trajectories was done. Using a 4\textsuperscript{th} order Runge Kutta method with adaptive step-size, the equation of the motion was solved numerically and the particle was initially classified as trapped if its trajectory was reaching an altitude of 40 km, taken as the dense atmosphere limit, before its detection in AMS.

Although satisfactory in most cases, this approach is less stable when the particle rigidity falls in the penumbra region, close to the cut off value. In this case, the trajectories become chaotic and small uncertainties in the reconstructed rigidity and in the B field can lead to a misclassification\(^2\). To avoid such effects, we defined an effective cut off as

\[\text{The validity of the adiabatic approach requires the smallness parameter } \varepsilon = \rho/R \text{ to be small } [[12], [16]], \rho \text{ being the equatorial Larmor radius of a particle and } \rho \text{ the field radius of curvature at equator. A critical value exists, above which motion becomes chaotic and the adiabatic approach is no longer valid. In [12] limits can be found for this parameter, if } \varepsilon \geq 0.1 \text{ the motion becomes chaotic. The AMS data are consistent with this limit even though they are high energy particles.}\]
the maximum rigidity value at a given magnetic latitude $\theta_m$ for which no traced lepton was found to be of cosmic origin. We rejected from our sample all particles with $R > R_{\text{eff}}$ also if traced as trapped.

The residence times of the under-cutoff particles are computed, i.e. the total time spent by each particle in its motion above the atmosphere, before and after detection. At the same time, the geographical location where the trajectories intercept the atmosphere determine the leptons production and impact points, defined as the position from which the particle emerges or enters in the atmosphere.

The residence time distribution as a function of energy is shown in Fig.3 for positrons, the same behaviour is found for electrons. All the leptons have residence times below $\sim 30$ s: 52% of $e^-$ and 38% of $e^+$ have $T_f < 0.3$ s with no dependence on the energy. The corresponding impact/production points are spread, for both $e^+$ and $e^-$, over the same bands out of the equatorial region, as reported in yellow in Fig.4. A scaling law, $T_f \approx E^{-2}$, is observed for the remaining leptons: they are disposed in two diagonal bands separated by a difference in $T_f$ of $\approx 1$s. The impact/production points for $e^+$ are localized in the red/blue spots of Fig.4: the same regions describe respectively the production/impact regions of $e^-$. This behaviour was presented by the AMS collaboration [2], where the nomenclature of short lived and long lived was used to classify the particles with $T_f$ below and above 0.2 s respectively. However, no interpretation was given in [2] to the observed distributions and only qualitative arguments were used in [14] to discuss the AMS results.
An exhaustive explanation must take into account the geometry of the shells encountered by AMS during its mission and the fact that all of them evolve partially under the atmosphere; no permanent trapping can therefore occur. The residence times are determined by the periodicity of the drifting ($T_d$) or bouncing ($T_b \ll T_d$) motion depending if a large fraction of the shell surface lies above or below atmosphere. The impact/production points correspond to the intersection of the shell surfaces with atmosphere, as shown in Fig.3, where particles generated in interactions are injected into the shells.

Long-lived and short-lived particles are moving along shells with different values of $B_m$ or, equivalently $\alpha_0$, which determine the mirror height on each field line. For high $B_m$ values, or low $\alpha_0$, the mirror height is very low and the shells penetrate into the atmosphere along all longitudes. This is shown by the yellow bands in Fig.3 corresponding to shells with $B_m \geq 0.48 L^{0.41}$ Gauss: they reproduce very well the impact/production points for short lived. When $B_m$ is lower, or $\alpha_0$ closer to 90°, shells go below atmosphere only around the SAA as shown in same figure by the blue region. It corresponds to shells with $B_m \leq 0.48 L^{0.41}$ Gauss and reproduces the impact/production points of the long lived component.

4 AMS Results

For the description of under cutoff fluxes, energy $E$, $L$ parameter and equatorial pitch angle $\alpha_0$ were used (this is preferred to $B_m$ because naturally limited in $0^\circ \div 90^\circ$). A
Figure 5: Distribution of intersection points with atmosphere for the drift shells crossed by AMS. Yellow region corresponds to shells with $B_m \geq 0.48L^{0.41}$ G, blue one to $B_m \leq 0.48L^{0.41}$ G.

A three-dimensional grid $(E, L, \alpha_0)$ was defined to build flux maps; a linear binning in $\alpha_0$ and logarithmic variable size for $L$ and $E$ bins were chosen to optimize statistics for each bin. Interval limits and bin widths are shown in Table 1.

The flux maps in $(L, \alpha_0)$ at constant $E$ give the distribution of particle populations at the altitude of AMS. Nine maps at constant $E$ have been done. Two different maps for two different energy bins for $e^+$ and $e^-$ are shown in Fig. 6.

The flux is limited by the cutoff rigidity $R_c$: on a given shell only particles with $R \leq R_c$ are allowed to populate the shell, so that only low energy particles populate higher shells.

The $e^+$, $e^-$ flux maps and their ratio in the energy interval 0.2-2.7 GeV are shown in Fig. 7 and Fig. 8 respectively. In both plots, the solid line identifies the lower boundary in $(L, \alpha_o)$ for which no leptons can be found with residence times larger than 0.3 s. Above that curve, going towards higher values of $\alpha_o$, the long lived component of fluxes begins to dominate: this can be better seen in Fig. 9 where the same distributions, integrated over $\alpha_o$ (C,D) and $L$ (A,B), are shown. The contributions of leptons with $T_f < 0.3$ s and $T_f > 0.3$ s are represented with dashed and solid lines respectively. Above $\alpha_o > 60^\circ$ the flux is substantially due to the long lived component;

the $e^+$ intensity represents $\approx 80\%$ of the total leptonic flux, while being at the same level of or less than $e^-$ in the low $\alpha_o$ region. In $L$, the long lived component clearly dominates only at very low values where the positron excess is more pronounced.

This can be clearly seen from the energy spectra for particles with $\alpha_0 \geq 70^\circ$, shown in Fig. 10, superimposed with measurements from MARIYA at lower energy [8].
Figure 6: Flux maps for 2 different energy bins: A), B) $e^+, e^-$ between $0.315 \leq E \leq 0.486$ GeV and C), D) $e^+, e^-$ between $1.77 \leq E \leq 2.73$ GeV.

Figure 7: Integral flux maps for $e^+$ (A) and $e^-$ (B) between $0.205 \leq E \leq 2.73$ GeV.
Figure 8: Integral $e^+/e^-$ ratio between $0.205 \leq E \leq 2.73$ GeV

Figure 9: Integral flux as function of $\alpha_0$ and as function of $L$ for $e^-$ (A, C) and $e^+$ (B, D) between $0.205 \leq E \leq 2.73$ GeV. The full line shows the long lived component, while the dashed one shows the short lived component.
high pitch angles region the $e^+$ is higher than $e^-$ flux by a factor $\sim 4.5$, in contrast with MARYA data which indicate the same level of flux for both $e^+$ and $e^-$. 

5 Discussion

The analysis of AMS data has clearly shown the existence of leptonic radiation belts underneath the Inner Van Allen belts with particle energies of several GeV. The measured fluxes are not stably trapped since all the corresponding drift shells are not closed over the SAA region.

At any given $L$, a critical value of the equatorial pitch angle, $\alpha_c$, can be defined to distinguish the long, or quasi-trapped, and short lived, or albedo, components of the fluxes. The same value is found to separate the regions where the $e^+/e^-$ ratio is above or around the unity: the charge composition shows a peculiar dominance of positively charged leptons in a definite region of the $(L,\alpha_o)$ space above $\alpha_c(L)$. Such characteristics make these belts quite different from the Inner Van Allen belts and limit the possible injection/loss mechanisms to those acting on a time scale much shorter than the typical particles residence time. Mechanisms related to Coulomb scattering, like pitch angle diffusion, are therefore ruled out because acting on much longer time scales. Moreover, the charge ratio distribution contains much of the information about the lepton origin, and any mechanism should account for it.
The interaction of primary cosmic rays and inner radiation belt protons with atmospheric nuclei in the regions of shell intersection with atmosphere are a natural mechanism of production of secondary leptons through the $\pi - \mu - e$ or $\pi - \gamma - e$ decay chains. This naturally leads to an $e^+$ excess over $e^-$ and seems suitable to explain the observed charge ratio for quasi-trapped flux [23]. However, for the albedo flux the charge ratio is of the order of unity, as seen from Fig. 8, and other mechanisms might be present.

Recent Monte Carlo studies based on this mechanism have been able to fully reproduce the under cutoff proton spectrum measured with AMS [5], while a looser agreement for the under cutoff lepton spectrum [6] was achieved. In [14], the influence of geomagnetic effects, mainly related to the East-West asymmetry for cosmic protons, is taken into account to qualitatively explain the observed charge ratio. However, only more refined studies can definitely exclude contributions from other mechanisms, i.e. acceleration processes acting on the leptons resulting from the decays of $\beta$-active secondary nuclei and neutrons of albedo and solar origin [24].

In conclusion, the AMS under-cutoff lepton spectrum can be described naturally in terms of the canonical adiabatic variables associated with the Earth’s magnetic field and of the role played by the atmosphere. There are clear indications that $\pi$ decays can account for the quasi-trapped component of the flux, while the situation is less clear for the albedo component where other processes may contribute.

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References


