Extending the Galactic Cosmic Ray electron + positron spectrum measured by the Fermi LAT

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Launched on the 11th of June 2008, the Fermi Large Area Telescope (LAT) has made several outstanding scientific contributions to the high energy astrophysics community. One of these contributions was the high statistics measurement of the Galactic Cosmic Ray (GCR) electron + positron spectrum from 20 GeV to 1 TeV. The Fermi satellite is in a nearly circular orbit with an inclination of 25.6 degrees at an altitude of 565 km. Given this orbit it is possible to measure the GCR electrons + positrons down to roughly 5 GeV. However, this lower limit in energy is highly dependent on the orbital position of the LAT in geomagnetic coordinates due to the rigidity cutoff. In order to measure the spectrum down to these energies it is necessary to sample the population of electrons + positrons in several different geomagnetic positions. In this poster we present the analysis performed to extend the lower limit in energy of the GCR electron + positron spectrum measured by the Fermi LAT.

I. INTRODUCTION

The electron component of the Galactic Cosmic Ray (GCR) radiation is widely recognized as a unique probe to address a number of significant questions concerning the origin of cosmic rays and their propagation in our galaxy (see [9] for a review). For energies above a few GeV the dominant energy loss mechanisms for electrons and positrons are the synchrotron and inverse compton processes. These processes have an energy loss rate whose magnitude increases with the square of the electron energy and as a consequence these electrons have a radiative lifetime inversely proportional to their energy [8]. Because of this relatively short radiative lifetime, the GCR electrons cannot travel intergalactic distances through the cosmic microwave background and thus excludes an extragalactic contribution to the measured spectra. After the first six months of nominal science data taking, the Fermi LAT was able to make the first systematics limited measurement of the GCR $e^- + e^+$ (referred to as electrons for the rest of this work) spectrum from 20 GeV to 1 TeV [2]. This measurement together with the recently published results from experiments such as PAMELA [4], ATIC [7] and HESS [5] has set the stage for new and exciting GCR science. To help make constraints on possible propagation models it is important to extend the measurement of the GCR electrons to lower energies. This task is the main topic of this work and the analysis used to extend the GCR electron spectrum measured by the Fermi LAT will be described in detail in this paper.

II. INSTRUMENT DESCRIPTION

The Large Area Telescope, the main instrument on-board the Fermi observatory, is a pair-conversion telescope composed of:

(i) a tracker-converter, including 18 Silicon Strip Detector (SSD) $x−y$ tracking planes, interleaved with tungsten conversion foils;

(ii) a CsI imaging calorimeter;

(iii) a segmented Anti-Coincidence Detector (ACD) surrounding the tracker subsystem.

Though it essentially follows in the footsteps of the previously flown pair-conversion telescopes (particularly EGRET [11]) in its basic design, the LAT is equipped with the state of the art in high-energy physics detector technology and features many design improvements with respect to its predecessor, resulting in a significant leap in sensitivity (for a detailed description of the detector see [6]).

From the standpoint of the electron detection, the tracker section effectively acts as a finely segmented pre-shower (1.5 radiation lengths on axis) which allows to image the initial part of the electromagnetic showers, providing a crucial handle for the background rejection. The hodoscopic configuration of the calorimeter (8.6 radiation lengths on axis) provides a full 3-dimensional reconstruction of the shower shape which is essential both for the energy reconstruction and for the discrimination between electromagnetic and hadronic showers. The ACD also provides a relevant contribution to the background rejection.

A. Trigger and filter

Two of the main design improvement of the LAT are a flexible trigger logic and onboard event filtering. The chosen detector technology allows a minimum dead time per event of about 26 $\mu$s (essentially due to instrument readout). Therefore the LAT can trigger at the passage of (almost) every particle, including cosmic rays (only events that clearly behave as MIPs or heavy ions are hardware-prescaled to avoid the induction of unnecessary deadtime). This is a
revolution with respect to the previous generation of pair conversion telescopes, in which the instrumental deadtime forced to apply a harsh photon selection at the level of the hardware trigger. The LAT trigger rate is of the order of few kHz but due to telemetry bandwidth limitations an onboard event selection is applied and roughly half of the events are actually written on spacecraft memory. This is accomplished by several software configurable onboard filters. The rate of events downlinked to Earth is of the order of few hundred Hz, still mostly charged particles (i.e. protons, electrons, GCR metals). The refined analysis, both for the photon (cfr.\cite{6}) and CR electron science is performed on the ground. For more details about the on-orbit rates, see \cite{3}. In the routine data taking configuration the onboard filter instance providing the main data source for photon science (the GAMMA filter) is configured to pass all the events depositing more than 20 GeV in the calorimeter. Therefore it constitutes the main source of data for the high-energy electron analysis, as well. In addition to that, an unbiased sample of all trigger types, prescaled by a factor of 250, is also downlinked for diagnostic purposes (through the so called DGN filter); it is perfectly adequate to study the electrons at relatively low energies, where the higher fluxes compensate for the lower statistics due to the event prescaling. The events collected through the DGN filter are essential for the extension of the GCR electron spectrum, in fact they constitute the main source of electrons for this study.

\section{III. GEOMAGNETIC ENVIRONMENT}

The Earth’s field is closely approximated by the field of a dipole positioned near the center of the Earth. For a dipole field,

\begin{equation}
R = R_0 \cos^2 \theta
\end{equation}

defines lines of constant magnetic field, also known as “L shells”. $R_0$ is the radial distance to the field line where it crosses the geomagnetic equator and $R$ is the radial distance to the point where the field is $B$ at latitude $\theta$. From equation \ref{1} it is possible to define the coordinate L, which is defined as $L = R_0/R_E$ where $R_E$ is the Earth’s radius (6371 km) \cite{12}. Therefore, positions around the Earth with the same value of L are magnetically equivalent. Due to the fact that the Earth’s dipole is offset and tilted with respect to the center of the Earth, L values must be calculated based on a detailed field model \cite{1} and are a function of geomagnetic latitude \cite{12}. The shielding effect of the Earth’s magnetic field is smaller (larger) for larger (smaller) values of L and with Fermi’s nearly circular orbit it is possible to measure the GCR electron spectrum in the range $1.0 < L < 1.73$ which translates into a minimum rigidity of $\sim 6$ GeV. Figure \ref{1} illustrates the distribution of L and the corresponding vertical rigidities for the Fermi orbit, based on the IGRF model \cite{1}. It important to stress here that the vertical cutoff rigidity distribution shown in figure \ref{1} is simply an illustration and we do not depend on this model in any way for this analysis.

Fermi’s orbit intersects the South Atlantic Anomaly (SAA) which is a region of the Earth’s radiation belt which features geomagnetically trapped protons with energies up to hundreds of MeV and electrons with energies up to tens of MeV. The extreme conditions within this region impose constraints on the LAT operations, in particular the triggering, recording and transmission of science data are stopped during the SAA passages \cite{3}. The SAA is represented by the dark shaded region in figure \ref{1}.

\section{IV. EVENT SELECTION}

The LAT is sensitive to electrons over more than five orders of magnitude in energy ($\sim 100$ MeV – $\sim 1$ TeV). Across this huge energy range both the typical event topology and the relative fractions of signal and background in the cosmic-ray flux impinging on the detector undergo dramatic variations. For these reasons it’s not trivial to develop a single, unitary analysis strategy providing the necessary electron detection efficiency and the hadron rejection power across the whole energy range. In fact we have elaborated two independent electron selections, tuned for relatively low energies and high energies respectively (which we shall refer to as LE and HE in the rest of the paper). The split point, in energy, between these two analyses can be naturally placed at 20 GeV for at least two reasons. The first one is that the onboard filtering is essentially disengaged above this energy (whereas we only have a prescaled unbiased sample below 20 GeV). The other one is that below $\approx 20$ GeV, the shielding effect of the geomagnetic field (which depends on the geomagnetic latitude and, hence, on the position of the spacecraft across its orbit) becomes important. In fact the HE selection has been mostly developed exploiting the data source provided by the GAMMA filter for the purpose of measuring the GCR electrons, whereas the LE selection was designed to measure both the GCR and the electron albedo population, using the DGN filter data source.

It must be stressed, however, that these divisions are partially artificial and there’s a significant overlap in energy between the two selections. This can be used as an independent cross check for both of the analyses. The details of the selection criteria for the LE selection can be found in \cite{10} and for the HE in \cite{2}.

One of the important figures of merit which come out of the selection is the effective geometry factor, defined as the effective area integrated over the field of view of the detector, and is shown in figure \ref{1}. The
FIG. 1: Map of McIlwain L values for the Fermi orbit. Overlaid in contours are the corresponding values for vertical rigidity cutoff. These values were calculated using the 10th generation IGRF model. It is important to note that the model is not valid inside the South Atlantic Anomaly (SAA) region, illustrated by the dark gray polygon in this figure.

LE geometry factor has multiplied by the DGN filter prescale factor of 250 for graphical clarity and in order to give an idea of the relative electron efficiencies of the two selections. The shape of the geometry factor is almost entirely due to the event selection that must obtain a good background rejection power in the whole energy range. The sharp decrease in HE selection just below 30 GeV is mainly due to the GAMMA filter onboard event filtering designed to remove charged particles with deposited energy lower that 20 GeV.

V. SPECTRUM RECONSTRUCTION

The electron flux is evaluated by subtracting the residual background from the count rate and then correcting the observed number of events with the geometry factor. The evaluation of the residual hadron background takes advantage of the detailed on-orbit particle environment model built by the LAT collaboration. This highly detailed model has been intensively used to develop all the γ-ray background rejection algorithms, both on-orbit and off-line. The model includes cosmic rays and earth albedo γ-rays starting from 10 MeV and is valid outside the South Atlantic Anomaly (since the LAT does not take data while passing through the SAA). The particle fluxes are chosen to fit experimental data of several past experiments, more details can be found in [6].

The event selection is tuned to keep the residual contamination below about 20% in the whole energy range. The sample of events passing the GAMMA filter are the main source of GCR electrons given that these are all those events with raw energy > 20 GeV and for these energies the effects of the Earth’s magnetic field on the incoming GCR electron flux are negligible. In order to extend the energy range of the measured spectrum (down to lower energies) it is necessary to use the events passing the DGN filter. This extension is not a straightforward task and requires to take advantage of the fact that the rigidity cutoff varies as a function of orbital position and consequently measure the spectra in various bins of geomagnetic position.

As already mentioned in section I, the shielding effect of the Earth’s magnetic field is smaller for larger values of the L coordinate and therefore to measure electrons of Galactic origin with energies in the lower end of our rigidity cutoff range it is necessary to sample all those events collected when the detector was located at large values of L. Each L bin has an associated rigidity cutoff value and it is possible to measure this value by considering that the shape of the primary spectrum around the geomagnetic rigidity cutoff can be parametrized as:

\[ f_c(E) \simeq \frac{1}{1 + (E/E_c)^{-6}} \]  

Therefore the full spectrum can be fitted with a func-
FIG. 3: Left panel: The measured electron flux in three McIlwain L bins. For each bin the fit of the flux with equation (3) and the resulting estimated cutoff rigidity, $E_c$, is shown. As described in the text, $E_c$ decreases for larger values of McIlwain L. Right panel: Illustration of the reconstruction technique used to measure the primary cosmic-ray electron spectrum down the lowest accessible energy for the Fermi orbit. The blue points represent the GCRE flux multiplied by the energy cubed obtained via the LE analysis and the red points are from the HE analysis. The solid lines depict the systematic uncertainties and the vertical dashed lines serve to show from which McIlwain L region of the orbit the flux was measured. These results are preliminary.

With LE and the HE are shown in this figure to illustrate the very good agreement in the overlap region. The solid (blue and red) lines represent the systematic uncertainties for the two selections.

### VI. Discussion

The GCR electron spectrum measured by the Fermi LAT from $\sim 7$ GeV to 1 TeV is shown in figure together with the measurements made from ground, balloon and spaced based experiments. The overlap region between the LE and the HE selections for energies between 20 and 80 GeV shows very good agreement and serves as an excellent cross check between the two separate analyses. The low energy part of the spectrum measured by Fermi shows the same rising trend in flux as both the AMS and HEAT measurements and is compatible with those measurements within the systematic errors. The extension of the GCR electron spectrum provides valuable information needed to make constraints on possible propagation models of the GCRs. However, a discussion on the interpretation of this new measurement is beyond the scope of this paper.

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FIG. 4: The GCR electron spectrum measured by the Fermi LAT, red points correspond to the HE selection and blue points to the LE. For comparison the measurements from the experiments AMS, HEAT, ATIC and HESS are also shown. The extension of the Fermi LAT measurement is in good agreement within the systematic errors with the measurements made by AMS and HEAT.

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