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AMS-02 Monthly Proton Flux: Solar Modulation Effect and Short Timescale Phenomena

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The Alpha Magnetic Spectrometer (AMS-02) is a high-energy particle detector designed to perform fundamental physics research in space. It was installed on the International Space Station (ISS) on May 19^{th}, 2011 where it will operate for the next decade. During the first 30 months of operation, AMS-02 collected 41 billion events of cosmic rays between 1 GV and 1.8 TV. In this work, the detailed time variation of the proton flux below 10 GV with a monthly time-based integration was analyzed. While at high energy the spectra remains stable versus time, the low-energy range exhibits a decreasing general trend, strongly reflecting the increase of the solar activity that recently reached its maximum. In addition to the overall modulation effect, the monthly AMS-02 proton flux shows periodic variations related to strong solar events *i.e.* Coronal Mass Ejections and Forbush decreases.

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1. Introduction

The Alpha Magnetic Spectrometer (AMS-02) was installed on the International Space Station (ISS) on May 19^{th}, 2011 where it will operate for the duration of the station (2024) to measure cosmic rays with unprecedented accuracy at the top of the atmosphere. AMS-02 can provide cosmic ray flux measurements over a wide period of time that covers the ascending phase of this solar cycle 24, through its maximum, and the descending phase into the next solar minimum. Thanks to its large geometrical acceptance, 0.45 m^2 sr, in the first 4 years of operation, AMS-02 collected over 60 billion events, which is the largest number of cosmic rays ever measured in space by a single instrument consecutively in time. These data will allow deep studies of the Galactic Cosmic Ray (GCR) fluxes and their time evolution over an entire solar cycle enabling a better understanding of the solar modulation effect. In this paper, the time variation of the proton flux measured during the first 30 months of AMS-02 operation will be presented. In addition to the solar modulation effect, since protons are the most abundant among cosmic rays, representing about 90% of the total flux, they are also the most suitable GCR species for a detailed study of the time variation of the GCR flux due to short timescale solar events.

The monthly time evolution of our recent proton publication [1] is analyzed here with particular attention to its lower rigidity range from 1 GV to 10 GV.

2. AMS-02 Detector

AMS-02 is a high energy particle detector designed to study the origin and nature of cosmic rays in the energy range from 1 GV to a few TV. In order to distinguish between different species of particles, AMS-02 is made of 5 sub-detectors which are described in more detailed in Ref [2]. From top to bottom (see Fig. 1) the detector is composed of a transition radiation detector (TRD), a time of flight system (TOF), a silicon tracker surrounded by a permanent magnet, an array of anti-coincidence counters (ACC), a ring imaging Cerenkov detector (RICH), and an electromagnetic calorimeter (ECAL). The TRD is designed to use the transition radiation to distinguish between hadrons and leptons. In addition, the total particle energy loss in the TRD gives the first detector absolute charge estimation. The particle absolute charge is also measured by the TOF [3] which is designed to measure velocity and particle direction. The TOF indeed is the instrument that provides the trigger and determines whether the particle is coming from the top or from the bottom of the detector. The TOF is made of 4 layers of plastic scintillators, two above and two below the permanent magnet. The average time resolution of each counter has been measured to be 160 ps and the overall velocity resolution for charge one particles to be $\Delta\beta/\beta^2 \approx 4\%$. The measurement of the particle velocity is also performed by the RICH sub-detector which is particularly efficient in the higher energy range of the spectrometer ($\beta > 0.75$ and $\beta > 0.95$) with a velocity resolution $\Delta\beta/\beta^2 \lesssim 1$ %. The ECAL, with its 17 radiation lengths, provides an additional separation power between hadrons and leptons and performs a precise energy measurement of this latter type of particles. The most precise measurement of the particle charge is given by the silicon tracker system that establishes the charge with a resolution of $\Delta Z \simeq 0.05$ for charge $|Z|=1$ particles. Moreover the tracker and magnet system gives a precise measurement of the particle rigidity and of its incoming direction. The tracker [4] is composed by 9 layers: layers 2 to 8 are inside the magnet (inner

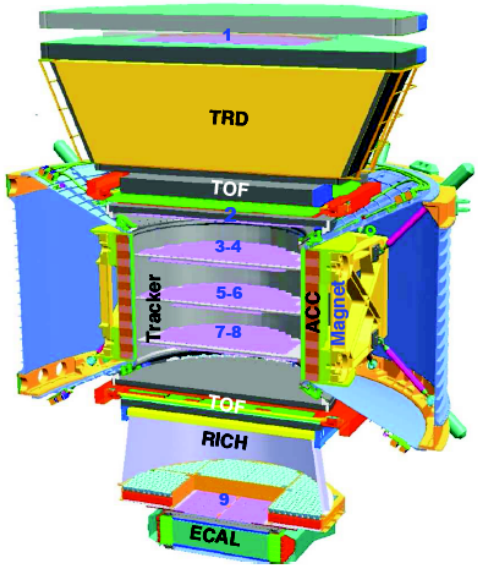

Figure 1: Schematic view of AMS-02 detector. Sub-detectors from top to bottom: transition radiation detector (TRD); time of flight (TOF); tracker (9 layers) and magnet; anti-coincidence counters (ACC); ring imaging Cerenkov detector (RICH); electromagnetic calorimeter (ECAL).

tracker) while layer 1 and layer 9 are respectively above and below the magnet (full span tracker). Each layer is made of double-side silicon microstrip to enable multiple measurement of the particle trajectory with a resolution of 10 μm in the bending coordinate direction. The full span tracker has a maximum level arm of 3 m for a maximum detectable rigidity (MDR) for protons of 2 TV.

3. Proton Flux Measurement and Analysis

In this work the AMS-02 data collected from June 2011 up to November 2013 are analyzed. During the first 30 months (7.96×10^7 seconds) of data taking, the AMS-02 live time was precisely measured at each ISS position. The effective data collection time *i.e.* exposure time, is measured by requiring that AMS-02 is in the nominal data taking status, the detector pointing direction is within 40° of the Earth zenith axis, and the ISS is orbiting outside the South Atlantic Anomaly. Since the ISS is immersed in the Earth's magnetic field at an altitude from Earth of about 400 km, the exposure time gradually increases with increasing measured rigidity, becoming constant (6.29×10^7 seconds) above 30 GV.

The proton sample is selected by requiring a downward going event with measured $\beta > 0.3$. The charge measurement must be consistent with a charge one particle, |Z|=1, along the full particle trajectory. The measured rigidity must be positive and above the International Geomagnetic Reference Field (IGRF[5]) cutoff according to the maximum value in the AMS-02 field of view. To eliminate further contamination of secondary particles coming from the penumbra region, an additional 1.2 safe factor was applied to the IGRF cutoff. To remove events with large scattering and to further clean the data sample, additional track fitting requirements on the χ^2 in the bending coordinate were included. Finally a cut on the combined TOF and tracker mass measurement (m >

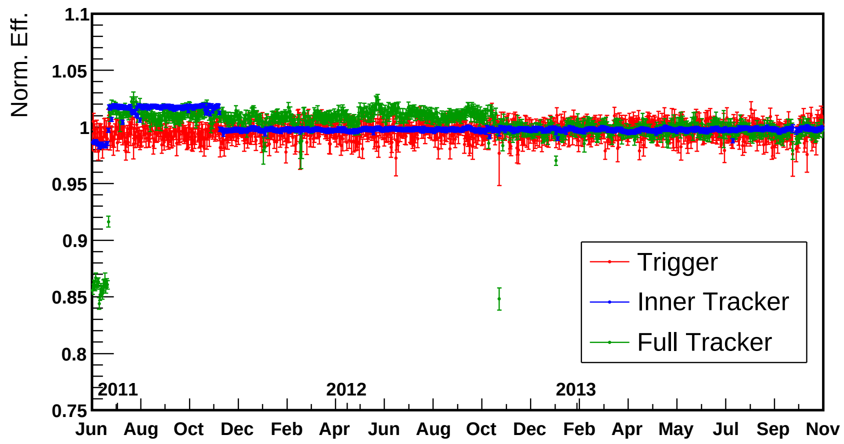

Figure 2: Daily trigger, inner and full span tracker efficiencies normalized to the entire period values.

0.5 GeV/c^2) was applied to suppress the small contamination of secondary pions produced in the upper part of the detector.

Protons are the most abundant species of GCRs, so the residual background from other particles is very low. Deuterons are not removed in this analysis: their contamination is less than 2% at 1 GV and decreases with increasing rigidity (0.6% at 20 GV). Contamination from interacting nuclei (Z>1) at the top of AMS-02 (layer 1 or TRD) is 0.5% at 1 GV and becomes negligible with increasing rigidity. Positron and electron contamination is less than 0.1% at all rigidities.

Assuming an isotropic flux for rigidities above the geomagnetic cutoff, the differential proton flux Φ_i for the ith rigidity bin can be written as follows:

$$\Phi_i = \frac{N_i}{T_i A_i \varepsilon_i \Delta R_i} \tag{3.1}$$

where: N_i is the number of events after proton selection; T_i is the exposure time; A_i is the effective acceptance; ε_i is the trigger efficiency; and ΔR_i is the rigidity bin width. The effective acceptance A_i was estimated by using a dedicated Monte Carlo (MC) program based on the simulation toolkit GEANT-4.9.6 [6]. In this MC program the electromagnetic and the hadronic interactions of particles in the AMS-02 material are simulated together with the detector responses. The effective acceptance includes both geometrical and detector efficiencies *i.e.* charge, inner and full span efficiencies. All detector efficiencies have been extensively studied and validated with ISS data. The trigger efficiency indeed is directly measured from ISS data by the use of a prescaled (1%) unbiased trigger sample with no ACC requirement and a coincidence of at least 3 out of the 4 TOF layers.

The number of events N_i was corrected with the rigidity resolution function to account for the bin-to-bin migration, *i.e.* unfolding procedure. Two unfolding procedures were used to crosscheck the result: the so called folded acceptance and the forward unfolding technique whose details are described in Ref. [8] and Ref. [7] respectively. The small difference between the two methods (less than 0.5%) is accounted into the systematic errors.

The systematic errors have been extensively studied and a detailed description is given in Ref. [1]. The order of magnitude of the systematic errors in the rigidity range from 1 GV to 10 GV is summarized here. One source of systematic errors comes from the uncertainties on the trigger efficiency due to the reduced statistics of the prescaled unbiased sample: this systematic is very low (< 0.4%) below 10 GV. Another source of systematic errors comes from the data to MC corrections that have to be applied to the acceptance: these corrections dominate our systematics at low rigidities being about 5% at 1 GV and decreasing below 2% at 10 GV. In addition, the acceptance suffers from the uncertainties on the model estimation of the inelastic cross sections. The total systematic on this latter was estimated to be about 1% at 1 GV and decreases to 0.6% at 10 GV. Finally the uncertainty on the rigidity scale resolution function, which is coming from a residual tracker misalignment and from the magnetic field map measurement, was found to be less than 1% below 10 GV.

To compute the monthly fluxes, additional tests were performed to verify the detector stability versus time. In Fig. 2, the daily trigger and both inner and full span tracker efficiencies in the rigidity range from 1 GV to 10 GV, are displayed and normalized to the average value of the entire period. The trigger efficiency remained stable over time during all the 30 months of operation. The inner and full span tracker efficiencies increased on July 21^{st}, 2011 due to the improvement of the tracker calibration and had a drop on December 1^{st}, 2011 due to the loss of 3% tracker readout channels in the non-bending coordinates. The small decrease of the full span tracker efficiency on October 31^{st}, 2012 is due to the loss of two voltage amplifiers on layer 1. The detector acceptance and all the efficiencies were calculated for each month to obtain the monthly fluxes. The monthly proton flux above 45 GV shows no observable effects related to the solar modulation and remained stable for this measurement period as reported in Ref. [1]. At low rigidities, instead, the presence of the solar modulation is extremely evident as described in the next session.

4. Monthly Proton Flux Results

The average proton flux, from 1 GV to 10 GV, integrated from June 2011 until November 2013 is plotted in Fig. 3 with the overall flux variation in this 30 months represented by the blue band. In Fig. 4 all the 30 monthly fluxes, from June 2011 until November 2013, are displayed. The monthly proton flux decreases, as time passes, due to the increase of the solar activity that reached its maximum in 2014: in total the flux has decreased by about 70% at 1 GV.

In addition to this overall modulation effect, shorter timescale trends are observed as monthly increases and decreases. These variations are clearly seen in Fig. 5, which shows the monthly proton flux in selected rigidity bins, normalized to the average value of the entire time period, and plotted versus time. This short timescale behavior is related to strong solar events such as Coronal Mass Ejections (CMEs) and Forbush decreases.

One example of solar event is March 7^{th}, 2012, which was one of the most intense events of solar cycle 24 with two solar flares of classes X5.4 and X1.3 and two fast CMEs. The time evolution of the daily proton flux observed by AMS-02 during the March 2012 month is plotted in Fig. 6 where the flux is normalized to the first day of the month at different rigidity bins. From March 1^{th} until March 6^{th} the daily flux was stable at all rigidities. At March 7^{th}, the increase in the lowest rigidity bin indicates the arrival of Solar Energetic Particles (SEPs) accelerated during the

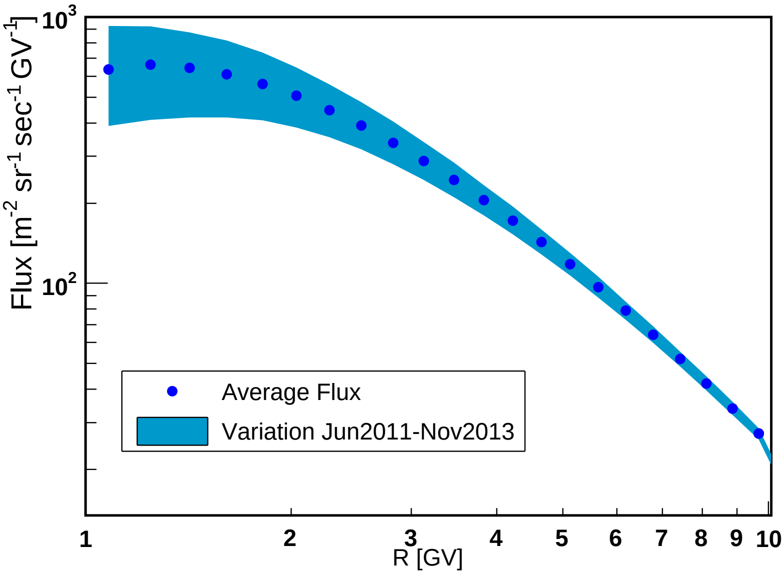

Figure 3: Average proton flux from 1 GV to 10 GV integrated over the first 30 months of AMS-02 operation on the ISS. The blue band represents the total variation observed in that period.

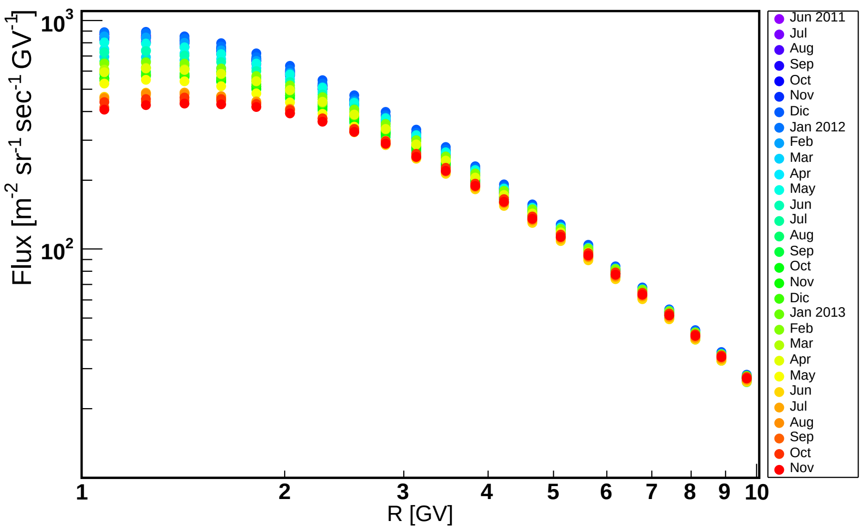

Figure 4: Monthly proton fluxes from 1 GV to 10 GV observed by AMS-02 from June 2011 until November 2013. The flux decreases versus time due to the increase of the solar activity.

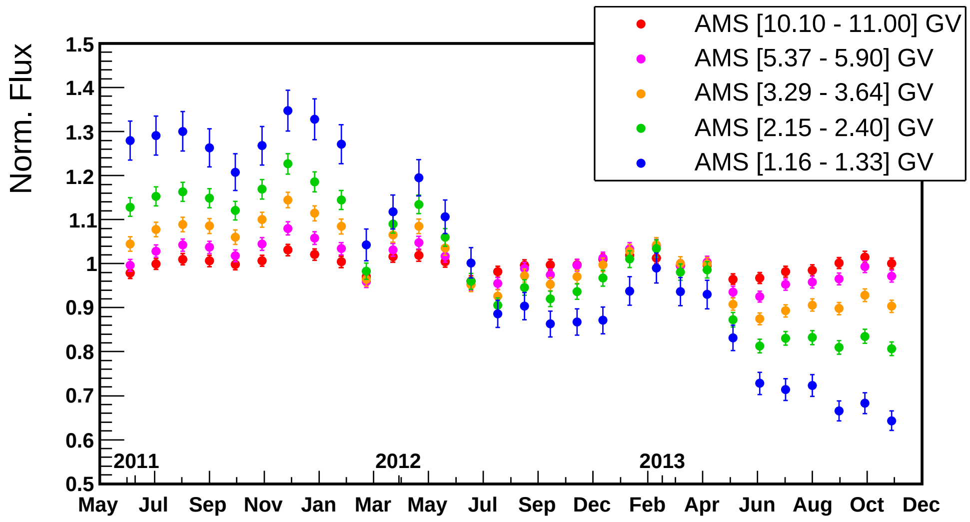

Figure 5: Normalized proton flux for 30 months at different rigidity bins versus time. The short timescale variation due to the solar activity is evident.

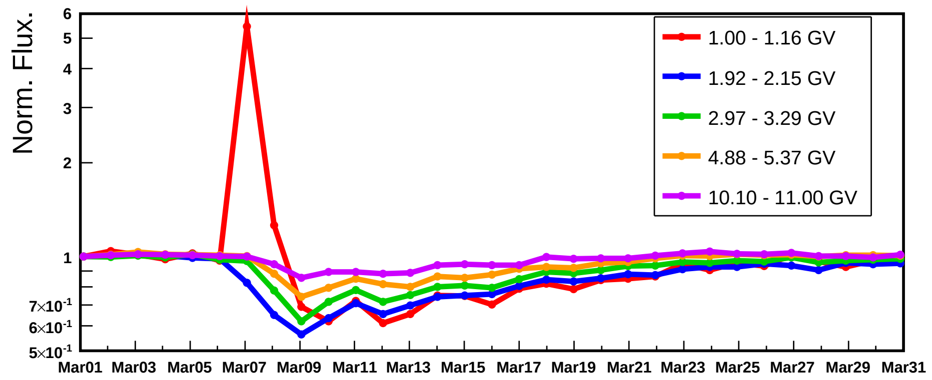

Figure 6: Normalized flux at different rigidity bins integrated in 24 hours during the month of March 2012. The Forbush decrease is evident, at all rigidities, following the peak around 1 GV due to the event of March 7^{th}, 2012.

flares and the CMEs. During the same day, all the other rigidity bins already suffer from the GCR flux suppression due to the propagation of the solar wind disturbances following the event. The Forbush decrease, that was measured during the following days, even in the higher rigidity bins, had its maximum on March 9^{th}. After this GCR minimum, the flux gradually recovered to nominal conditions within about 20 days.

5. Conclusions

In this work, the proton flux in the range of 1 -10 GV measured by AMS-02 in the first 30 months of operation on the ISS and its time evolution was analyzed. The overall flux behavior consists in a suppression of the proton GCR flux at low rigidities due to the increase of the solar activity that was reaching its maximum during that period. In addition to the solar modulation effect, shorter timescale variations of the GCR spectra were observed. These monthly variations of the proton flux are the consequences of short timescale phenomena related to solar activity. Since AMS-02 will be taking data on the ISS for more than a decade, these and future data will allow deeper studies of GCR fluxes and their time evolution over an entire solar cycle, enabling a better understanding of the solar modulation effect and of the shorter timescale solar activity.

6. Acknowledgment

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