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Anisotropy of cosmic ray fluxes measured with AMS-02 on the ISS

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Abstract. A measurement of the cosmic ray anisotropy on the arrival directions of elementary particles (electrons, positrons and protons) and light nuclei (helium, carbon and oxygen) has been performed in galactic coordinates by the Alpha Magnetic Spectrometer onboard the International Space Station. The analysis is based on the sample of events collected in the first 6.5 years (electrons and positrons), and 7.5 (protons, helium, carbon and oxygen) of data taking. The results are consistent with isotropy for all cosmic ray species and upper limits on the dipole amplitude have been computed. In particular, 95% credible interval upper limits of $\delta < 1.9\%$ and $\delta < 0.5\%$ are obtained for positrons and electrons, respectively, above 16 GeV. On the other hand, the upper limits of protons, helium, carbon and oxygen above 200 GV are found to be $\delta < 0.38\%$, $\delta < 0.36\%$, $\delta < 1.9\%$ and $\delta < 1.7\%$, respectively.

1. Introduction

In the last years, the Alpha Magnetic Spectrometer (AMS-02) onboard the International Space Station (ISS) has provided precise measurements of cosmic ray fluxes, which have revealed many unexpected features that cannot be fully explained within the current understanding of cosmic rays acceleration and propagation.

On the one hand, the positron spectrum [1] shows a significant excess above ∼25 GeV followed by a sharp dropoff above ∼284 GeV with a finite exponential energy cutoff at ∼810 GeV established at more than 4σ. The observation is not consistent with a pure secondary origin of cosmic ray positrons and, in many models, the inclusion of a source term, either from dark matter annihilation or astrophysical sources [2, 3], is required to explain the origin of the excess. Furthermore, the electron spectrum [4] exhibits a significant excess above ∼42 GeV compared to the lower energy trends, which is well described by the sum of two power law contributions in the entire energy range. Contrary to the positron flux, the electron flux does not have an energy cutoff below 1.9 TeV, which suggests a different origin for high energy electrons and positrons.

On the other hand, the proton [5] and nuclei [6] spectra show a deviation from a single power law, with a progressive hardening of the spectral index above ∼200 GV. The origin of

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this spectral feature may be due to the existence of nearby sources in the Galaxy contributing at high rigidities, or may require a modification of the cosmic ray transport models [7, 8].

In all cases, the existence of nearby compact sources of cosmic rays may induce a sizable anisotropy in their arrival directions. Thus, the measurement of the cosmic ray anisotropy is a complementary study to characterize the observed spectral features and may help to understand their origin.

2. The AMS-02 detector

AMS-02 is a multipurpose particle physics detector designed to carry out accurate measurements of cosmic ray charged particles in the GeV-TeV range. It was installed on 19 May 2011 onboard the International Space Station and it continues taking data steadily since then. So far, AMS-02 has collected more than 140 billion events of galactic cosmic rays in a long term mission, which is supposed to continue during ISS lifetime until 2024.

The detector consists of nine layers of precision silicon tracker (STD), with an inner tracker (L2-L8) inside a permanent magnet and two outer layers (L1 and L9); a transition radiation detector (TRD); four planes of time of flight counters (TOF); an array of anti-coincidence counters (ACC) surrounding the inner tracker; a ring imaging Čerenkov detector (RICH); and an electromagnetic calorimeter (ECAL). More details on the sub-detectors can be found in [9].

3. Data selection

Positron and electron events are selected by requiring a track in the TRD and in the tracker, a cluster of hits in the ECAL, and a measured velocity $\beta \sim 1$ in the TOF consistent with a downward-going $Z = 1$ relativistic particle. Proton background is reduced to below the percent level by means of a cut based selection on TRD and ECAL estimators, and good energy-momentum matching. The final sample contains 9.9×10^4 positrons and 1.3×10^6 electrons above 16 GeV. For the anisotropy analysis, events are grouped into 5 cumulative energy ranges from 16 to 350 GeV according to their measured energy in the ECAL, with minimum energies: 16, 25, 40, 65 and 100 GeV respectively.

Preselected proton, helium, carbon and oxygen events include downward-going particles with velocity measured by four TOF planes and charge measurement consistent with the corresponding to each particle species. Events reconstructed by the 7 inner layers, passing through the outer layer L1, and satisfying additional track quality criteria are finally selected. For the proton sample, an additional hit in the outer layer L9 is required. Above 18 GV, the final samples include 1.3×10^8 protons, and 1.0×10^8, 2.9×10^6 and 2.8×10^6 helium, carbon and oxygen events, respectively. The anisotropy analysis is performed on 9 cumulative rigidity ranges of minimum rigidity: 18, 30, 45, 80, 150, 200, 300, 500, 1000 GV.

In addition, to select only primary cosmic rays well above the geomagnetic cutoff, the measured rigidity is required to be greater than 1.2 times the maximum geomagnetic cutoff within the AMS field of view.

4. Methodology

The analysis of anisotropies in a sample is performed by comparing the observed distribution of arrival directions in galactic coordinates, (l, b), with a reference map.

The reference map for anisotropy studies describes the directional response of the detector to an isotropic flux, and its computation requires a detailed understanding of experimental effects. In particular, a geographical variation of detector efficiencies may project onto the galactic coordinate system and induce an spurious signal if not accounted. Therefore, a precise knowledge of these variations is needed to disentagle a possible physical signal from the effects related to the performance of the detector. A systematic procedure, valid for all cosmic ray species, has been developed to obtain these isotropic skymaps [10].

A spherical harmonics expansion in terms of multipolar coefficients, $a_{\ell m}$, is used to described the directional dependence of the flux:

$$\Phi(l,b) = \Phi_0 \left(1 + \sum_{\ell > 0} \sum_{m=-\ell}^{m=+\ell} a_{\ell m} Y_{\ell m}(l,b) \right) \tag{1}$$

At first order, $\ell = 1$, the dipole is fully described by three orthonormal functions corresponding to three orthogonal axes: Y_{1+1} is aligned with the *forward-backward* direction, pointing to the galactic center; Y_{1+0} is aligned with the *north-south* direction, pointing to the north galactic pole; and Y_{1-1} is aligned with the *east-west direction*, contained in the galactic plane and complets the right-handed coordinate system. Dipole components in each direction are defined as

$$\rho_{EW} = \sqrt{\frac{3}{4\pi}} a_{1-1} \quad ; \quad \rho_{NS} = \sqrt{\frac{3}{4\pi}} a_{1+0} \quad ; \quad \rho_{FB} = \sqrt{\frac{3}{4\pi}} a_{1+1} \tag{2}$$

Finally, the dipole amplitude, which quantifies the asymmetry between the maximum and minimum of the flux, is

$$\delta = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}} = \sqrt{\rho_{EW}^2 + \rho_{NS}^2 + \rho_{FB}^2} \tag{3}$$

5. Positron and electron anisotropy

The measurement of the anisotropy in the arrival directions of the positrons and electrons collected by AMS-02 in the first 6.5 years of data taking revealed no deviation from isotropy expectation. Consequently, upper limits on the dipole amplitude at the 95% credible interval (C.I.) were computed for the different energy ranges of the analysis (figure 1). In particular, the upper limits for positrons and electrons above 16 GeV are found to be $\delta < 1.9\%$ and $\delta < 0.5\%$, respectively. In addition, the agreement between data and reference maps, quantified in terms of the chi-square value ($\chi^2/d.f. = 11083.3/11330$ for e^+ and $\chi^2/d.f. = 11370.8/11455$ for e^- above 16 GeV) indicates that there is no significant contribution of higher-order multipoles.

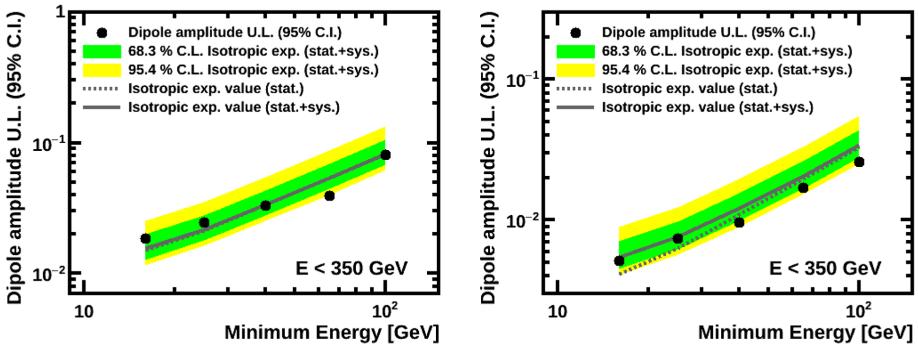

Figure 1. Positron (*left*) and electron (*right*) 95% C.I. upper limits on the dipole amplitude (dots). Solid (dashed) lines correspond to the isotropic expectation due to statistics and with (without) systematics. Green and yellow bands show the 68.3% and 95.4% regions, respectively.

6. Proton and light nuclei anisotropy

The results of the anisotropy analysis on the 7.5-years proton and light nuclei samples were found to be consistent with isotropy. Therefore, 95% C.I. upper limits on the dipole amplitude were calculated for each rigidity range and cosmic ray species (figure 2). In particular, the proton anisotropy is limited by statistics above 70 GV and systematics limit the measurement at low rigidities to 0.1%. Finally, for rigidities above 200 GV, the upper limits are set to 0.38% for protons, and 0.36%, 1.9% and 1.7% for helium, carbon and oxygen, respectively. Additionally, the compatibility between data and reference maps (e.g. $\chi^2/d.f. = 12658.5/12261$ for protons and $\chi^2/d.f. = 12491.6/12287$ for helium above 18 GV) is an indication that the contribution of higher-order multipoles is not significant.

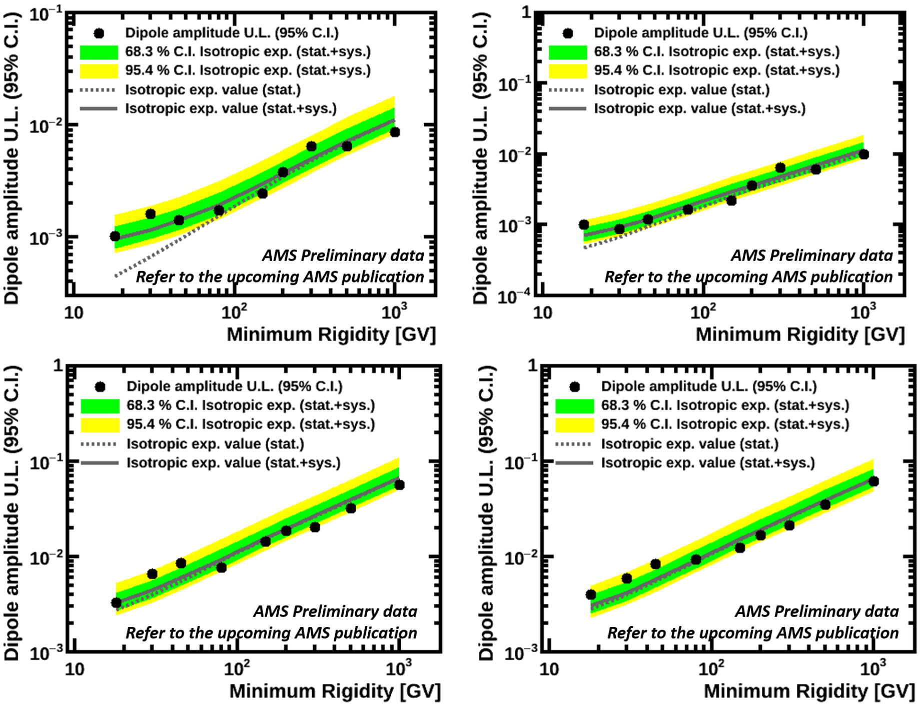

Figure 2. Proton (*upper-left*), helium (*upper-right*), carbon (*bottom-left*) and oxygen (*bottom-right*) 95% C.I. upper limits on the dipole amplitude.

7. Conclusions

The measurement of the anisotropy in the arrival directions of cosmic ray electrons, positrons, protons and light nuclei (helium, carbon and oxygen) has been carried out by the AMS-02 experiment on the ISS. The results in galactic coordinates show no deviation from isotropy and 95% C.I. upper limits on the dipole amplitude were obtained. In particular, limits of $\delta < 1.9\%$ and $\delta < 0.5\%$ have been set for positrons and electrons, respectively, above 16 GeV. On the other hand, above 200 GV, the limits to the dipole amplitude were found to be $\delta < 0.38\%$ for protons, and $\delta < 0.36\%$, $\delta < 1.9\%$ and $\delta < 1.7\%$ for helium, carbon and oxygen, respectively.

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