

Anisotropy of Protons and Light Primary Nuclei in Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the ISS

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A measurement of the cosmic ray anisotropy on the arrival directions of protons and light primary 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 first 10 years of data taking. Results are consistent with isotropy for the different species and upper limits on the dipole amplitude (δ) at the 95% C.I. have been established. In particular, for rigidities above 200 GV limits of $\delta < 0.30\%$, $\delta < 0.30\%$, $\delta < 1.41\%$, and $\delta < 1.73\%$ are obtained for protons, helium, carbon and oxygen respectively.

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1. Introduction

As of today, AMS has provided the most precise measurements for the different primary cosmic ray species in the GV-TV rigidity range. These results have revealed unexpected features in the fluxes that cannot be fully explained with the traditional models of cosmic rays.

In particular, the precise measurements of the proton [1] and light primary nuclei helium, carbon and oxygen [2] fluxes progressively deviate from a single power law above 200 GV. These features are typically explained with different acceleration mechanisms [3–5], modification of the propagation models [6–8] or the inclusion of nearby primary sources [9, 10].

In this context, the measurement of a sizable anisotropy in the different cosmic ray fluxes may indicate the presence of nearby primary sources and, therefore, the study of the directionality constitutes an additional characterization that may help to understand the origin of the aforementioned observations.

2. The AMS-02 Detector

AMS is a multipurpose particle physics detector installed onboard the ISS since May 19th 2011. The detector has been designed to carry out precise measurements of charged cosmic rays in the GeV-TeV energy range, and has continuously collected data since its installation, with more than 200 billion events for more than 11 years. The end of the ISS operation is currently scheduled for 2030 and AMS will continue taking data until that date.

The detector consists of different sub-detectors that measure the velocity ($\beta = v/c$), charge (Z), energy (E), and rigidity ($R = p/Z$) independently. The AMS-02 subdetectors are the following: a Silicon Tracker Detector (STD) with an inner tracker composed of seven layers (L2-L8) inside a permanent magnet and two outer layers (L1 and L9), one at the top and the other at the bottom of the detector; a Transition Radiation Detector (TRD); a Time Of Flight (TOF); a Ring Imaging Cherenkov detector (RICH); and an Electromagnetic CALorimeter (ECAL).

The key elements used for the present analysis include the STD together with the permanent magnet that provide the rigidity, R , and the charge, Z , and the TOF that provides precise measurements of the velocity ($\beta = v/c$) and of the charge (Z). A detailed description can be found in [11, 12].

3. Proton and Light Primary Nuclei Selection

Selected events are required to be downward-going particles with a relativistic velocity ($\beta \sim 1$) measured by the four TOF planes and charge reconstructed by the TOF and the STD consistent with $Z=1, 2, 6$, and 8 for protons, helium, carbon and oxygen respectively.

In addition, events are required to have a track reconstructed with the inner tracker layers (L2-L8) and the top external layer (L1) satisfying quality criteria in the track. For protons, selected events should also pass through the bottom external layer (L9) with the corresponding quality criteria to ensure a good accuracy of the track reconstruction.

In order to select primary cosmic rays, the measured rigidity is required to be greater than the maximum local geomagnetic rigidity cutoff within the AMS field of view.

Finally, for the anisotropy analysis, selected events are grouped into 9 cumulative rigidity ranges from 18 to 1000 GV with minimum rigidities R_{min} : 18, 30, 45, 80, 150, 200, 300, 500, and 1000 GV. The final sample corresponding to the first 10 years of data taking with AMS-02 in the lowest rigidity range, $R_{min} = 18$ GV, contains 1.24×10^8 , 1.24×10^8 , 4.06×10^6 and, 3.75×10^6 proton, helium, carbon and oxygen events respectively.

4. Methodology

The measurement of large scale anisotropies for different cosmic ray species is performed by comparing the skymap of measured events in galactic coordinates with an isotropic reference map. Both maps are created with the HEALPix scheme [13], which provides pixels of equal area in the sphere.

The reference map describes the directional response of the detector to an isotropic flux and its computation requires a detailed understanding of the detector's behavior. In particular, the precise understanding of the geographical dependences of the detector efficiencies is necessary in order to avoid possible spurious effects. More details on the construction of the isotropic reference maps can be found in [14].

In order to describe the directional dependence of the fluxes a spherical harmonic expansion in terms of multipolar coefficients, $a_{\ell m}$, is performed. The large scale anisotropy is described at first order by a dipole ($\ell = 1$) and its projection onto 3 orthogonal directions (East-West, North-South and Forward-Backward). In galactic coordinates the North-South (NS) direction is perpendicular to the galactic plane, the Forward-Backward (FB) is pointing to the galactic center, and the East-West (EW) completes the right-handed coordinate system and is contained in the galactic plane. The three dipole components can be defined as

$$\rho_{EW} = \sqrt{\frac{3}{4\pi}} a_{1-1} \quad ; \quad \rho_{NS} = \sqrt{\frac{3}{4\pi}} a_{10} \quad ; \quad \rho_{FB} = \sqrt{\frac{3}{4\pi}} a_{1+1} \quad (1)$$

Finally, the dipole amplitude is computed as follows

$$\delta = \sqrt{\rho_{EW}^2 + \rho_{NS}^2 + \rho_{FB}^2} \quad (2)$$

5. Proton Anisotropy

The measurement of the anisotropy for proton events in galactic coordinates for the first 10 years of operation with AMS-02 has been found to be consistent with isotropy.

Results on the dipole components ρ_{EW} , ρ_{NS} and ρ_{FB} are shown in figure 1 for the different rigidity ranges and with the 1 and 2 σ deviations corresponding to the statistical and the statistical plus systematic uncertainties.

Results on the dipole amplitude are computed using the three dipole components, equation 2, and displayed as a function of the minimum rigidity in figure 2a. In particular, for rigidities $R > 200$ GV the proton dipole amplitude is $\delta_M^p = 0.12\%$.

In addition, since the results are consistent with isotropy, the 95% C.I. upper limit on the dipole amplitude can be established (figures 2b). Again, for rigidities $R > 200$ GV, the upper limit for protons is $(\delta_{UL}^{95\%})^p = 0.30\%$.

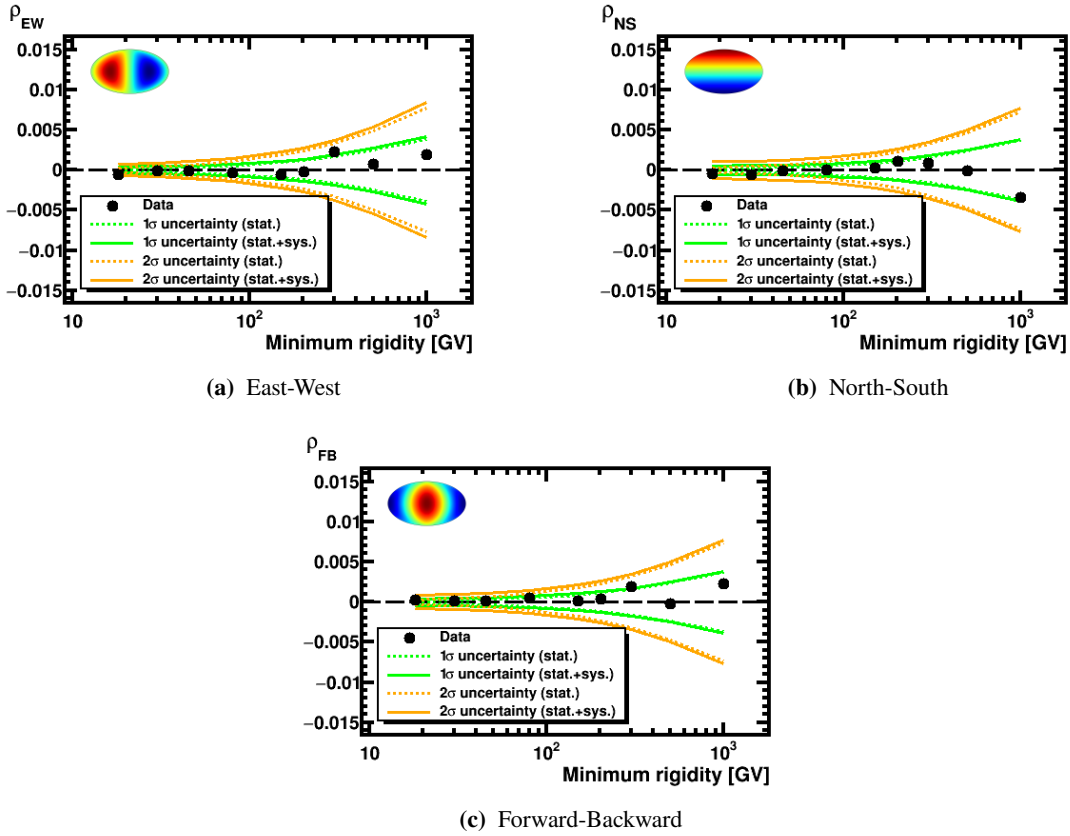


Figure 1: Proton dipole components, ρ_{EW} , ρ_{NS} and ρ_{FB} in galactic coordinates where the 1 and 2 σ deviations from isotropy (green and yellow, respectively) corresponding to the statistical (dotted line) and total (solid line) uncertainties are shown.

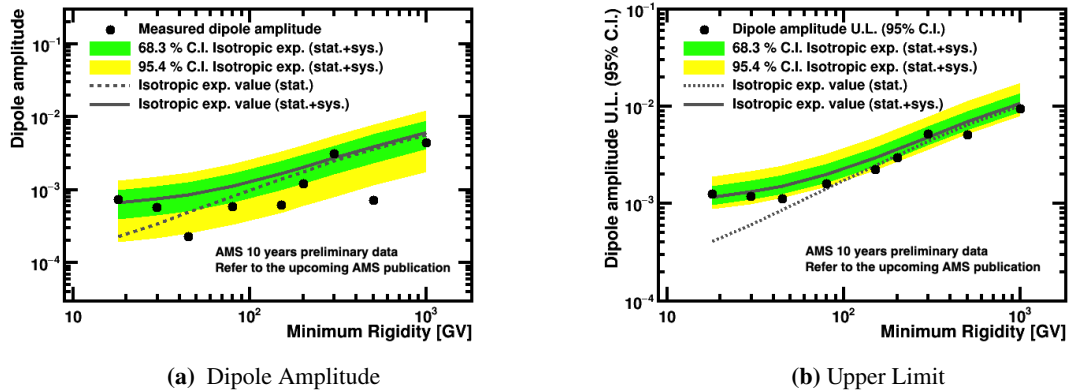


Figure 2: Proton measured dipole amplitude (a) and 95% C.I. upper limit (b) as a function of the minimum rigidity in galactic coordinates. The 1 and 2 σ total uncertainty bands are shown in green and yellow respectively. The expected value from isotropy considering the statistical (dotted line) and the statistical + systematic (solid line) uncertainties is also displayed.

6. Light Primary Nuclei Anisotropy

Similarly to protons, the measurement of the anisotropy for helium, carbon and oxygen events is computed in galactic coordinates for the first 10 years of operation with AMS-02.

Results are found to be consistent with isotropy for the dipole components and for the three species. The dipole amplitudes are computed and shown in figures 3a, 4a and 5a for the 3 light primary nuclei. For rigidities $R > 200$ GV, a value of $\delta_M^{He} = 0.17\%$, $\delta_M^C = 0.69\%$ and $\delta_M^O = 0.98\%$ is measured for helium, carbon and oxygen respectively.

The 95% C.I. upper limits on the dipole amplitude are also computed and displayed in figures 3b, 4b and 5b. The limits for rigidities $R > 200$ GV are $(\delta_{UL}^{95\%})^{He} = 0.30\%$, $(\delta_{UL}^{95\%})^C = 1.41\%$ and $(\delta_{UL}^{95\%})^O = 1.73\%$ for helium, carbon and oxygen respectively.

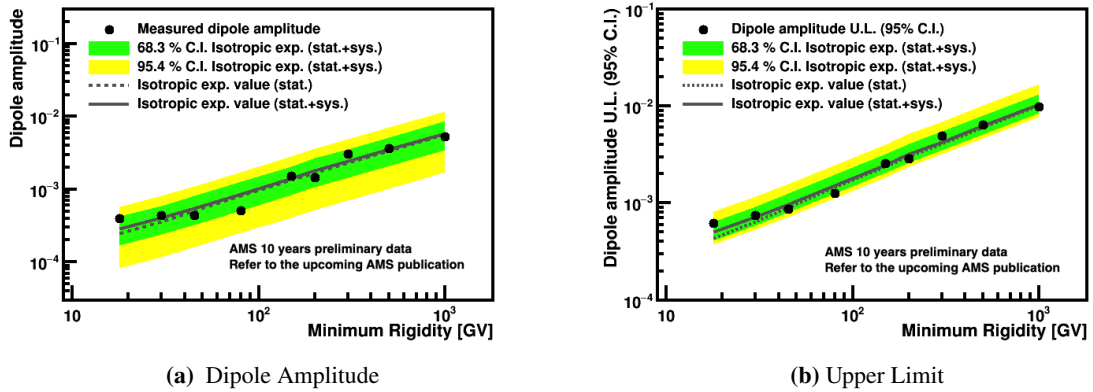


Figure 3: Helium measured dipole amplitude (a) and 95% C.I. upper limit (b) as a function of the minimum rigidity in galactic coordinates. The 1 and 2 σ total uncertainty bands are shown in green and yellow respectively. The expected value from isotropy considering the statistical (dotted line) and the statistical + systematic (solid line) uncertainties is also displayed.

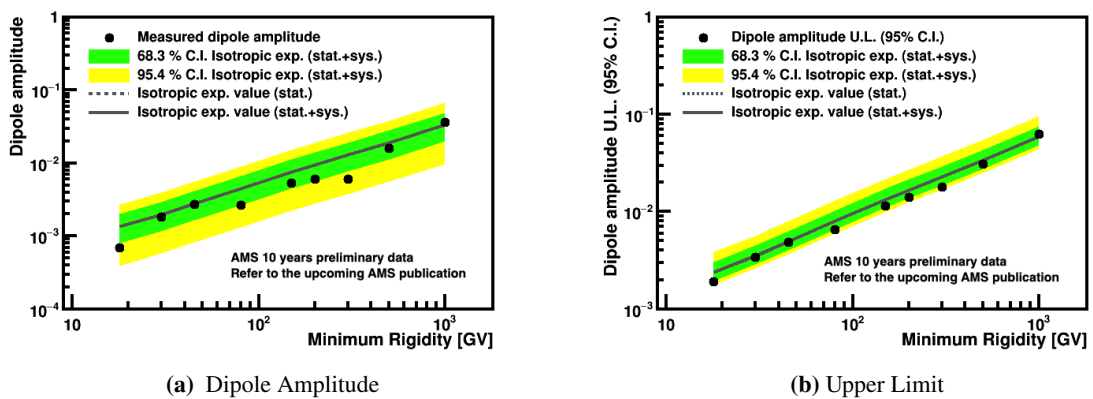


Figure 4: Carbon measured dipole amplitude (a) and 95% C.I. upper limit (b) as a function of the minimum rigidity in galactic coordinates. The 1 and 2 σ total uncertainty bands are shown in green and yellow respectively. The expected value from isotropy considering the statistical (dotted line) and the statistical + systematic (solid line) uncertainties is also displayed.

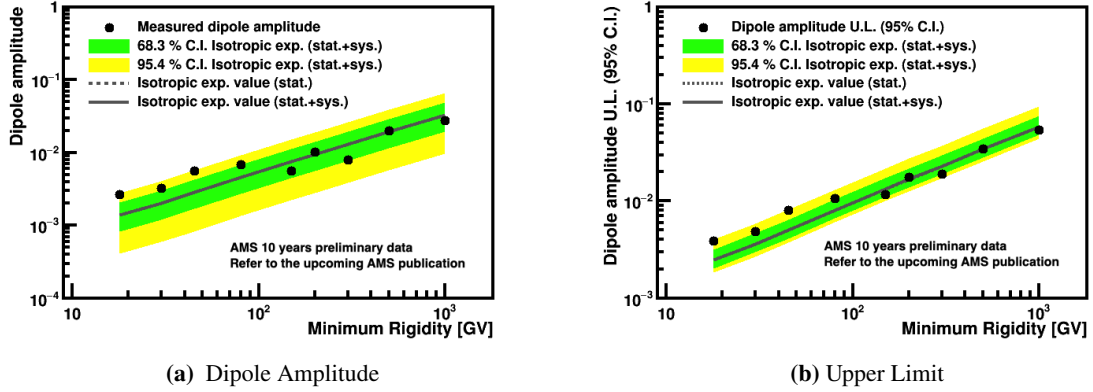


Figure 5: Oxygen measured dipole amplitude (a) and 95% C.I. upper limit (b) as a function of the minimum rigidity in galactic coordinates. The 1 and 2 σ total uncertainty bands are shown in green and yellow respectively. The expected value from isotropy considering the statistical (dotted line) and the statistical + systematic (solid line) uncertainties is also displayed.

7. Conclusions

The measurement of the anisotropy in the arrival directions of cosmic ray proton, helium, carbon and oxygen events in galactic coordinates has been performed with AMS-02. Results are presented for 10 years of data taking. No deviation from isotropy have been found and upper limits to the dipole amplitude (δ) are established. In particular, for rigidities $R > 200$ GV the limits are $\delta < 0.30\%$, $\delta < 0.30\%$, $\delta < 1.41\%$ and $\delta < 1.73\%$ for protons, helium, carbon and oxygen respectively.

AMS will continue taking data until the end of the ISS operation (currently 2030) and, therefore, the increased on the statistics will allow to improve the current limits.

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