PROCEEDINGS OF SCIENCE

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

M. Molero[a,*] **and J. Casaus, M. A. Velasco**[b]

[a] *Instituto de Astrofísica de Canarias (IAC), Calle Vía Láctea 1, La Laguna, Santa Cruz de Tenerife, Spain*

[b] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avda. Complutense 40, Madrid, Spain*

E-mail: mmolerog@iac.es

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.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)103

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 accelaration 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 ($\beta = v/c$), mass (m), charge (Z), energy (E), and rigidity (R = p/Z) independently. The elements of AMS-02 are the following: a Silicon Tracker Detector (STD) with an inner tracker (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 (provides 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 reconstructed by the inner layers (L2-L8) and the top external layer (L1) satisfying quality criteria in the track are selected. For protons, events must 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 above the geomagnetic cutoff, the measured rigidity is required to be greater than the maximum 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 repectively.

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

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

Finally, the dipole amplitude is computed as follows

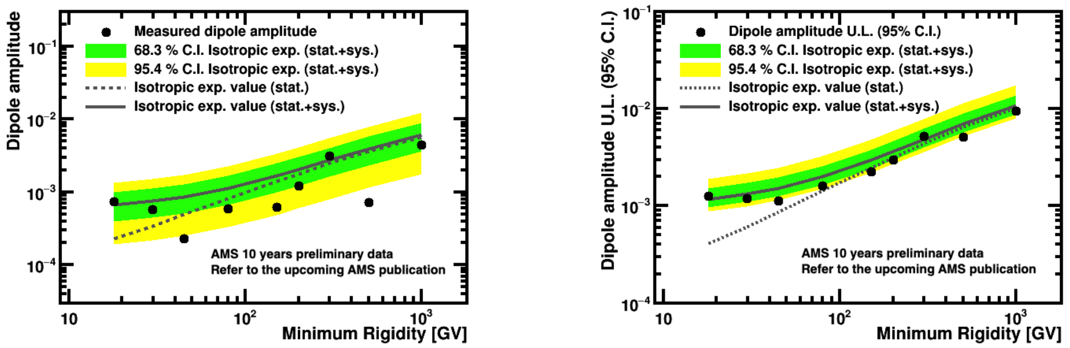
$$\delta = \sqrt{\rho_{EW}^2 + \rho_{NS}^2 + \rho_{FB}^2} \tag{2}$$

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 amplitude are computed using the three dipole components, equation 2, and displayed as a function of the minimum rigidity in figure 1a. 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 1b). Again, for rigidities $R > 200$ GV, the upper limit for protons is $(\delta_{UL}^{95\%})^p = 0.30\%$.



(a) Dipole Amplitude **(b)** Upper Limit

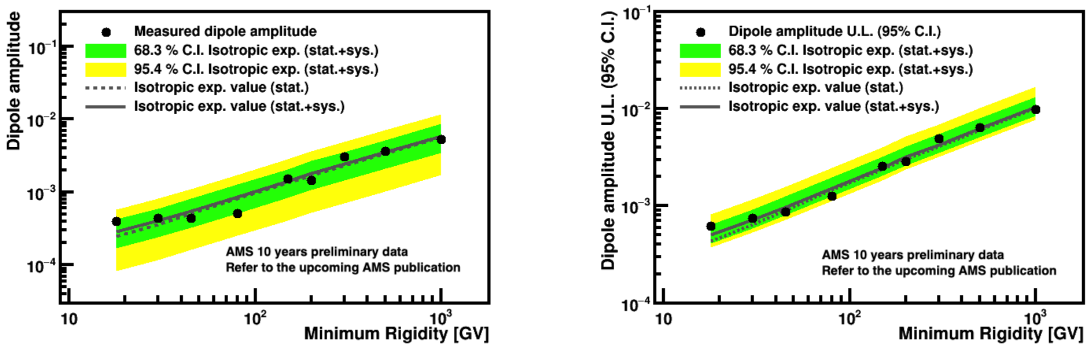
Figure 1: Proton measured dipole amplitude (a) and 95% C.I. upper limit (b) as a function of the minimum rigidity in galactic coordinates. The 1 and 2 σ total uncertainty bands are shown in green and yellow respectively. The expected value from isotropy considering the statistical (dotted line) and the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

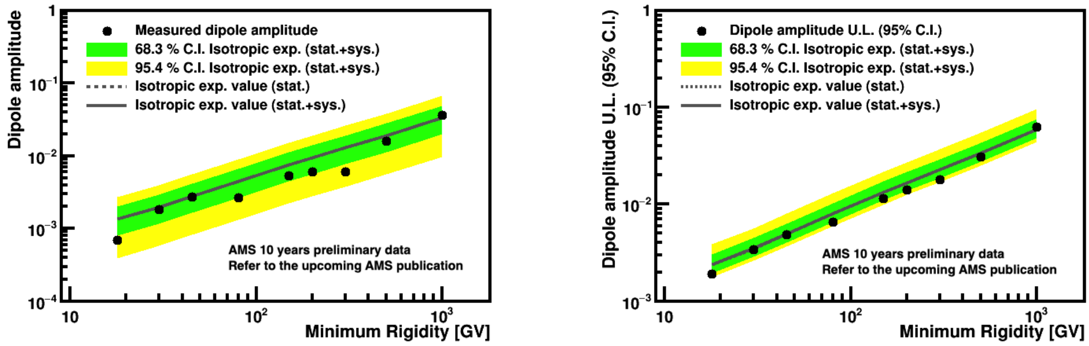
Results are found to be consistent with isotropy for the dipole components and for the three species. The dipole amplitudes are computed and shown in figures 2a, 3a and 4a for the 3 light primary nuclei. For rigidities $R > 200$ GV, a value of $\delta_M^{He} = 0.17\%$, $\delta_M^{C} = 0.69\%$ and $\delta_M^{O} = 0.98\%$ 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 2b, 3b and 4b. 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.



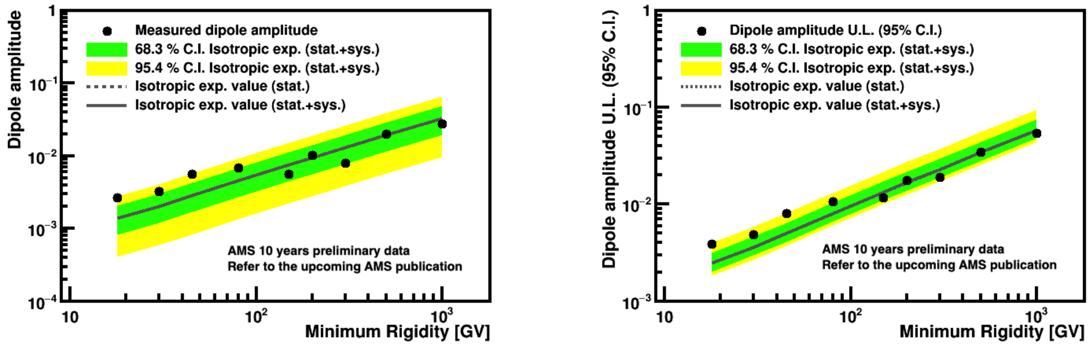
(a) Dipole Amplitude **(b)** Upper Limit

Figure 2: 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.



(a) Dipole Amplitude **(b)** Upper Limit

Figure 3: 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.



(a) Dipole Amplitude **(b)** Upper Limit

Figure 4: 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 present limits.

References

[1] M. Aguilar *et al*. [AMS Collaboration], *Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station*, *Phys. Rev. Lett* **114** 171103 (2015)

[2] M. Aguilar *et al*. [AMS Collaboration], *Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities by the Alpha Magnetic Spectrometer on the International Space Station*, *Phys. Rev. Lett* **119** 251101 (2017)

[3] Wen-Hui Lin, Bi-Wen Bao, Ze-Jun Jiang and Li Zhang, *Spectral hardening of cosmic ray protons and helium nuclei in supernova remnant shocks* , *Chinese Phys. C* **43** 053103 (2019)

[4] Yiran Zhang, Siming Liu, and Qiang Yuan, *Anomalous distributions of primary cosmic rays as evidence for Time-dependent particle acceleration in supernova remnants*, *ApJ* **844:L3** (2017)

[5] Vladimir Ptuskin, Vladimir Zirakashvili, and Eun-Suk Seo, *Spectra of cosmic-ray protons and helium produced in supernova remnants*, *ApJ* **763(1):47** (2013)

[6] Yi-Qing Guo, Zhen Tian, and Chao Jin, *Spatial-dependent propagation of cosmic rays results in spectrum of proton, ratios of* $\bar{p}/p$*, B/C and anisotropy of nuclei*, *ApJ* **819:54** (2016)

[7] Nicola Tomassetti, *Origin of the cosmic-ray spectral hardening*, *ApJ L* **752:L13** (2012)

[8] Pasquale Blasi, Elena Amato, and Pasquale D. Serpico, *Spectral breaks as a signature of cosmic ray induced turbulence in the Galaxy*, *Phys. Rev. Lett.* **109** 061101 (2012)

[9] Wei Liu, Xiao-Jun Bi, Su-Jie Lin, Bing-Bing Wang, and Peng-Fei Yin, *Excesses of cosmic ray spectra from a single nearby source*, *Phys. Rev. D* **96** 023006 (2017)

[10] G. Bernard1, T. Delahaye, Y.-Y. Keum, W. Liu, P. Salati and R. Taillet, *TeV cosmic-ray proton and helium spectra in the myriad model*, *A&A* **A48** 555 (2013)

[11] M. Aguilar *et al*. [AMS Collaboration], *First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV*, *Phys. Rev. Lett.* **110** 141102 (2013)

[12] M. Aguilar *et al*. [AMS Collaboration], *The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II — Results from the first seven years*, *Physics Reports* (2020)

[13] K. M. Gorski et al., *HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere*, *APJ* **622** 759 (2005)

[14] M.A. Velasco, Ph.D Thesis, Universidad Complutense de Madrid, 2018;
M. Molero, Ph.D Thesis, Universidad Autónoma de Madrid, 2021