Phosphorus flux in cosmic rays: preliminary analysis from AMS-02

A. Ubaldi (*)
INFN, Sezione di Perugia - Perugia, Italy
Dipartimento di Fisica e Geologia, Università degli Studi di Perugia - Perugia, Italy

Summary. — This contribution presents a preliminary analysis of cosmic ray (CR) phosphorus (P) flux measured by the Alpha Magnetic Spectrometer (AMS-02) onboard the International Space Station (ISS) during 13.5 years of data taking, in the rigidity range from 2.15 gigaelectronvolts (GV) to 1.2 teraelectronvolts (TV). After a short introduction on CRs and a brief overview of the AMS-02 experiment, the methodology for flux evaluation will be presented including: event selection, background rejection, exposure time estimation and effective detector acceptance.

1. – Introduction

CRs are high-energy charged particles originating from astrophysical sources both inside and outside our Galaxy. They consist primarily of protons and helium nuclei, with a smaller fraction of heavier nuclei, electrons, positrons, antiprotons, photons, and neutrinos. During their propagation through the interstellar medium (ISM), CRs undergo processes such as diffusion, convection, energy losses, and nuclear interactions, leading to the production of secondary particles via spallation reactions. When entering the heliosphere, low energy charged CRs are influenced by the solar magnetic field and solar wind, a phenomenon known as solar modulation [1]. Direct detailed measurements of CR composition and energy spectra offer crucial information about their sources, acceleration mechanisms and transport properties in the Galaxy.

AMS-02 is a magnetic spectrometer installed on the ISS designed to study the universe by searching for dark matter, antimatter, as well as studying the composition, spectra, and temporal variations of CRs. The detector consists of several sub-detectors, including a permanent magnet, a silicon tracker, a time-of-flight system (TOF), a transition radiation detector (TRD), a ring imaging Cherenkov detector (RICH), an electromagnetic calorimeter (ECAL) and an anti-coincidence-counters (ACC). Together, they provide

(*) on behalf the AMS-02 Collaboration

redundant charge, velocity, and energy measurements, allowing for precise particle identification and background rejection across a wide range of rigidities.

Since its installation, AMS-02 has provided precise measurements of the fluxes of primary and secondary CR nuclei in a wide range of rigidities: primary and secondary CRs have different dependencies in rigidity and there is a third group which is a mix of the other two [2, 3, 4, 5].

2. – Analysis

In contrast to neighboring nuclei such as silicon (Si) and sulfur (S), which are abundantly produced in massive stars during the oxygen-burning process [6], P is mainly a secondary CR nucleus produced through the spallation of heavier elements in the ISM.

2˙1. *Flux.* – In the i-th rigidity bin, the flux is given by:

$$\phi_i = \frac{N_i}{\Delta R_i \cdot \Delta T_i \cdot A_i} \tag{1}$$

where N_i is the number of selected P nuclei, after background subtraction and correcting for bin-to-bin migration, ΔR_i is the width of the i-th bin, ΔT_i is the exposure time and A_i is the detector unfolded acceptance, corrected for the differences between data and Monte Carlo (MC).

2˙2. *Exposure time.* – Since AMS-02 is installed on the ISS, orbital parameters can't be fixed by the experiment and activities on the ISS may interfere with AMS-02 data taking. To keep track of this, the AMS-02 collaboration developed a database called Real Time Information (RTI) where all the information regarding the orbital and DAQ parameters are stored with one second granularity.

The exposure time quantifies the amount of time in seconds that AMS-02 was ready to register an event. For each second, trigger rates, DAQ settings as well as reconstructed error rates and orbital conditions are analyzed and only good seconds are used in the analysis and summed up in the exposure time calculation.

Additionally, the Earth's geomagnetic field must be considered to ensure only galactic cosmic rays (GCRs) are accepted. Secondary particles trapped in the magnetosphere are excluded by applying a rigidity cutoff, which defines the minimum rigidity required for a particle to reach a certain depth in the magnetosphere. This cutoff depends on altitude and direction and is computed every second using the IGRF geomagnetic field model [7].

With all this considerations, is possible to evaluate the exposure time, as a function of rigidity, for 13.5 years of data taking (see Fig. 1).

2˙3. *Counts.* – The series of cuts on the AMS-02 observables is called event selection: the goal is to reject as many poorly reconstructed events as possible while maintaining a high efficiency for the signal events.

Event selection for P includes all data quality criteria based on the RTI database, excluding seconds with poor data acquisition, non-nominal detector conditions, or passages in the South Atlantic Anomaly (SAA). The trigger cut selects events consistent with physical particles according to the AMS-02 trigger logic [8]. The TOF cut requires valid velocity and charge measurements from the TOF system. The inner tracker cut ensures the presence of a well-reconstructed track, allowing for reliable rigidity and charge determination. The tracker layer one (L1) cut requires a charge measurement in the L1

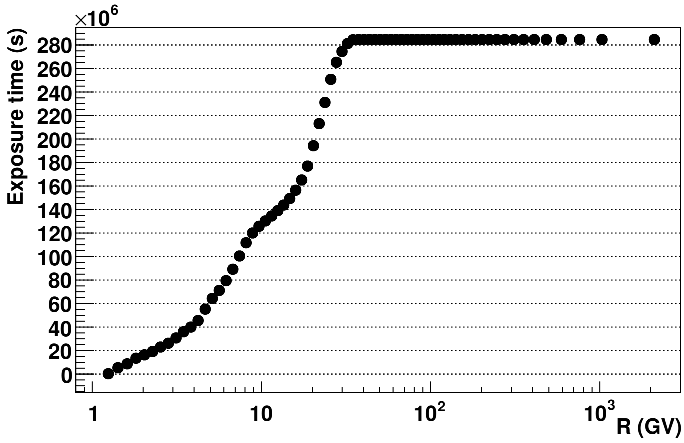

Fig. 1. – Exposure time as a function of rigidity, for 13.5 years of data taking. As can be seen in the figure, above 30 GV the geomagnetic effects disappear and the total cumulated exposure time is 2.85×10^8 s.

with proper hit association to the inner tracker track. Finally, the geomagnetic cutoff cut selects only particles with rigidity above the local geomagnetic cutoff, effectively rejecting trapped secondary particles.

After applying these cuts, the number of contaminated counts, P_i, is obtained. However, this number must be corrected for background and bin-to-bin migration.

2˙4. *Background sources.* – Beside the charge cuts on the L1 and inner tracker, there are two sources of background that we need to consider.

Above the L1 there is a thin support structure made mainly of aluminum and carbon: a nucleus with higher charge than P (for example S) can fragment and produce a P that may passes the whole selection. This background given by the fragmentation at the top of the instrument (TOI) can be only estimated via MC.

Between the L1 and the layer two (L2), a nucleus with charge competible with L1 charge cut, can fragment inside the TRD (made of polyethylene radiators and tubes filled with CO_2 and Xe) and in the TOF (plastic scintillators), producing P in the inner tracker: this background (purity) is estimated via template fit on the L1 charge distribution.

2˙5. *Purity evaluation.* – L1 selection allows a portion of S and chlorine (Cl) to pass through the L1 charge cut, fragment within the TRD or TOF, and be reconstructed in the inner tracker as P. To evaluate this contribution, the adopted procedure consists of fitting the L1 charge distribution, while selecting P with the TOF and the inner tracker. The probability density function (PDF) used to fit the distribution is built from four templates, three describing background taken from the L1 and one describing the signal taken from L2. To take into account the differences between L1 and L2, a shift parameter was introduced in the L2 signal template, in every rigidity bin, performing the fit by varying the shift and choosing the one giving the minimum reduced chi square. For one particular bin, the fit and its pull distribution are reported in Fig. 2.

Finally, in the i-th rigidity bin, the contamination fraction g given by the fragmentation between L1 and L2 is given by:

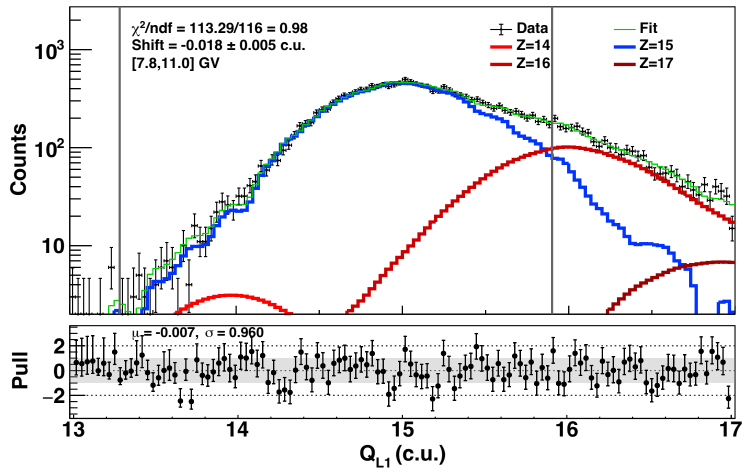

Fig. 2. – On the top pad there is the L1 charge distribution, in charge unit (c.u), while selecting P with the TOF and the inner tracker. The red curves represent the background, with the Si template included because of misidentification in the inner tracker. The vertical gray lines represent the L1 charge cut. On the bottom pad there is the pull distribution. The shaded gray band represents a $\pm$ 1σ interval.

(2) $$g_i = \frac{\int (n_{Si} f_{Si} + n_S f_S + n_{Cl} f_{Cl}) dq}{\int (n_P f_P + n_{Si} f_{Si} + n_S f_S + n_{Cl} f_{Cl}) dq}$$

where n_k is the parameter, given by the fit, representing the fraction contribution to the total signal from species k-th, and f_k is the template of the species k-th. The integral is restricted on the L1 charge cut interval, namely $[13.3, 15.9]$ c.u. The total fraction is between 20% and 25% on the whole rigidity range.

2˙6. *TOI evaluation.* – In order to evaluate the TOI, one has to take into account all nuclei with higher charge than P and evaluates the contribution to the total TOI correction. The number of contaminant nuclei from specie k to nucleus under study j, in the i-th rigidity bin, is:

(3) $$N_i^{k\to j} = \phi_i^k \cdot T_i \cdot \Delta R_i \cdot A_i^{k\to j}$$

where ϕ_i^k is the flux of contaminant k, ΔT_i is the exposure time, ΔR_i is the width of bin i-th and $A_i^{k\to j}$ is the MC acceptance of the contaminant k obtained with charge selection for the nucleus under study j. The procedure to evaluate the MC acceptance is explained in subsection **2**˙7. The TOI background fraction, in the i-th rigidity bin, is given by:

(4) $$f_i = \frac{\sum_k N_i^{k\to j}}{\hat{P}_i^j}$$

where $\hat{P}_i^j = P_i \cdot (1 - g_i)$ is the number of P nuclei selected with the cuts described in subsection **2**˙3 and subtracted from the contamination below L1 obtained with the procedure described in subsection **2**˙5. The total TOI background is below 12% in the whole rigidity range.

The final counts are $N_i = P_i \cdot (1 - g_i) \cdot (1 - f_i)$, with g_i contamination given by fragmentation between L1 and L2, and f_i background given by fragmentation above the L1 (TOI).

2˙7. *Acceptance.* – The acceptance, in particle physics, is a function that describes the angular and spatial efficiency of particle detection. In general, if we had an ideal instrument in which the response of each sub-detector and the properties of its materials are known, it could be calculated analytically. In reality, any detector used in true particle experiments is too complex for a complete analytical description of its components, so we make use of the full MC simulation of the instrument.

The acceptance, is evaluated in MC as the ratio between the events that pass the same selection described in subsection **2**˙3 and the total generated events, scaled to the event generation area. The MC acceptance in the i-th rigidity bin is:

$$A_i = \frac{N_{sel,i}}{N_{gen,i}} 3.9^2 \pi \tag{5}$$

where $N_{sel,i}$ are the simulated events that pass the selection and $N_{gen,i}$ are the total generated events.

Since the acceptance is evaluated in MC, we need to take into account the differences between data and MC, of every sub-detector used in the selection: to do this, the efficiency of each sub-detectors used in the selection has been evaluated in both data and MC dataset and then the ratio data/MC has been used to correct the MC acceptance. Because of poor statistics and high contamination, the corrections for P have been evaluated via interpolation between Si and S corrections. The total correction is shown in fig 3.

2˙8. *Unfolding procedure.* – Unfolding is a procedure used to correct for detector effects that cause events to migrate to incorrect rigidity bins due to finite detector resolution. In the AMS-02 collaboration, a widely adopted method to address this is the iterative "folded acceptance" approach.

The MC dataset is generated assuming a flux proportional to $1/R$. To obtain a power law typical of CRs, the MC acceptance and efficiencies are reweighted according to a reference CR flux—for example, the published fluorine flux [3], smoothed using a force-field [9] fit. Using these reweighted quantities, a new unfolded acceptance is calculated, and from it, a new flux is derived. This updated flux is used in the next iteration as model to reweigh again all the MC quantities, build a new acceptance and a new flux. The new flux is then compared bin-by-bin to the flux from the previous iteration. The iterative process continues until the maximum relative difference between consecutive flux estimates in all rigidity bins falls below a chosen threshold (0.1%). At this point, the acceptance is considered properly unfolded, allowing for the final flux evaluation.

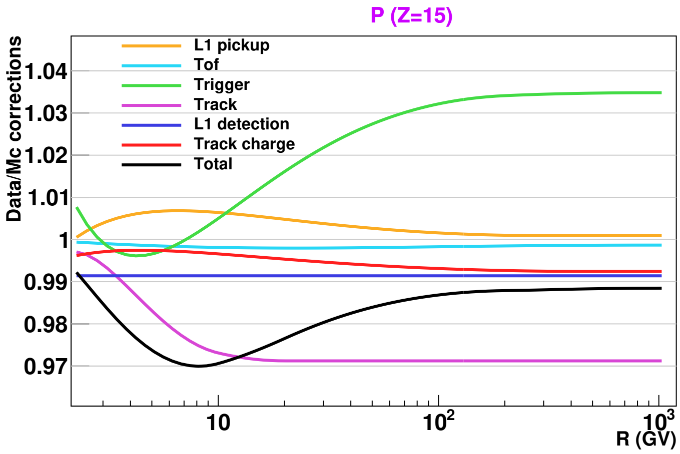

Fig. 3. – The black line represents the total data/MC correction applied to the MC acceptance, as a function of rigidity. The colored lines represent the single contribution of each sub-detector used in the selection, obtained via interpolation between Si and S corrections.

3. – Conclusions and discussion

Based on 13.5 years of data taking, the analysis methodology for the evaluation of the P CR flux with the AMS-02 detector has been presented.

Preliminary results have been shown during the conference. The measurements allow for a direct comparison with other secondary and primary species, providing constraints on propagation models.

The finalized results, including systematic uncertainties, will be reported in a forthcoming AMS-02 collaboration publication.

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