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# A full solar cycle of proton and helium measurements

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Time-dependent energy spectra of galactic cosmic rays (GCRs) carry fundamental information regarding their origin and propagation. When observed at the Earth, these spectra are significantly affected by the solar wind and the embedded solar magnetic field that permeates the heliosphere, changing significantly over an 11-year solar cycle. Energy spectra of GCRs measured during different epochs of solar activity provide crucial information for a thorough understanding of solar and heliospheric phenomena. The PAMELA experiment had collected data for almost ten years (15 June 2006 - 23 January 2016), including the minimum phase of solar cycle 23 and the maximum phase of solar cycle 24. Here, we present spectra for protons and helium-nuclei measured by the PAMELA instrument from 2006 to 2014. Time profiles of the proton-to-helium flux ratio at various rigidities were also investigated, allowing the study of all characteristic features resulting from their different mass-to-charge ratio and the difference in the shape of their respective local interstellar spectra. The force-field approximation of the solar modulation was used to relate these dependencies to the different shapes of the local interstellar proton and helium-nuclei spectra.

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## 1. Introduction

Protons and helium are the most abundant species in cosmic rays, representing about 99% of the total flux. Measurements of their absolute fluxes and spectral shapes are extremely important for better understanding both the origin and propagation mechanisms of galactic cosmic rays (GCRs). Moreover, both proton and helium fluxes are essential ingredients to estimate the spectra of secondary particles resulting from the interaction of GCRs with the interstellar medium (ISM). The propagation of CR in the galaxy modifies their spectra and composition. Before reaching the Earth, cosmic rays particles enter the heliosphere and they are affected by the heliospheric magnetic field (HMF) transported by the expanding solar wind from the Sun to the outermost regions of the heliosphere. The interaction of these particles with HMF changes significantly the intensity profile of energy spectra below $\sim 30\,GeV$ for protons and $\sim 15\,GeV/n$ for helium with respect to the Local Interstellar Spectrum (LIS), i.e. the spectrum which would be measured outside the heliospheric boundaries. The magnitude of the intensity attenuation depends on the solar activity; this effect is known as solar modulation, e.g. see [1, 2]. Solar activity varies strongly with time, rising from a minimum level when the Sun is quiet (with cosmic rays then having a maximum intensity at Earth) to a maximum period (when cosmic rays have a minimum intensity at Earth) and then returning to a new minimum repeating the cycle. This solar cycle has a periodicity of approximately 11 years. The unusually long minimum activity of solar cycle $23^{rd}$ form 2006 to late 2009 (e.g. see [3]) caused ideal low modulation conditions for GCRs and this is translated into a perfect environment to study the various processes that affect particles inside the heliosphere. After 2009, the solar activity increased again reaching its maximum in January 2014; the $24^{th}$ solar cycle maximum was classified as one of the weakest in recent years, e.g. see [4–6]. The PAMELA experiment collected data for almost 10 years and the instrument was well suited to measure the effect of solar modulation on many cosmic rays species. With his low minimum detectable energy at ~ 80 MeV/n is fitted to probe the solar modulation effects where they have the major impacts on the CRs spectra. Moreover, its redundant detectors and high precision measurements permitted unprecedented statistics. The PAMELA collaboration already published several papers on CR solar modulation: protons [7, 8], electrons and positrons [9, 10], the time-dependent helium spectra during the 23rd solar minimum (July 2006 - December 2009) [11] and it is in preparation an article on the time-dependent helium spectra during the 24th solar maximum (January 2010 - September 2014).

In this work, we present a complete study of proton and helium-nuclei components measured from the decaying phase of the 23rd solar cycle (July 2006) to the maximum of the 24th cycle (September 2014). These fluxes cover a nearly complete solar cycle. Additionally, for the entire time period, we studied the proton-to-helium flux ratios as a function of time and rigidity to highlight dependencies possibly due to the different particle masses and to different shapes of the LIS [12, 13]. Finally, a simplified approach to solar modulation, the force-field approximation [14], was used to show how these dependencies can be related to the different shapes of the local interstellar proton and helium-nuclei spectra.

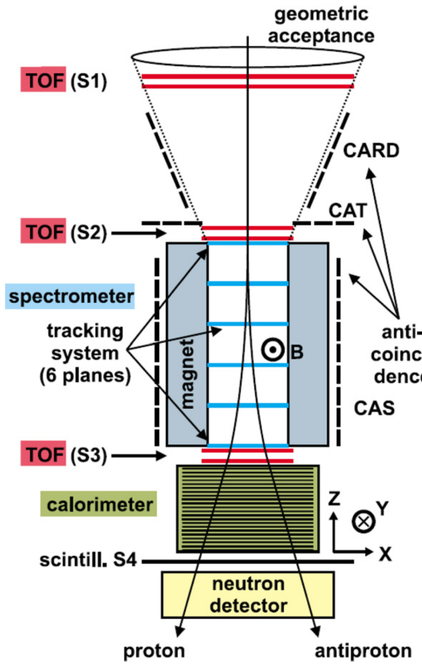


**Figure 1:** PAMELA and its sub-detectors.

## 2. The instrument

PAMELA (A Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics) is a satellite-borne experiment designed to make long duration observations of the cosmic radiation from Low Earth Orbit [15]. The instrument collected GCRs for almost 10 years from 2006 June 15 when it was launched from the Baikonur cosmodrome in Kazakhstan, until January 2016. The PAMELA instrument was hosted on board of the Russian satellite DK1 that orbited Earth at an altitude ranging between 350 and 610 km with an inclination of 70°. After 2010 the orbit was changed to a circular one at a constant altitude of about 500 $km$.

The payload comprises a number of highly redundant detectors capable of identifying particles by providing charge, rigidity and velocity measurements over a very wide energy range. Multiple sub-detectors are arranged around a magnetic spectrometer, composed of a silicon tracking system [16] placed inside a 0.43 $T$ permanent magnet. The 300 $mm$ thick double-sided Silicon sensors of the tracking system measure two independent impact coordinates on each plane, reconstructing with high accuracy the particle deflection, with a maximum detectable rigidity of $\sim 1.2\,TV$, and the sign of the electric charge $Z$. A system of six layers of plastic scintillators, arranged in three double planes (S1, S2, and S3), provides a fast trigger to acquire data. It contributes to particle identification measuring the ionization energy loss and the time of flight (ToF) of particles passing through with a resolution of $\sim 300\ ps$; this assures the determination of the absolute value of the particle charge plus allowing albedo particles rejection [17]. An electromagnetic imaging W/Si calorimeter (16.3 radiation lengths and 0.6 interaction lengths deep) provides hadron-lepton discrimination [18]. A neutron counter [19] contributes to the discrimination power by detecting the increased neutron production in the calorimeter associated with hadronic showers compared to electromagnetic ones,

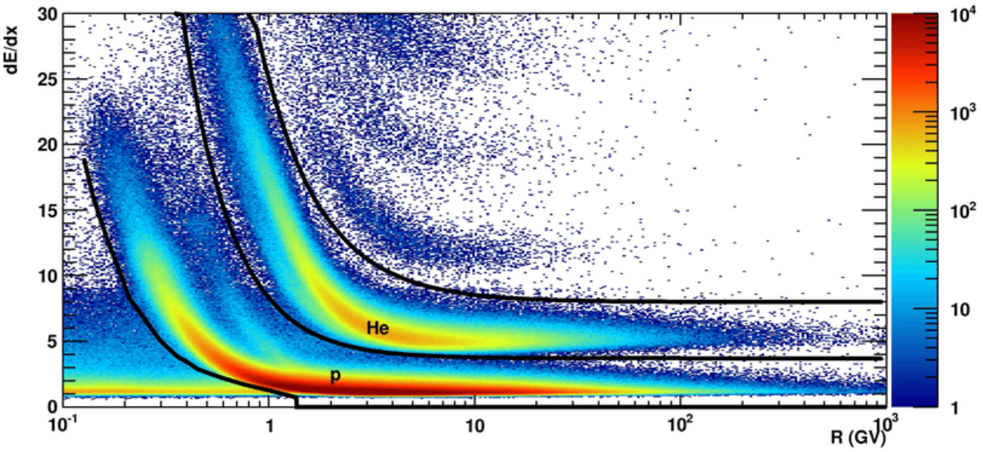


**Figure 2:** Energy loss distribution in the tracking system as a function of particle rigidity. The proton and helium nuclei band are clearly separated from each other.

while a plastic scintillator, placed beneath the calorimeter, increases the identification of high-energy electrons. The whole apparatus is surrounded by an anti-coincidence system (AC) of three scintillators (CARD, CAS, and CAT) for the rejection of background events [20]. A comprehensive description of the instrument can be found in [21]. The payload is schematically shown in Figure 1.

## 3. Data analisys

The previously published proton fluxes were evaluated on a Carrington rotation (CR) time basis (∼ 27 days). In the period after January 2010, the solar activity was at its maximum and characterized by many solar events. Most of these events produced high-energy particles capable to reach Earth and, consequently, the PAMELA detector. Hence, the periods corresponding to these solar events, according to the measurements of low-energy (> 60 MeV) proton channel of GOES-15[1], were not included in the flux computation [8]. The statistics of selected helium events found to decrease over time. This effect was mainly due to the sudden, random failure of a few front-end chips in the tracking system and particularly significant after the second half of 2009. Therefore, the last four CR of 2009 were combined in a single spectrum for statistical reasons. The helium fluxes during the solar maximum period were evaluated on a three CR time basis and the periods corresponding to the solar events, as for protons, were not included in the flux computation. Figure 2 shows the ionization energy losses over the silicon planes of the tracking system as a function of the rigidity.

The absolute proton and helium-nuclei fluxes $\Phi(E)$ in kinetic energy were obtained as follows:

$$\Phi(E) = \frac{N(E)}{G(E) \times LT \times \epsilon(E) \times \Delta E} \tag{1}$$

where $N(E)$ is the unfolded count distribution of selected events, $\epsilon(E)$ the product of the single selections efficiencies, $G(E)$ the geometrical factor, $LT$ the live-time, and $\Delta E$ the width of the

[1] ftp://satdat.ngdc.noaa.gov/sem/goes/data/

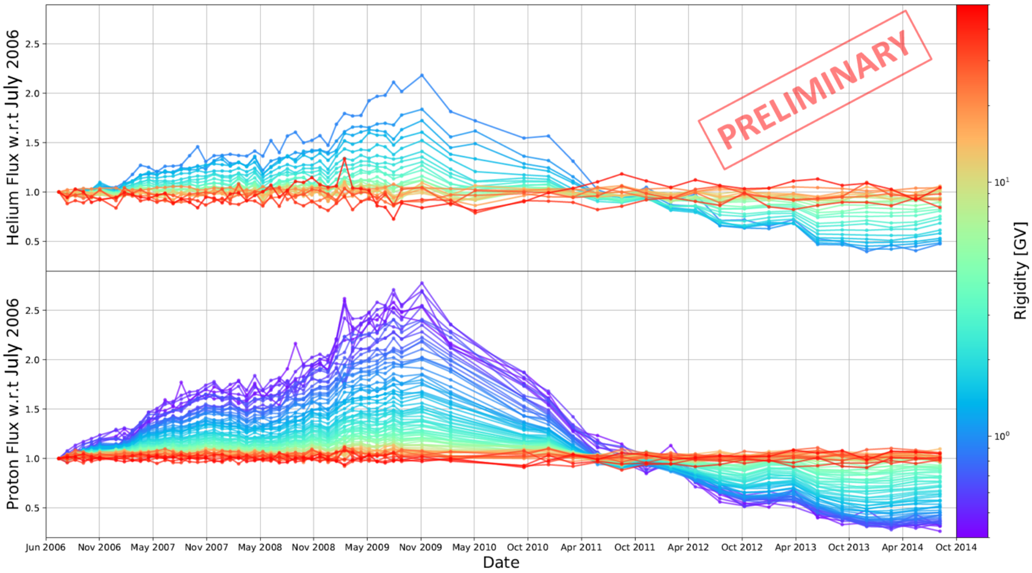


**Figure 3:** Time-dependent intensities (normalized to July 2006) for helium-nuclei, top panel, and for protons, bottom panel, measured by PAMELA experiment between July 2006 and September 2014.

energy interval. No isotopic separation (possible only up to ~ 1.4 GeV/n [22]) was performed in this analysis. For the conversion from rigidity to kinetic energy, all helium-nuclei events were treated as $^4$He. More details on the analysis procedure used, the selection efficiencies, and systematic errors, can be found in [7, 8, 11].

## 4. Results

The temporal evolution of the helium-nuclei and proton fluxes over a nearly complete solar cycle is shown in Figure 3, top and bottom panel respectively. The fluxes were estimated as a function of rigidity, i.e. particles per m$^2$ sr s GV, and were normalized to the fluxes measured at the beginning of the data taking in July 2006. Unsurprisingly the time dependence of the helium-nuclei intensities resembles closely the time evolution of the proton intensities increasing from 2006 to the solar minimum in 2009, followed by a gradual decrease up to early 2014, when the maximum of solar cycle 24th was reached, and a subsequent increase. The lowest rigidity fluxes are those mostly affected by solar modulation.

To highlight any dependencies possibly due to the different particle masses and to the different LIS shapes between protons and helium-nuclei, the proton-to-helium ratio as a function of time and rigidity was studied. With the PAMELA proton and helium data, it is possible to study the proton-to-helium flux ratio down to the low rigidity of ~ 860 MV. Moreover, the long period of data taking allows investigating his behavior during the whole solar activity phases. To be consistent between proton and helium flux periods to compute the proton-to-helium flux ratio, proton fluxes were combined to the same periods of helium fluxes. The results for the new helium-nuclei spectra measured during the solar maximum period, as well as the proton-to-helium flux ratio time profile extended to this period, will be presented at this conference. The force-field approximation for solar modulation was applied to these data to relate the features observed in the proton-to-helium ratio time profile to the different LIS shapes of the two species. The modeled profile for the proton-to-helium ratio obtained with this approach will also be presented at the conference.

Assuming the spherically symmetric model for solar modulation suggested by Gleeson & Axford [14], the differential intensity $J(r, E, t)$ at a given distance $r$ from the Sun, total energy $E$ and time $t$, is related with the time-independent interstellar intensity $J(\infty, E)$ through the equation:

$$J(r, E, t) = \frac{E^2 - E_0^2}{(E + \Phi)^2 + E_0^2} J(\infty, E + \Phi(t)) \tag{2}$$

where $E_0$ is the rest energy (mass) of the particle and $\Phi = |Z| e\phi$ a parameter that can be interpreted as the energy loss experienced by the cosmic-ray particle when approaching the Earth from infinity. With this assumption and having available observational data on $J$ at different times, it is possible to determine the time profile of parameter $\phi$. Namely, plotting $J/R^2$ against the kinetic energy divided by the charge (Ze) of the particle, we obtained a set of curves with identical shapes but displaced along the abscissa. This displacement gave $\Delta\phi(r, t_i, t_j) = \phi(r, t_j) - \phi(r, t_i)$, the change in the modulation parameter, which should be the same for all particles species. From the horizontal displacement of these curves, we determined the variation of the modulation parameter $\phi$, finding a similar value for both species. Chosen an arbitrary initial $\phi_0$, we extrapolated the value of the modulation parameter at any time corresponding to the measured fluxes. For each of these, we applied the Eq. 2 to obtain the corresponding local interstellar spectra. The fluxes thus acquired were combined to obtain a single LIS and the result was interpolated at lower rigidities with the Voyager 1 data [23, 24]. As one can imagine, the decision of $\phi_0$ affects the LIS shape. Its optimal value was chosen according to the LIS which best agreed with the Voyager 1 data and was found to be $\sim$ 500 MV. Finally, the resulting LIS were modulated with the estimated modulation parameter of each period and the proton-to-helium flux ratio time profiles were obtained. An interesting consistency with the experimental data was observed and it will be presented at the conference.

## 5. Conclusions

The time dependence of the proton and helium fluxes measured by PAMELA offers the possibility to study the propagation mechanism of GCRs inside the heliosphere. Thanks to the long period of almost 10 years of data taking, the PAMELA experiment allows probing different epochs of a nearly complete solar cycle. Proton and helium-nuclei measured spectra for the period from July 2006 to September 2014 were presented. The proton-to-helium ratio as a function of time and rigidity was studied to investigate any dependencies possibly due to the different particle masses and to the different LIS shapes between the two species. The force-field approximation of the solar modulation was used to relate these dependencies to the different shapes of the local interstellar proton and helium-nuclei spectra.

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