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SOLAR MODULATION OF THE PROTON LOCAL INTERSTELLAR SPECTRUM WITH AMS-02, VOYAGER 1 AND PAMELA

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Abstract

In recent years, the increasing precision of direct cosmic rays measurements opened the door to indirect searches of dark matter with high-sensitivity and to more accurate predictions for radiation doses received by astronauts and electronics in space. The key ingredients in the study of these phenomena are the knowledge of the local interstellar spectrum (LIS) of galactic cosmic rays (GCRs) and the understanding of how the solar modulation affects the LIS inside the heliosphere. Voyager 1, AMS-02 and PAMELA measurements of proton fluxes provide invaluable information, allowing us to shed light on the shape of the LIS and the details of the solar modulation during solar cycles 23 and 24. A new parametrization of the proton LIS is presented, based on the latest data from Voyager 1 and AMS-02. Using the framework of the force-field approximation, the solar modulation parameter is extracted from the time-dependent proton fluxes measured by PAMELA. A modified version of the force-field approximation with an energy-dependent modulation parameter is introduced, yielding better results on proton data than the force-field approximation. The results are compared with the modulation parameter inferred by neutron monitors.

Keywords: cosmic rays — Sun: heliosphere — Sun: activity

1. INTRODUCTION

The search for the local interstellar spectrum (LIS) of galactic cosmic rays (GCRs) and a full understanding of the solar modulation are long-standing issues in the field of cosmic rays and heliophysics. In recent years, hints of possible dark matter (DM) signatures or new astrophysical phenomena have accumulated accumulated as a results of accurate measurements of the anti-matter component in cosmic ray fluxes (Adriani et al. 2013a; Accardo et al. 2014; Aguilar et al. 2014; Adriani et al. 2010). In order to define the astrophysical background of GCRs over which to look for the excess coming from DM annihilation or decay, the knowledge of the LIS is of utmost importance. Uncertainties in the low energy part of the LIS due to the solar modulation reduce the sensitivity of these type of searches (Fornengo et al. 2014, 2013; Yuan & Bi 2015). With the ever-growing number of satellites orbiting Earth and NASA plans for human missions to Mars, the characterization of the radiation dose received by astronauts and electronics in different periods of the solar cycle is becoming more and more important: a precise knowledge of the LIS and the temporal variation of GCR fluxes inside the heliosphere is needed for reducing the uncertainties on the estimated dose (Townsend et al. 1994; O'Neill 2010).

Data collected over many decades from ground observations, balloon experiments and spacecraft have deepened our understanding of how the heliosphere affects the spectrum of GCRs: many numerical models have been developed to solve the Parker equation governing the propagation of GCRs in the heliosphere (Parker 1958) and to explore the different processes induced by their interactions between the heliospheric magnetic field and the solar wind. Nevertheless, the force-field approximation (Gleeson & Axford 1968) is still routinely used as a reference, due to its simplicity. Under the assumptions of spherical symmetry, radial solar wind, an isotropic diffusion coefficient and no particle drift, the differential GCR flux dJ/dT, measured at Earth at the time t, is related to the LIS dJ_{LIS}/dT via the formula

$$\frac{dJ}{dT}(T) = \frac{T(T+2M)}{(T+\Phi)(T+\Phi+2M)}\frac{dJ_{LIS}}{dT}(T+\Phi) \quad (1)$$

where T is the kinetic energy of a nucleus of charge Z and mass M and $\Phi = Ze\phi(t)$. $\phi(t)$ is known as the solar modulation parameter or solar modulation potential and has the units of an electric potential.

In August 2012, the Voyager 1 spacecraft, launched in 1977, crossed the heliopause and entered interstellar space (Stone et al. 2013). A debate is still ongoing whether the heliopause can be considered the modulation boundary or not (Scherer et al. 2011; Kóta & Jokipii 2014; Guo & Florinski 2014), but so far the GCR flux measured by Voyager 1 has remained steady [1], thereby suggesting that what is being observed is actually a LIS. In 2006, just before the minimum of solar cycle 23, the PAMELA experiment was launched on board a satellite in low Earth orbit and since has provided a precise and direct measurement of the top-of-atmosphere proton flux and its time variation up to 50 GeV (Adriani et al. 2013b). The AMS-02 experiment was installed in 2011 on the International Space Station during the ascending phase of solar cycle 24 and recently published the proton flux up to 2 TeV, integrated over 3 years, with an error at the % level (Aguilar et al. 2015a), which provides the most accurate measurement of the high energy part of the proton LIS. AMS-02 is expected to take data until the decommissioning of the ISS in 2024, allowing a precise

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[1] See, for example, the proton rates from 2013 to 2015 at `http://voyager.gsfc.nasa.gov/heliopause/yearplot24h.html`

measurement of the time variation of GCRs throughout an entire solar cycle and of the solar modulation effects on different species of cosmic rays.

In this paper, we provide a new parametrization for the proton LIS based on Voyager 1 and AMS-02 proton data. This new LIS model, modulated with the force-field approximation, is used to fit the monthly proton fluxes measured by PAMELA. We propose a modified version of the force-field approximation with an energy-dependent ϕ to better describe PAMELA data and finally, we compare the extracted $\phi(t)$ with the one derived from neutron monitors (NMs).

2. A NEW PARAMETRIZATION FOR THE PROTON LIS

The majority of the LIS models found in literature are based on spacecraft and balloon measurements of GCRs before Voyager 1 entered the interstellar space and do not take into account a change of spectral index at high rigidities ($R \gtrsim 300$ GV), which has been observed by PAMELA (Adriani et al. 2011) and AMS-02 (Aguilar et al. 2015a). The availability of the high-accuracy high energy proton flux from AMS-02 and the low energy proton flux from Voyager 1 represent important progress towards the reduction of the uncertainty on the LIS shape, enabling a more accurate determination of the solar modulation parameter and improving the understanding of GCR propagation in the heliosphere. Figure 1 shows the ratio of various proton LIS models to the BPH00 model used in (Usoskin et al. 2005) to extract the solar modulation parameter from NMs, along with the ratio of Voyager 1 (Stone et al. 2013) and AMS-02 (Aguilar et al. 2015a) proton fluxes to the same model. It is clear that the new data from Voyager 1 and AMS-02 are not well described by these models. These discrepancies compel us to find a new LIS parametrization based on the new results from Voyager 1 and AMS-02.

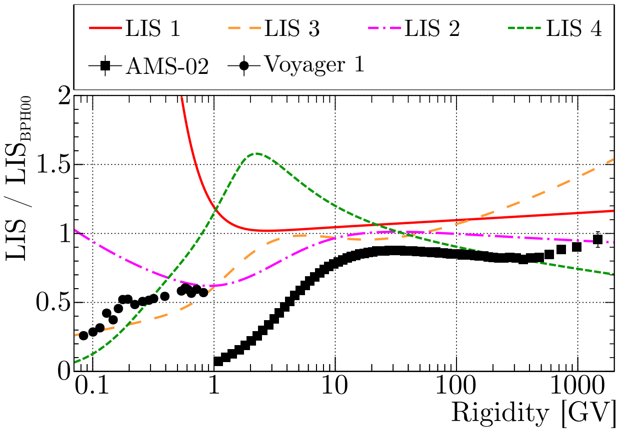

Figure 1. Ratio of various proton LIS models (lines) and Voyager 1 (black dots) and AMS-02 proton (black squares) fluxes to the BPH00 model. The used models are: 1 (Shikaze et al. 2007); 2 (Garcia-Munoz et al. 1975); 3 Langner (2004); 4 (Webber & Higbie 2003). A color version of this figure is available in the online journal.

For the high-energy end of the proton LIS, we use the model adopted by the AMS-02 collaboration (Aguilar et al. 2015a) to describe a double power-law:

$$R^{\gamma}\left[1+\left(\frac{R}{R_b}\right)^{\Delta\gamma/s}\right]^{s} \tag{2}$$

where $\Delta\gamma$ is the change in spectral index, R_b is the rigidity where the two power-laws cross each other and s determines the smoothness of the change ($s = 0$ means a broken power-law). Recently, the analysis of γ-ray emissions from giant molecular clouds point to a low-energy break around 9 GeV, with the spectral index changing from ≈ -2 to ≈ -3 (Neronov et al. 2012). We generalize equation 2 to describe two power-law breaks:

$$R^{\gamma_1}\left\{1+\left[\frac{R}{R_{b1}}\left(1+\left(\frac{R}{R_{b2}}\right)^{\Delta\gamma_2/s_2}\right)^{s_2}\right]^{\Delta\gamma_1/s_1}\right\}^{s_1} \tag{3}$$

where the indices 1 and 2 stand for the low- and high-rigidity break respectively: if $R \ll R_{b1}$, equation 3 reduces to $\approx R^{\gamma_1}$; if $R_{b1} \ll R \ll R_{b2}$, equation 3 becomes $\approx R^{\gamma_1+\Delta\gamma_1} = R^{\gamma_2}$; and if $R \gg R_{b2}$, equation 3 goes as $\approx R^{\gamma_1+(1+\Delta\gamma_2)\Delta\gamma_1} = R^{\gamma_3}$.

To describe the energy range spanned by the Voyager 1 data, we note that if we divide the Voyager 1 proton flux by a generic power law, as shown in Figure 2, the resulting ratio looks like a sigmoid function in $\ln R$; we assume the following parametrization to describe this ratio:

$$\left[1+\exp\left(-\frac{\ln R-\mu}{\sigma}\right)\right]^{-1/\nu} \tag{4}$$

where μ is related to the rigidity where the ratio is 1/2, σ determines the steepness of the rise and ν describes a possible asymmetry.

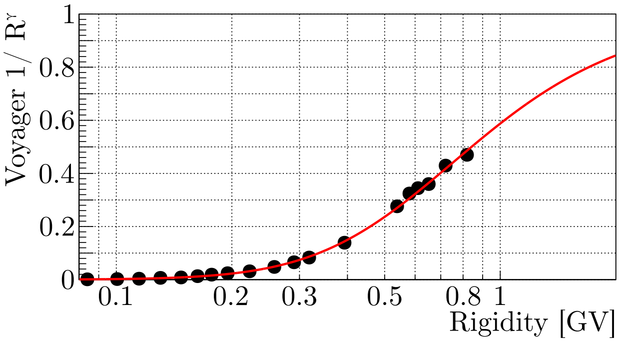

Figure 2. Ratio of the proton flux measured by Voyager 1 to R^{γ} ($\gamma = -2$). The solid line (colored red in the electronic edition) is the formula in equation 4. A color version of this figure is available in the online journal.

The new parametrization for the LIS is therefore:

$$\begin{aligned}\frac{dJ_{LIS}}{dR}(R) &= N\left[1+\exp\left(-\frac{\ln R-\mu}{\sigma}\right)\right]^{-1/\nu}R^{\gamma_1}\\ &\times\left\{1+\left[\frac{R}{R_{b1}}\left(1+\left(\frac{R}{R_{b2}}\right)^{\Delta\gamma_2/s_2}\right)^{s_2}\right]^{\Delta\gamma_1/s_1}\right\}^{s_1}\end{aligned} \tag{5}$$

where N is a normalization factor.

The available data in the rigidity range between up to a few tens of GV are all affected by the solar modulation, therefore a simple fit of equation 5 to Voyager 1 data and AMS-02 data above 100 GV (to remove any residual modulation) is not able to correctly constrain all the parameters, especially γ_1, R_{b1}, $\Delta\gamma_1$ and s_1. To resolve this issue, we proceed by simultaneously fitting Voyager 1 data with equation 5 and AMS-02 data with equation 5 modulated with the force-field approximation; this way, we obtain at the same time the parameters for the LIS and the average solar modulation parameter throughout the AMS-02 data time period. The least-squares fit is done with `MINUIT` (James & Roos 1975), minimizing the following quantity:

$$\begin{aligned}\chi^2_{glob} &= \chi^2_{V1} + \chi^2_{AMS} \\ &= \sum_i \sigma^{-2}_{V1}(i)\left(y_{V1}(i) - \frac{1}{\Delta R_i}\int_{R_i}^{R_{i+1}} \frac{dJ_{LIS}}{dR}(R)dR\right)^2 \\ &+ \sum_i \sigma^{-2}_{AMS}(i)\left(y_{AMS}(i) - \frac{1}{\Delta R_i}\int_{R_i}^{R_{i+1}} \frac{dJ(R)}{dR}(R)dR\right)^2\end{aligned} \quad (6)$$

where i is the binning index, R_i and R_{i+1} are the bin edges and $\Delta R_i = R_{i+1} - R_i$, $y(i)$ and $\sigma(i)$ are respectively the data and its associated error in the i-th bin and $dJ(R)/dR$ is defined as in equation 1 after converting from kinetic energy to rigidity.

The results of the fit ($\chi^2_{glob}/\text{ndf} = 56/79$) are shown in Figure 3.

Voyager 1 errors are only statistical, so they overconstrain the LIS parameters; the residuals above 10% in the bottom panel of Figure 3 occur in the energy range where Voyager 1 changes its energy measurement method[2]. The fitted parameters are presented in Table 1.

Parameter	Value	Error
N (m^{-2} sr^{-1} s^{-1} GV^{-1})	11740	±180
μ	-0.559	±0.011
σ	0.563	±0.005
ν	0.4315	±0.0048
γ_1	-2.4482	±0.0054
R_{b1} (GV)	6.2	±0.2
$\Delta\gamma_1$	-0.4227	±0.0081
s_1	-0.108	±0.015
R_{b2} (GV)	545	±210
$\Delta\gamma_2$	-0.6	±0.2
s_2	-0.4	±0.2
ϕ (MV)	600	±8

Table 1
Fitted parameters of the combined fit of Voyager 1 and AMS-02 data with the force-field approximation.

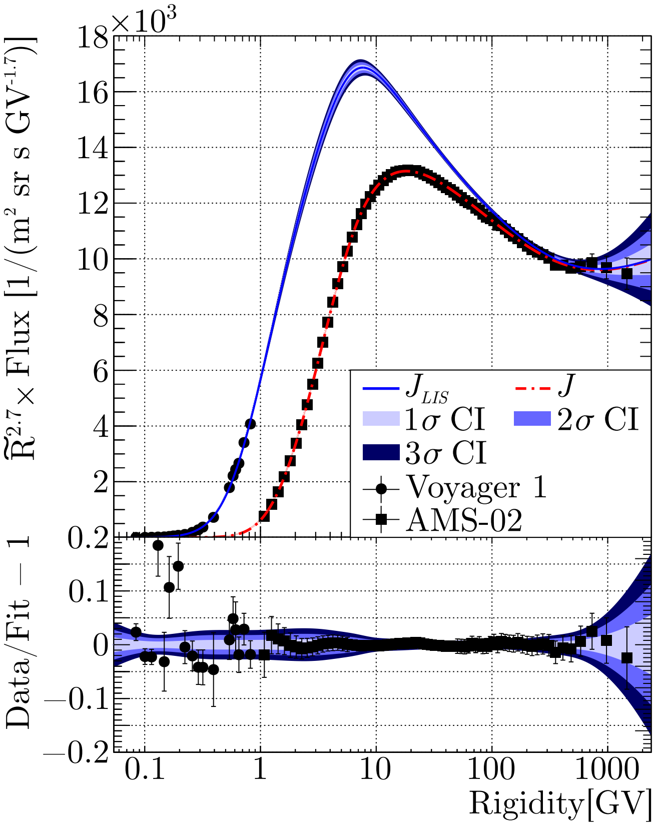

Figure 3. The top panel shows the combined least-squares fit of Voyager 1 data (black dots) with J_{LIS} (solid line) and AMS-02 data (black square) with J (dashed-dotted line), as described in the text; the shaded bands represent the 1, 2 and 3 σ confidence intervals around the best fit. Data and fit are rescaled by $\widetilde{R}^{2.7}$: see (Lafferty & Wyatt 1994) for the definition of $\widetilde{R}$. The bottom panel shows the fit residuals along with the confidence intervals. A color version of this figure is available in the online journal.

The PAMELA experiment published the proton flux between 0.4 GV and 50 GV, integrated in Carrington rotation periods, from July 2006 to January 2010 [3] (Adriani et al. 2013b). This dataset provides valuable information for understanding the impact of the solar modulation on the differential flux. Using the force-field approximation from equation 1, we fit the PAMELA data with the LIS in equation 5. In order to take into account the uncertainty on the LIS in the error on the fitted ϕ, we also fit the PAMELA data with the LIS plus or minus the 1σ confidence interval, thus getting $\phi_{\pm1}$, and we take the difference $\phi - \phi_{\pm1}$ as an estimate of the LIS uncertainty propagated to the fitted modulation parameter. Figure 4 illustrates an example of the fit results for the proton flux measured by PAMELA between July 2006 and March 2008 (top) and during Carrington rotation 2066 (bottom); Table 3, columns 2 to 4, presents the fitted values of ϕ with the errors coming from the fit itself and from the LIS.

Although the reduced chi-square is good for both fits (respectively 79/79 and 55/77), the residuals have a structure with a bump around 1 GV and a dip around 7 GV, meaning that the fit does not completely describe the data. The same behavior is observed in the residuals of the fits to all PAMELA monthly fluxes, with the bump and the dip occurring around the same rigidities. We believe that these structures are due to the fact that the force-field approximation does not correctly reproduce the solar modulation during the minimum of solar cycle 23 because some processes (like drift) are not considered. (Potgieter et al. 2013).

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[2] Private communication with E. Stone and A. Cummings, 2015.

[3] Tables for all the Carrington rotation periods are available online in the COSMIC RAY database of the Italian Space Agency: http://tools.asdc.asi.it/cosmicRays.jsp

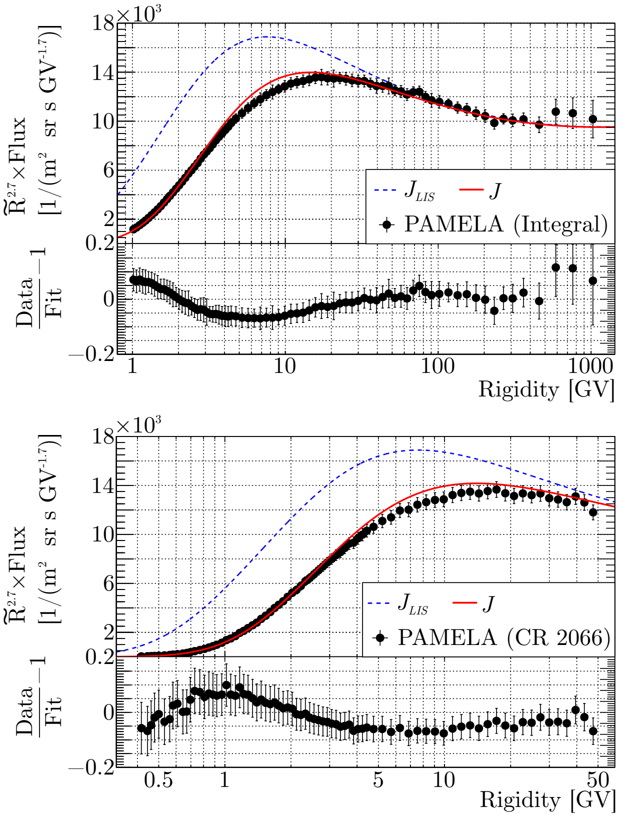

Figure 4. Fit of the LIS modulated with the force-field approximation to the PAMELA integral proton flux (top figure) and to the PAMELA proton flux measured during the Carrington rotation 2066 (bottom figure). The dashed line represent the LIS, while the solid line is the modulated LIS fitted to the data (black dots). The lower panels in both figures show the fit residuals. A color version of this figure is available in the online journal.

3. BEYOND THE FORCE-FIELD APPROXIMATION

These results suggest that the solar modulation may affect GCRs below and above a few GVs in different ways; a similar conclusion is also found in (Gieseler et al. 2015) by comparing data from NMs, PAMELA and the EPHIN instrument on board the SOHO spacecraft. To account for this effect, we modify the force-field approximation by considering an energy-dependent solar modulation parameter:

$$\phi(T)=\begin{cases}\phi_L, & T<T_L\\ f(T,\,\phi_L,\,\phi_H), & T_L\le T\le T_H\\ \phi_H, & T>T_H\end{cases}\tag{7}$$

where the indices L and H stand for "low" and "high" energy and f is a transition function between ϕ_L and ϕ_H. We want f to have a zero derivative at T_L and T_H to avoid discontinuities in the spectral index: the simplest function that has this property is a third degree polynomial, which is completely constrained by the given boundary conditions. Defining $t=(T-T_L)/(T_H-T_L)$, the transition function is $f(T,\,\phi_L,\,\phi_H)=\phi_L+(\phi_H-\phi_L)t^2(3-2t)$.

We then proceed as previously done: simultaneously fitting Voyager 1 and AMS-02 data, minimizing the global chi-square defined in equation 6 and replacing the solar modulation parameter in equation 1 with the one defined in equation 7.

The results of the fit ($\chi^2_{glob}/\mathrm{ndf}=55/78$) are shown in Figure 5.

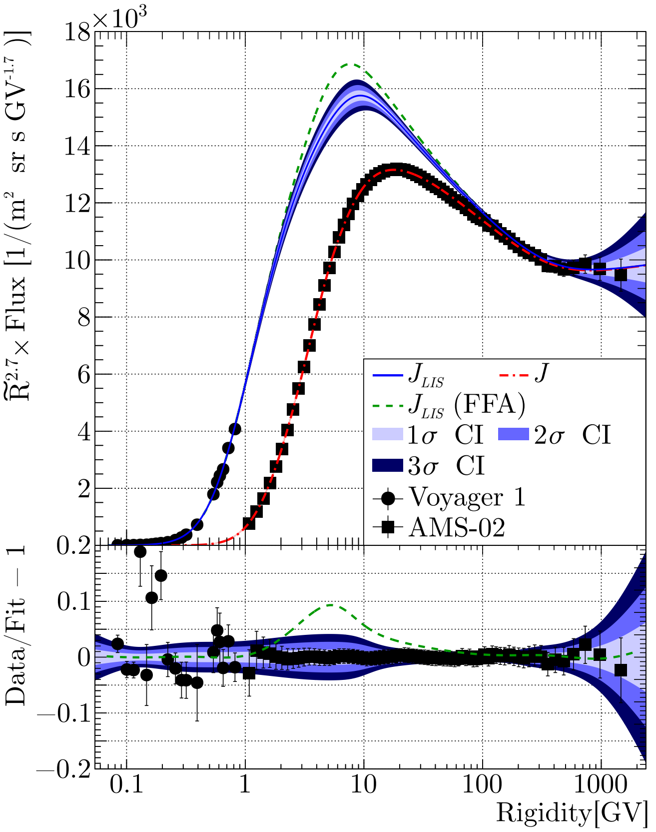

Figure 5. Same as Figure 3, but using the energy dependent solar modulation parameter of equation 7. For comparison, the LIS derived in Section 2 with the usual force-field approximation, J_{LIS} (FFA), is shown as a dashed line. A color version of this figure is available in the online journal.

In the fit, the values of T_L and T_H have been fixed at 0.125 and 4.65 GeV, while the fitted parameters are presented in Table 2. The asymptotic spectral indices at intermediate and high rigidities are, respectively, $\gamma_2=-2.853\pm0.015$ and $\gamma_3=-2.674\pm0.073$.

Parameter	Value	Error
N (m^{-2} sr^{-1} s^{-1} GV^{-1})	13020	±240
μ	-0.526	±0.011
σ	0.579	±0.005
ν	0.4052	±0.0046
γ_1	-2.5794	±0.0059
R_{b1} (GV)	8.69	±0.49
$\Delta\gamma_1$	-0.2735	±0.0089
s_1	-0.068	±0.016
R_{b2} (GV)	410	±190
$\Delta\gamma_2$	-0.65	±0.29
s_2	-0.27	±0.24
ϕ_L (MV)	589	±8
ϕ_H (MV)	485	±22

Table 2
Fitted parameters of the combined fit of Voyager 1 and AMS-02 data with the modified force-field approximation.

Figure 6 shows the proton flux measured by PAMELA during the same time periods shown in Figure 4 fitted with the energy dependent solar modulation parameter: the reduced chi-squares are, respectively, 13/78 and 36/76 and the structures of the residuals are now smaller with respect to the ones obtained with the force-field approximation.

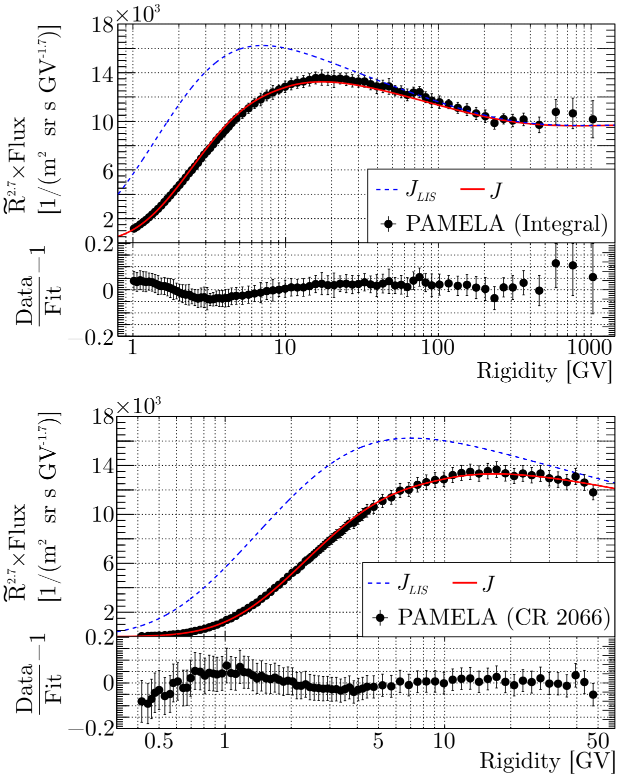

Figure 6. Same as Figure 4, but using the energy dependent solar modulation parameter of equation 7. A color version of this figure is available in the online journal.

The fit has been repeated for all monthly proton fluxes measured by PAMELA and the time dependence of the fitted solar modulation parameters ϕ_L and ϕ_H is plotted in the top panel of Figure 7. The fitted values of ϕ_L and ϕ_H are presented in Table 3, columns 5 to 10. The two modulation parameters are well-correlated (the correlation coefficient is $\rho = 0.93$), as shown in the central panel of Figure 7. A linear fit to the modulation parameters has been performed, yielding a $\chi^2/ndf = 0.64$ with a slope of 0.87 ± 0.07 and an intercept compatible with zero. If we interpret the solar modulation parameters as the average energy losses experienced by the particles traveling from the edge of the heliosphere up to the Earth, these results show that, during the minimum of solar cycle 23, the energy losses are slightly higher at lower rigidities, while the force-field approximation predicts the same energy loss at all rigidities. The bottom panel of Figure 7 shows the correlation between ϕ_L and the ϕ previously obtained with the force-field approximation: the correlation coefficient is 0.9994 and a linear fit yields a $\chi^2/ndf = 0.08$ with a slope of 1.02 ± 0.02 and an intercept compatible with zero. This result means that the force-field approximation is able to capture the leading effects of the solar modulation down to 0.5 GV even when the assumptions of the approximation are not completely satisfied, such as during a solar minimum.

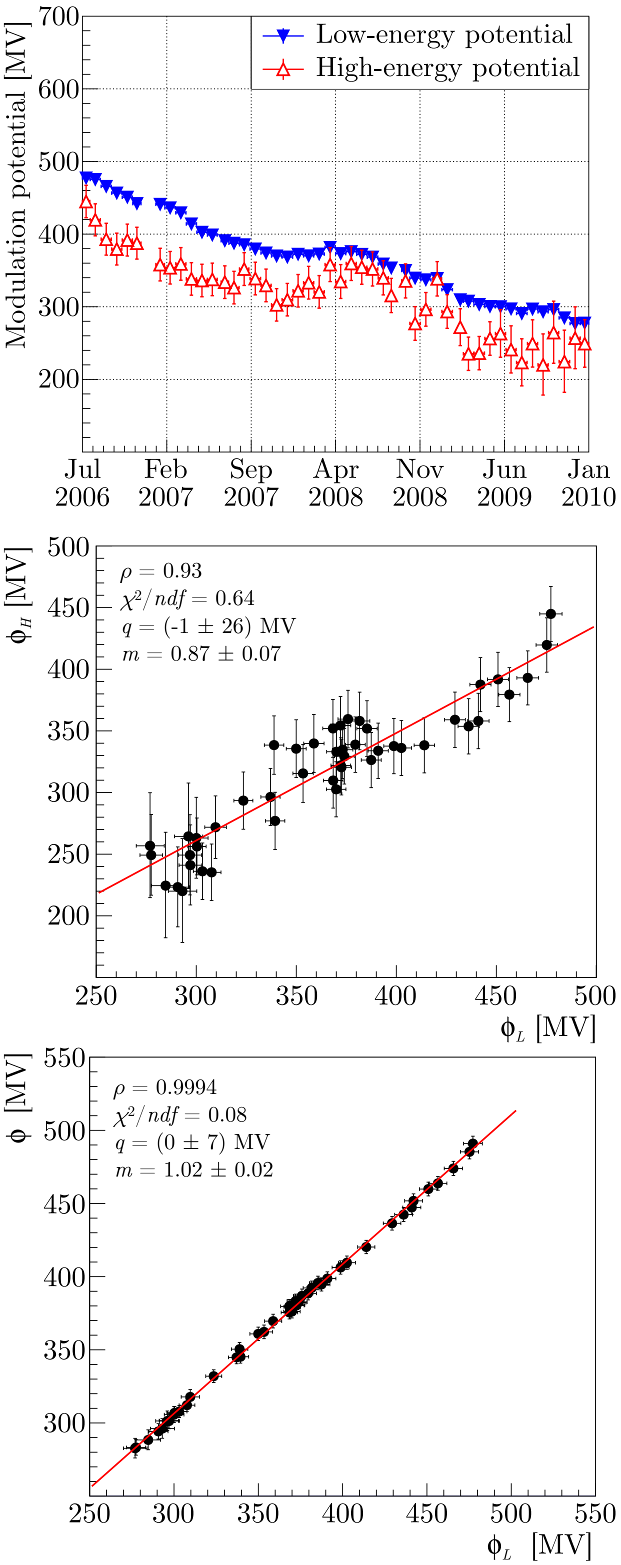

Figure 7. (Top) Time dependence of the solar modulation parameters ϕ_L (down triangles) and ϕ_H (up triangles) derived from the monthly proton fluxes measured by PAMELA during the minimum of solar cycle 23. (Center) Correlation between ϕ_L and ϕ_H; the solid line is a linear fit. (Bottom) Correlation between ϕ_L and ϕ, the solar modulation parameter obtained with the force-field approximation. A color version of this figure is available in the online journal.

4. COMPARISON WITH NEUTRON MONITORS

The effect of the solar modulation on GCRs has been continuously measured on ground since the 1950's with the world network of NMs, which measure the integral of the GCR flux above the rigidity cutoff pertaining to the NM location. In order to extract the solar modulation parameter from NM data, the shape of the LIS and the elemental composition of GCRs must be assumed, usually from measurements made by balloon- and space-borne experiments.

Figure 8 top shows the comparison between the low-energy solar modulation parameter, ϕ_L, obtained from the fits of equation 5 to the PAMELA proton fluxes and the parameter derived from NMs, ϕ_{NM} (Usoskin et al. 2011; Gil et al. 2015), using the BPH00 model as the LIS (see Figure 1).

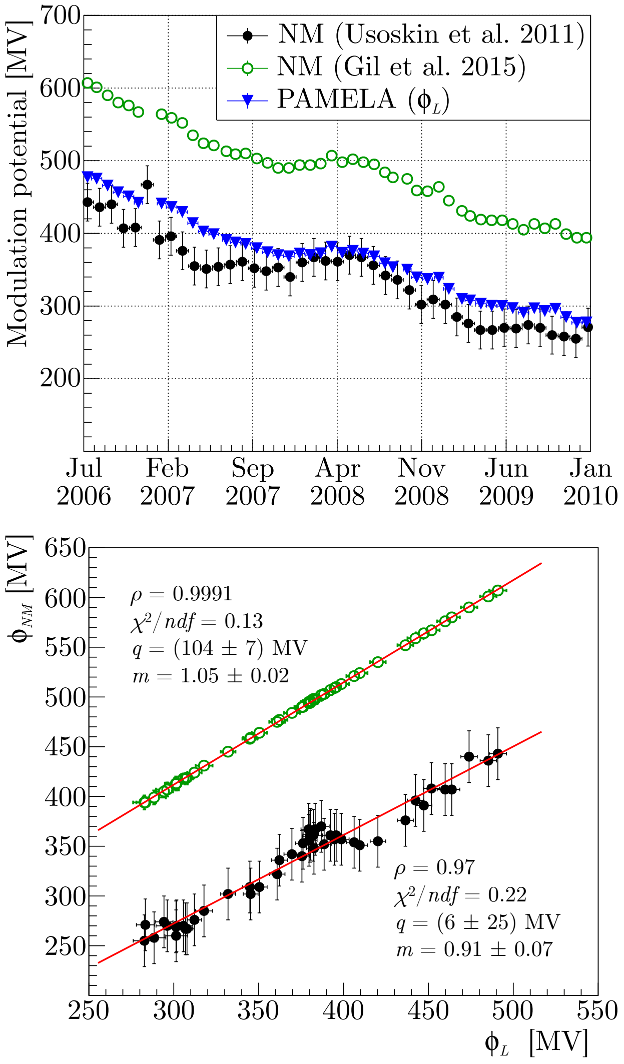

Figure 8. (Top) Low energy solar modulation parameter extracted from PAMELA monthly proton fluxes (down triangles) compared with the one derived from neutron monitors (filled and hollow dots). (Bottom) Correlation between ϕ_L and ϕ_{NM}; the solid lines are linear fits. A color version of this figure is available in the online journal.

With respect to Usoskin et al. (2011), Gil et al. (2015) use a new improved yield function that takes into account the effect of the finite lateral size of the atmospheric showers induced by GCRs (Mishev et al. 2013) and calibrate the normalization of different NM stations with the proton monthly fluxes measured by PAMELA. The very small difference between ϕ_L and ϕ_{NM} from (Usoskin et al. 2011) is by accident, since in this case, in addition to the different LIS used to fit the data, the yield function did not include the effect described in (Mishev et al. 2013). The comparison with ϕ_{NM} from (Gil et al. 2015) results in a better correlation ($\rho = 0.9991$ versus $\rho = 0.97$) and the shift of ≈ 100 MV is due only to the different LIS adopted in (Gil et al. 2015) with respect to the one used in this work. Figure 8 bottom shows the correlation between ϕ_L and ϕ_{NM} from the two cited works. Assuming that the linear relation between ϕ_L and ϕ_{NM}, shown in Figure 8 bottom, holds also for different periods of solar modulation, we can use the following expressions to compute the modulation parameter associated with the new parametrization of the proton LIS throughout the whole period of data taking of NMs:

$$\begin{aligned} \phi_L &= (1.10 \pm 0.08)\phi_{NM,Usoskin} - (7 \pm 27)\ \text{MV} \\ \phi_L &= (0.95 \pm 0.08)\phi_{NM,Gil} - (99 \pm 7)\ \text{MV}. \end{aligned} \tag{8}$$

5. CONCLUSIONS

A new parametrization of the proton LIS from 80 MV up to 2 TV has been derived in this work using the measurements of the proton flux performed by Voyager 1 and AMS-02. The LIS is characterized by two power-laws with breaks at (8.69 ± 0.49) GV and (410 ± 190) GV with a spectral index changing from -2.5794 ± 0.0059 to -2.853 ± 0.015 at low energy and to -2.674 ± 0.073 at high energy. The force-field approximation is not able to accurately describe the solar modulation measured by PAMELA during the minimum of solar cycle 23, therefore we introduce an energy-dependent modulation parameter that yields a better result for the PAMELA data. A linear relation between the published values of the modulation parameter derived from NMs and the one obtained in this work is given. With the availability of precise measurements directly from space, we can finally start to understand the details of the processes that cause the solar modulation of galactic cosmic rays. It would be interesting to see how the monthly proton fluxes measured by AMS-02 during the current solar maximum compares with the results presented in this work.

NOTE ADDED. During the completion of this work, we became aware of a related study by Ghelfi, Barao, Derome and Maurin. It focuses on the determination of interstellar proton and helium flux with splines. Both the data sets and methods used differ from those of our study, making the two analyses complementary. A comparison of their proton LIS (obtained with the force-field approximation) and ours (obtained with the energy-dependent solar modulation parameter) shows a very good agreement in the range 4 GV − 1 TeV, but with different uncertainties.

We would like to thank E. Stone and A. Cummings for the discussion about the Voyager 1 data; M. Potgieter for the fruitful discussion about the theoretical interpretation; I. Usoskin for the help with the neutron monitor comparison.

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APPENDIX

SOLAR MODULATION PARAMETERS FROM PAMELA PROTONS FLUXES

Date	ϕ	σ_{fit}	σ_{LIS}	ϕ_L	σ_{fit}	σ_{LIS}	ϕ_H	σ_{fit}	σ_{LIS}
2006/07/07 – 2006/07/26	490.9	3.8	3.4	477.3	4.0	4.0	445	14	17
2006/07/27 – 2006/08/22	485.3	3.6	3.3	475.2	3.7	3.9	420	14	17
2006/08/24 – 2006/09/19	474.0	3.6	3.3	465.7	3.8	3.9	393	14	17
2006/09/20 – 2006/10/16	463.8	3.5	3.2	456.5	3.7	3.8	379	14	17
2006/10/17 – 2006/11/12	459.9	3.5	3.2	450.8	3.7	3.8	392	14	17
2006/11/13 – 2006/12/04	451.8	3.5	3.2	442.1	3.7	3.8	388	14	17
2007/01/11 – 2007/02/02	447.3	3.6	3.1	441.0	3.8	3.8	358	15	17
2007/02/03 – 2007/03/02	442.4	3.6	3.1	436.2	3.8	3.7	354	15	17
2007/03/03 – 2007/03/29	436.5	3.5	3.1	429.3	3.7	3.7	359	15	17
2007/03/30 – 2007/04/25	420.2	3.5	3.0	414.0	3.6	3.6	338	15	17
2007/04/26 – 2007/05/22	409.5	3.5	3.0	402.5	3.6	3.6	336	15	17
2007/05/23 – 2007/06/17	406.2	3.4	3.0	398.8	3.6	3.6	338	15	17
2007/06/27 – 2007/07/16	398.7	3.5	3.0	390.9	3.6	3.5	334	15	17
2007/07/17 – 2007/08/12	394.7	3.4	2.9	387.5	3.6	3.5	326	15	17
2007/08/13 – 2007/09/06	395.7	3.5	3.0	385.3	3.7	3.5	352	15	17
2007/09/09 – 2007/10/06	388.6	3.4	3.0	379.5	3.5	3.5	339	15	17
2007/10/07 – 2007/11/02	382.6	3.4	2.9	374.0	3.5	3.5	329	15	17
2007/11/03 – 2007/11/29	376.1	3.3	2.9	369.9	3.5	3.4	303	15	17
2007/11/30 – 2007/12/27	375.5	3.4	2.9	368.4	3.5	3.4	310	15	17
2007/12/28 – 2008/01/23	380.2	3.4	2.9	372.2	3.5	3.5	322	15	17
2008/01/24 – 2008/02/19	379.4	3.4	3.0	370.1	3.5	3.5	333	15	17
2008/02/20 – 2008/03/17	380.6	3.5	3.0	372.6	3.6	3.5	321	15	17
2008/03/19 – 2008/04/14	392.3	3.6	3.0	381.7	3.7	3.5	358	16	17
2008/04/15 – 2008/05/11	382.2	3.6	2.9	373.2	3.7	3.5	335	16	17
2008/05/12 – 2008/06/07	386.9	3.6	3.0	375.9	3.7	3.5	360	16	17
2008/06/08 – 2008/07/04	383.3	3.7	3.0	372.1	3.8	3.5	354	16	17
2008/07/05 – 2008/08/01	379.7	3.7	3.0	368.3	3.8	3.5	352	16	17
2008/08/02 – 2008/08/28	369.6	3.7	2.9	358.8	3.8	3.4	340	16	17
2008/08/29 – 2008/09/11	362.2	3.7	2.9	353.4	3.8	3.4	316	16	17
2008/10/01 – 2008/10/21	360.9	3.6	2.9	350.0	3.7	3.4	336	16	17
2008/10/22 – 2008/11/18	345.3	3.4	2.7	339.4	3.6	3.3	277	16	17
2008/11/19 – 2008/12/15	344.8	3.4	2.8	337.1	3.5	3.3	296	16	17
2008/12/20 – 2009/01/11	350.4	3.6	2.9	338.9	3.6	3.3	338	16	17
2009/01/12 – 2009/02/08	332.0	3.4	2.8	323.5	3.5	3.2	293	16	17
2009/02/21 – 2009/03/07	317.8	4.2	2.8	309.6	4.3	3.3	272	19	17
2009/03/08 – 2009/04/03	312.2	3.3	2.6	307.7	3.5	3.2	235	16	17
2009/04/04 – 2009/05/01	307.8	3.2	2.6	303.1	3.4	3.1	236	16	17
2009/05/02 – 2009/05/28	306.9	3.3	2.6	300.3	3.4	3.1	256	16	17
2009/05/29 – 2009/06/24	305.7	4.9	2.5	300.0	5.0	3.1	263	28	17
2009/06/25 – 2009/07/21	301.3	4.7	2.4	297.0	4.8	3.0	241	28	17
2009/07/22 – 2009/08/18	294.2	4.7	2.4	290.7	4.8	3.0	223	28	17
2009/08/19 – 2009/09/14	301.6	4.8	2.4	296.9	4.9	3.0	249	28	17
2009/09/15 – 2009/10/11	296.1	6.3	2.4	293.1	6.5	3.0	220	39	17
2009/10/12 – 2009/11/07	301.4	6.3	2.4	296.1	6.4	3.0	264	39	17
2009/11/08 – 2009/12/05	288.4	6.4	2.3	284.7	6.6	3.0	224	40	17
2009/12/06 – 2010/01/01	282.7	6.3	2.4	276.9	6.4	2.9	257	39	17
2010/01/02 – 2010/01/23	283.3	4.8	2.4	277.5	4.9	3.0	249	28	17

Table 3

Solar modulation parameter in units of MV derived from PAMELA monthly proton fluxes. The error contributions from the fit of the PAMELA fluxes (σ_{fit}) and from the uncertainty on the LIS (σ_{LIS}) are reported separately. ϕ is the modulation parameter obtained with the force-field approximation, while ϕ_L and ϕ_H are the modulation parameters obtained with the modified force-field approximation.

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