A simulation study of galactic proton modulation from solar minimum to maximum conditions

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Abstract

The observation of various cosmic ray particles at the Earth had been done with the PAMELA space detector for almost 10 years, from June 2006 to January 2016. The AMS-02 space experiment provides similar cosmic ray data. The purpose of this work is to utilize the available state-of-the-art numerical modulation model for the transport of cosmic rays in the heliosphere to compute the modulation of galactic protons from minimum to maximum solar activity. These modeling results, which simulate realistic heliospheric conditions, are compared to proton observations from PAMELA taken between 2006 and 2010 and to similar AMS-02 observations after 2011. It will be shown how differently modulation mechanisms influence the time-evolution of the proton spectra when modulation conditions change from minimum to maximum, including a reversal of the polarity of the heliospheric magnetic field.

Introduction

This work focuses on studying the modulation of galactic protons from solar minimum to maximum conditions. A 3D numerical code, including all four major modulation processes, is applied to simulate galactic protons spectra between 2006 and 2017. The primary objective of the study is to establish necessary adjustment required in mathematical and numerical models with respect to the elements of the diffusion and drift tensor in the relevant transport equation in order to reproduce GCR observations at Earth. This work discusses element of diffusion coefficient parallel to the heliospheric magnetic field. To achieve this objective this study take advantage of simultaneous and continuous observations of galactic protons from the PAMELA [3] and AMS02 [2]. The computed spectra are directly compared to the observations to determine relevant adjustment to diffusion coefficients to reproduce observations at Earth.

Model

The model is based on the numerical solution of Parker's [1] transport equation (TPE):

$$-(\mathbf{V}+\langle\mathbf{v}_D\rangle)\cdot\nabla f+\nabla\cdot(\mathbf{K}_s\cdot\nabla f)+\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial lnP}+J_{source}=0,$$

where $f(\mathbf{r},P)$ is the cosmic ray distribution function; P is rigidity, $\mathbf{r}$ is position, and $\mathbf{V}$ is the solar wind velocity. The terms from left to right represent convection caused by expanding solar wind, gradient, curvature and HCS drifts, diffusion, adiabatic energy changes and a source function (in our case equal to zero), respectively. The diffusion tensor $\mathbf{K_s}$ consists of a parallel diffusion coefficient, $K_\|$, and two perpendicular diffusion coefficients in the radial direction $K_{\perp r}$ and in the polar direction $K_{\perp\theta}$. the general expression for $K_\|$ to the average background HMF, with magnitude B, is given by:

$$K_\| = \left(K_\|\right)_0 \beta\left(\frac{B_0}{B}\right)\left(\frac{P}{P_0}\right)^{c_1}\left[\frac{(\frac{P}{P_o})^{c_3}+(\frac{P_k}{P_o})^{c_3}}{1+(\frac{P_k}{P_o})^{c_3}}\right]^{\frac{c_{2\|}-c_1}{c_3}}, \quad (1)$$

where $\left(K_\|\right)_0$ is a scaling parameter in units of 10^{22} cm^2 s^{-1}, with P_0 = 1.0 GV and B_0 = 1.0 nT. The constants c as power indices, provide for two power laws and P_k specifies the rigidity at which the transition between the two power laws occurs

References

[1] E.N. Parker, *Planet. Space Sci.* 13, 9. 1965

[2] M. Aguilar et al., *PhRVL*, 141102, 110, 2013.

[3] O. Adriani, et al., *PhR*, 323, 544, 2014.

Modulation parameters

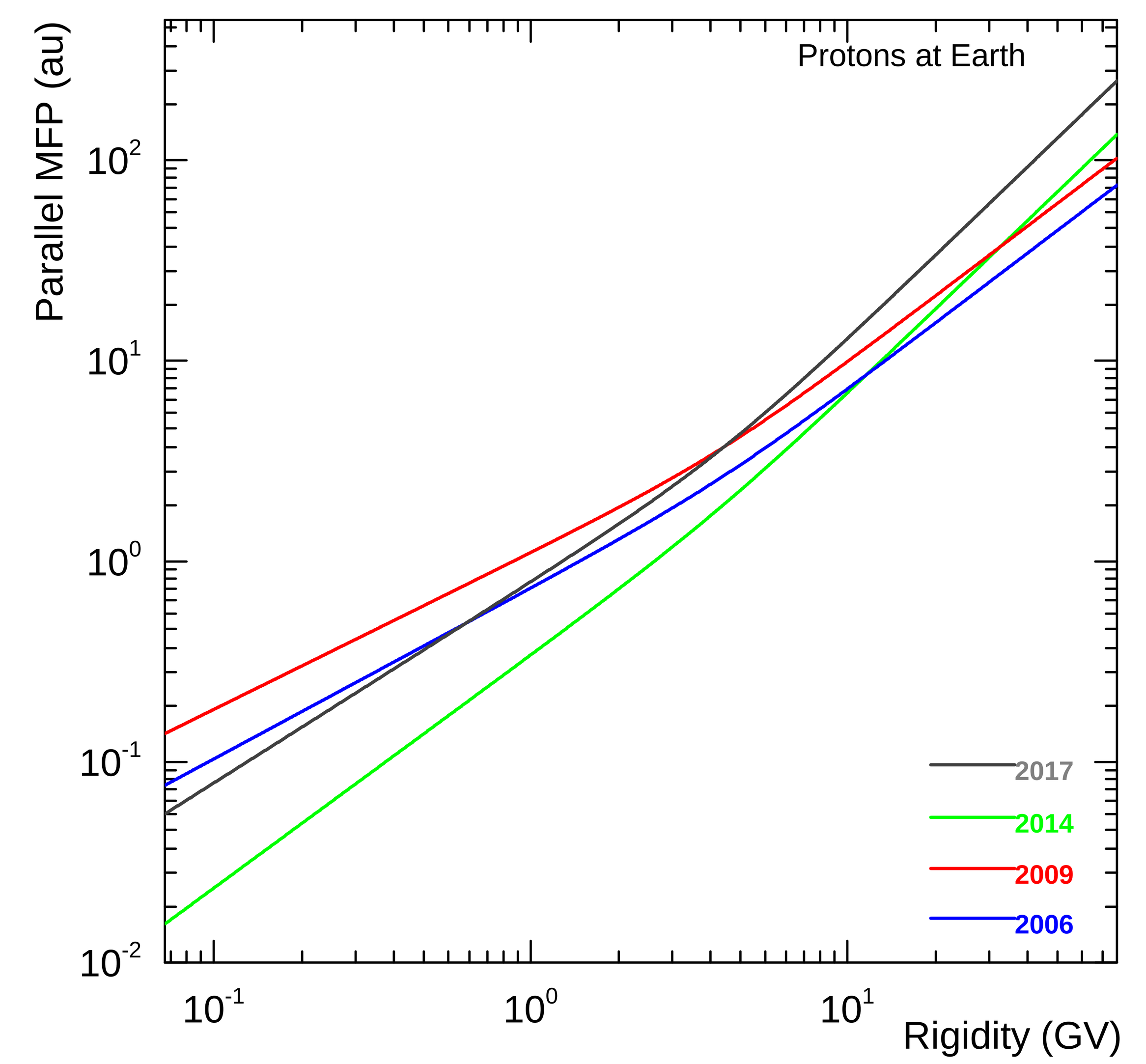

Figure 1. The rigidity dependence of $K_\|$, indicating the two power-law slopes, at Earth as the corresponding parallel mean free paths (MFP; $\lambda_\|$) for four selected times[for spectra shown in Figure 3]; with $K = \lambda(v/3)$ where v is the particle speed and $\beta = v/c$, with c the speed of light.

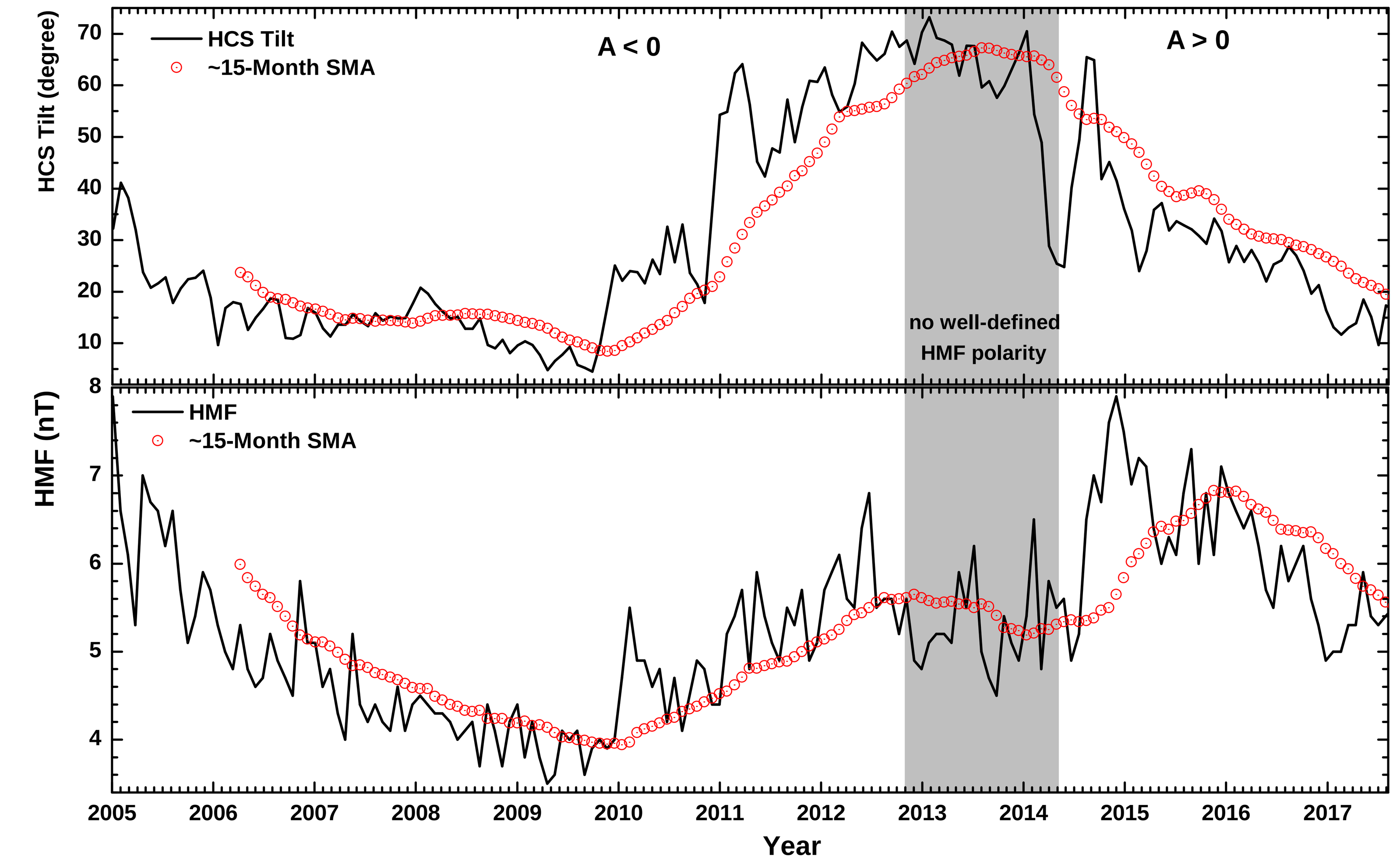

Figure 2. Top panel shows the tilt angle α of the HCS (black line) at the Earth from January 2005 to June 2017 taken from http://wso.stanford.edu along with 17 Carrington rotation (15 months) moving averages (red dots). Bottom panel shows the magnitude of the HMF at the Earth (black line) for the same period taken from http://omniweb.gsfc.nasa.gov, along with 17 Bartels (15 months) moving averages (red dots). Shaded portions indicate the estimated period of the polarity reversal of the HMF which is considered a period of no well-defined HMF polarity.

Simulated Spectra

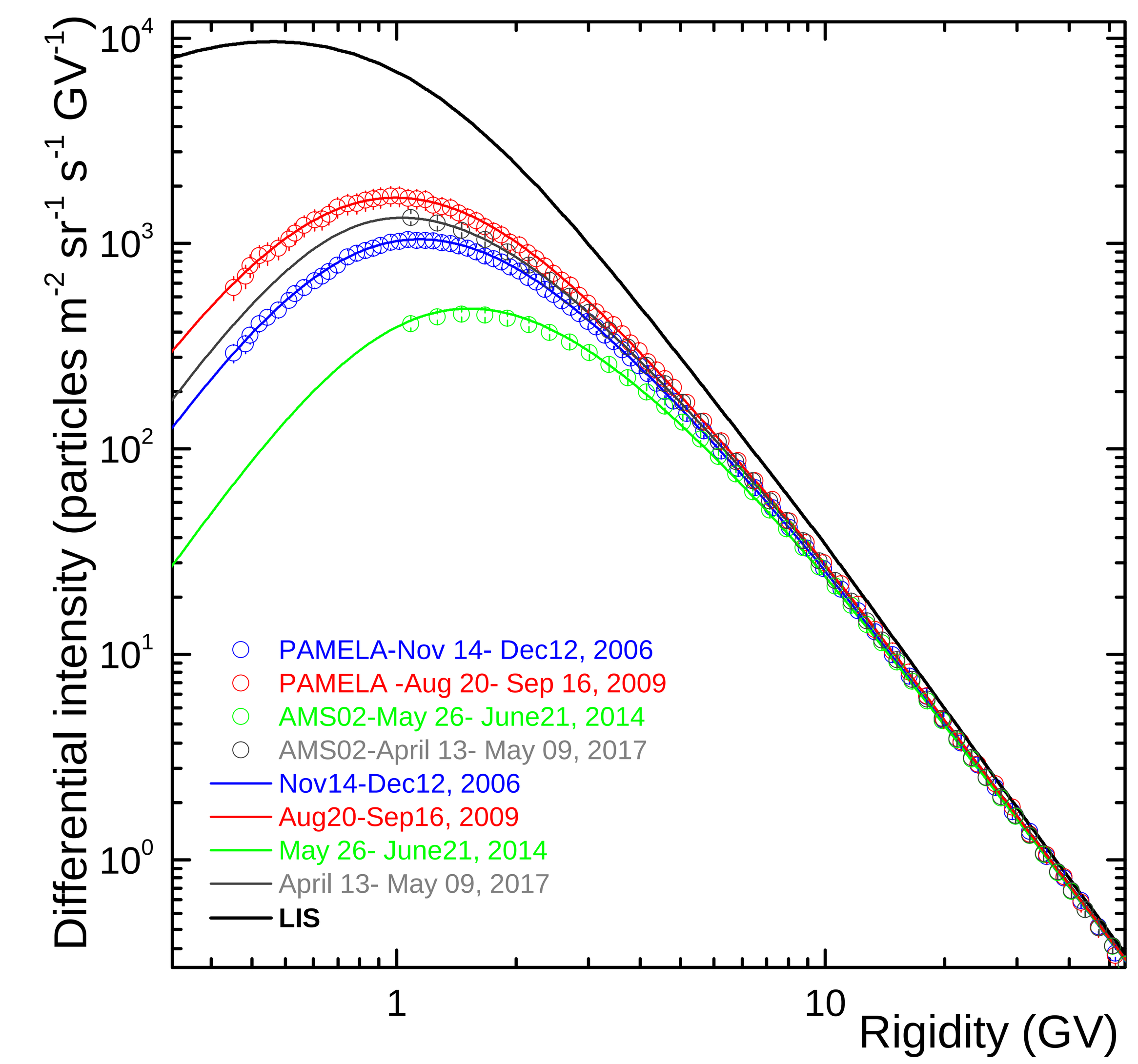

Figure 3. Modulated proton spectra (coloured lines) computed with respect to the very LIS at 122 au for protons (upper black solid line) during periods of different solar activity for selected times as indicated, and compared to PAMELA and AMS02 observations at Earth as indicated by open coloured circles.

Power indices and constants

To achieve spectra compatible to observation as shown in Figure 3, a different rigidity dependence had to be assumed, as shown in the first figure 1, by changing the value of $\left(K_\|\right)_0$ and c_1 in Eq. 1 with time as shown in Table 1 for the years from 2011 to 2017; here indicated in six months intervals.

Parameter	2011a	2012a	2013a	2014a	2015a	2016a	2017a
CR	2426	2440	2453	2467	2480	2494	2506
c_1	0.81	0.90	1.01	1.16	1.25	1.25	1.0
$\left(K_\|\right)_0$	51.443	45.743	33.021	27.460	30.240	50.262	68.128
Parameter	2011b	2012b	2013b	2014b	2015b	2016b	
CR	2433	2447	2460	2474	2487	2501	
c_1	0.87	1.01	1.14	1.10	1.28	1.14	
$\left(K_\|\right)_0$	49.150	38.166	26.764	32.326	41.363	64.304	

Table 1. Power indices and constants used in Eq. 1 to reproduce the observed proton spectra for every six-months period of each year, from 2011 to 2017; CR indicates Carrington rotation.

Summary and Conclusion

.A 3D numerical model has been applied to compute proton spectra that in all respects are compatible with PAMELA and AMS02 observations. It follows from this comparison of simulated spectra with precise observations how the rigidity dependence of the parallel diffusion coefficient for protons needs to change with solar activity to reproduce observations from 2006 to 2017.