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Reconstruction of solar modulation potential from AMS-02 daily data for the period 2011 – 2019 and its comparison with indirect cosmic-ray measurements

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Force-field approximation (FFA) of Parker's solar modulation equation is a simplification widely used for practical purposes. The wide use of FFA is motivated by the fact that the modulation strength can be described, with reasonable accuracy, using a single variable parameter ϕ, which is called the solar modulation potential. While FFA does not allow us to study the solar modulation process in detail, the one-parameter feature is useful, especially in the context of energy- and particle-integrating detectors, such as neutron monitors and cosmogenic isotopes, which allows for studies of solar modulation on timescales beyond the direct measurements. New daily data on proton and helium fluxes measured by cosmic-ray experiment AMS-02 for the period from 2011 to 2019 open new opportunities in the verification of the FFA of the solar modulation equation on a daily basis and in a systematic comparison of the solar modulation deduced from different detectors (including energy-integrating ones). In this work, we reconstruct the solar modulation potential from daily AMS-02 data, compare it to daily solar modulation potential values reconstructed from NM data, and discuss the proper way to evaluate the solar modulation potential from different detectors to make them comparable.

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1. Introduction

Galactic cosmic rays (GCRs) are charged particles accelerated in different sources in our Galaxy. The local GCR spectrum, known as the local interstellar spectrum (LIS), is believed to be constant before entering the heliosphere. Within the heliosphere, GCR fluxes are subject to the solar modulation process, which alters the observed GCR flux. Parker's transport equation [1] describes this modulation process, incorporating convection, particle drifts, diffusion, and adiabatic energy changes [2]. The force-field approach (FFA) [3] provides a solution to simplified Parker's equation using a single parameter called the solar modulation potential ϕ. Despite its limitations [4], the FFA is widely used, especially when detailed studies of solar modulation physics are not feasible.

The last two decades have seen exceptional advancements in GCR observations and modeling, including also the effects of solar modulation. High-precision, time-dependent direct measurements of GCRs have been made by the PAMELA [5–10] and AMS-02 [11–15] experiments. In the same time Voyager spacecraft [16–18] have performed the LIS observations outside the heliosphere. This led to significant advances it the full modeling of Parker equation (e.g., [19–21]). Prior to 2005, GCR observations were limited, with neutron monitors (NMs) being a crucial source of information on long-tern solar modulation. NMs register secondaries produced by primary cosmic rays in the atmosphere, providing integrated measurements of cosmic ray fluxes [22]. Neutron monitors located worldwide with varying cutoff rigidity allow for the estimation of cosmic-ray modulation within FFA [23, 24]. Additionally, information on GCR fluxes within FFA can be obtained from cosmogenic isotopes (CIs) deposited in tree rings and ice cores, providing insights into GCR variability over longer timescales [25].

Therefore, it is essential to achieve consistency between direct and indirect measurements of GCRs to quantify solar modulation on different timescales. However, different methods of reconstructing ϕ from various data sources can lead to significant uncertainties and discrepancies. This issue has been highlighted previously in comparison between neutron monitors and cosmogenic isotopes [26].

In this study, we address this issue by incorporating precise measurements of GCR spectra obtained from daily data on proton fluxes by the AMS-02 experiment, reconstructing the ϕ value from the data and comparing it with the recent ϕ reconstruction from NM data [24].

2. Force-field approach

FFA allows to "modulate" the LIS spectrum within the heliosphere using the following expression:

$$J(T) = J_{\mathrm{LIS}}(T + \Phi)\frac{T(T + 2M/A)}{(T + \Phi)(T + \Phi + 2M/A)}, \tag{1}$$

where J_{LIS} is GCR spectrum (LIS) outside the heliosphere, M represents the rest mass of GCR particle in eV, A is a number of nucleons and $\Phi = e(Z/A)\phi$, where Z is a charge, e an elementary charge, and ϕ being modulation potential. FFA is heavily simplified in comparison to the full solution of Parker's modulation equation [4, 27] and does not allow capturing some features of solar modulation. However, it is extremely useful for quantification of the GCR variability and related solar activity over long timescales [25, 28].

Depending on the data in use, the procedure of estimation of solar modulation potential will be different. When working with direct GCR measurements, one can fit the data and the model, minimizing the difference between them (however, even here some attention should be paid to details, as we will show in this paper). In case of indirect cosmic-ray measurements performed, e.g., by NMs and CIs, one needs to find such a value of ϕ, which, integrated with the yield function of a given detector (e.q., [22, 29]), will give an NM or CI response comparable with the measurements. The difference in the energy dependence of yield functions of different detectors results in fact that ϕ values deduced from different indirect data should be corrected. For this purpose, the linear relationship was shown to be sufficient [26].

3. Solar modulation potential during 2011 – 2019 from AMS-02 daily data

For this analysis, we used the daily GCR proton flux measurements [13] performed by the AMS-02 experiment for the period from May 2011 to December 2019. Original AMS-02 includes only GCR fluxes, while data with possible registration of solar energetic particles are excluded (on an energy-bin-wise basis) from the analysis. For dataset purity, we did not use daily data with excluded energy bins.

For the reconstruction of solar modulation potential, we used a standard χ^2 approach which minimizes the difference between observed and modeled data.

During the ϕ reconstruction, we noted several features which are important to highlight.

First, the relative flux uncertainty of proton fluxes is energy-dependent, being a function of collected statistics and systematic uncertainties from the detector simulation, etc. Despite on clear nature of this effect, using the uncertainty in the fitting procedure will produce additional weighting to the fitting procedure, increasing the weight of energy bins with lower relative uncertainties.

Second, the reported AMS-02 daily proton flux energy binning is not evenly distributed in linear nor logarithmic scale. That indirectly adds additional weight to the fitting procedure.

To illustrate these features, we considered four scenarios, which are called models (M1 – M4) thereafter:

- M1: provided in the paper energy binning; uncertainties are taken to be 10% of flux value;
- M2: provided in the paper energy binning; uncertainties are taken as provided in the paper;
- M3: rebinned to be logarithmically uniform (using the linear interpolation for logarithmic values); uncertainties are taken to be 10% of rebinned flux value;
- M4: rebinned to be logarithmically uniform; uncertainties are rebinned correspondingly.

Testing of models M3 and M4 is motivated by the fact that the energy binning in AMS-02 daily proton is not logarithmically uniform. Therefore, we wanted to check what effect can introduce different energy binning, which can be necessary for comparing direct cosmic-ray measurements and deduced ϕ values, especially for cosmic-ray experiments operated in not intersected periods of time.

We plot on Figure 1 the best-fit solutions obtained for considered scenarios. For all calculations shown here, the fitting range was chosen to be from 1 to 30 GeV. One can see that different models

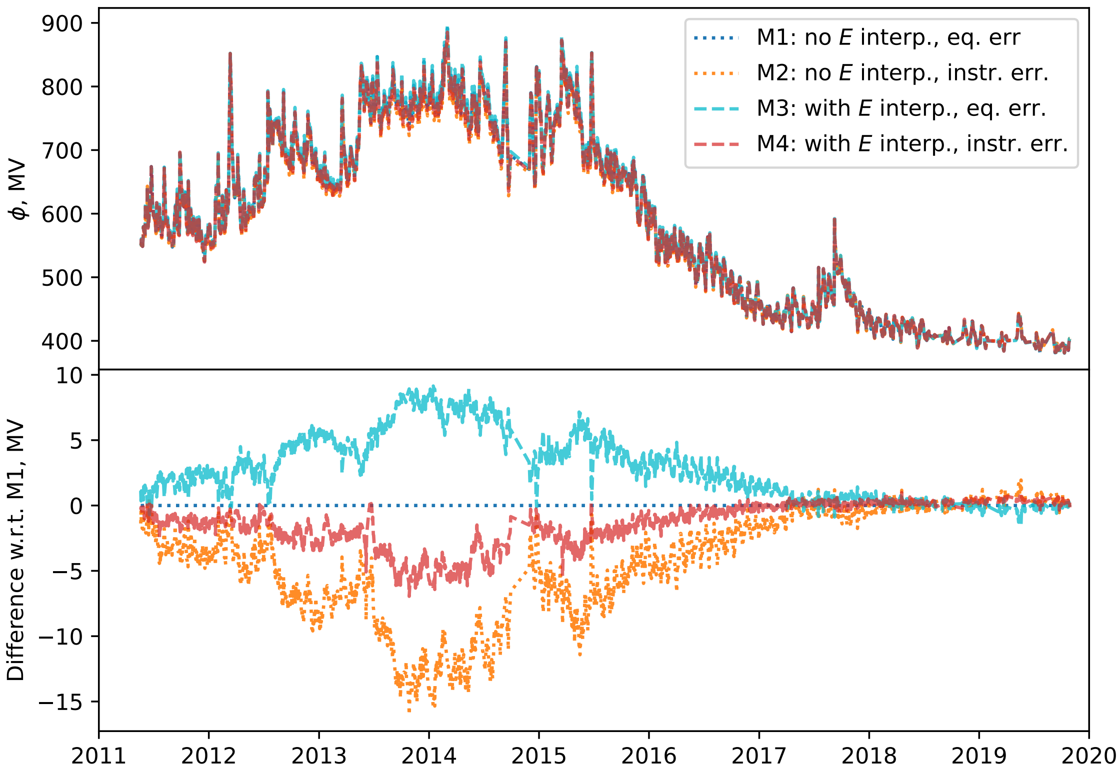

Figure 1: Solar modulation potential values deduced for AMS-02 daily proton data for 2011 – 2019 for models M1 – M4 described in the text. Different colors and line styles correspond to different fitting features (models), as denoted in the legend. The lower subplot shows the difference between model M1 and other models.

of fitting result in different ϕ values with clear solar-cycle dependence. However, the magnitude of the difference is not big, changing by 3% between different models. However, we emphasize that the comparison was performed for the solar cycle 24, which was much weaker in comparison to previous ones [30]. For solar cycles with higher activity, the magnitude of differences can be probably higher.

4. Testing the binning range and comparison with data from NM network

Next, we tested how different choice of the fitting range changes the obtained numerical values of ϕ. For that purpose, we used M1 as our reference model and created four submodels with different starting bin of energy E_{low} for the fitting procedure, ranging from 1 to 4 GeV. Next, we compared obtained results with the recently updated ϕ reconstruction performed with the data from the data from polar NMs [24] in the Fig. 2. NMs are energy-integrating detectors whose response is the count rate per time unit. To model the NM response, one needs to know the spectrum of cosmic-ray particles and the yield function, which incorporates the development of the shower of secondary particles in the atmosphere and its registration by NM. Recently, the YF calculated by Mishev et al. 2020 [22] calculated using Monte-Carlo simulations was validated using AMS-02 data with

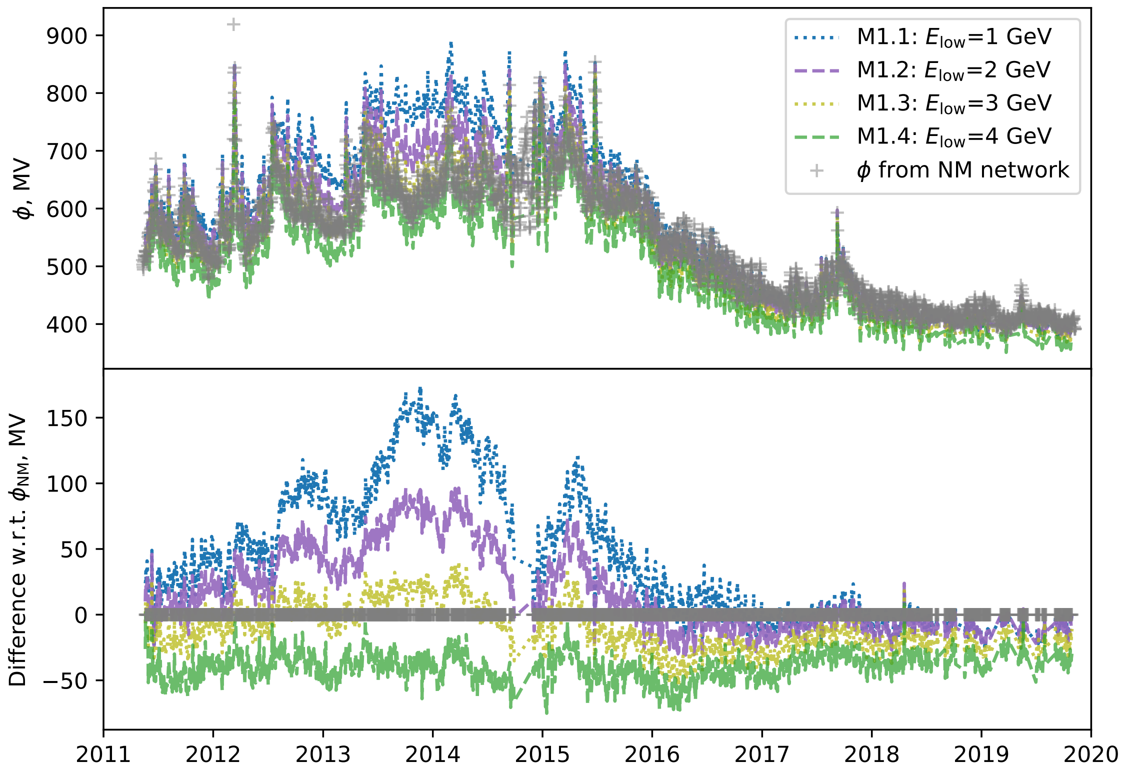

Figure 2: Comparison of ϕ values deduced from the AMS-02 daily data for protons considering different choices of the first energy bin (from 1 to 4 GeV) and ϕ values reconstructed from the NM network [24]. The lower subplot shows the difference between ϕ deduced from NM data and ϕ obtained from AMS-02 data.

Bartels rotation time cadence [11]. For the study of Väisänen et al. [24], this yield function was used together with the selection of data from different NMs [31].

The comparison shows a significant difference (up to 30%) between ϕ values obtained with different choices of E_{low}, especially around the maximum of solar activity. ϕ values obtained from the NM network show satisfactory agreement (within 5%) with the M1.3 model, which corresponds to E_{low}=3 GeV.

5. Conclusion

In this short communication, we emphasize the importance of fitting features when discussing numerical values of solar modulation potential ϕ obtained from direct cosmic-ray measurements or ground-based NMs. Additional study is needed to cover other complications, such as different choices of LIS and also the modulation of heavier-than-helium cosmic rays. We also made a comparison with ϕ values obtained from the NM network and show that they are in good agreement with ϕ numerical values obtained from daily AMS-02 proton data with a choice of lower energy boundary to be 3 GeV.

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