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Neutron monitors and muon detectors for solar modulation studies: 2. ϕ time series

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Abstract

The level of solar modulation at different times (related to the solar activity) is a central question of solar and galactic cosmic-ray physics. In the first paper of this series, we have established a correspondence between the uncertainties on ground-based detectors count rates and the parameter ϕ (modulation level in the force-field approximation) reconstructed from these count rates. In this second paper, we detail a procedure to obtain a reference ϕ time series from neutron monitor data. We show that we can have an unbiased and accurate ϕ reconstruction ($\Delta\phi/\phi \simeq 10\%$). We also discuss the potential of Bonner spheres spectrometers and muon detectors to provide ϕ time series. Two by-products of this calculation are updated ϕ values for the cosmic-ray database and a web interface to retrieve and plot ϕ from the 50's to today (http://lpsc.in2p3.fr/crdb).

Keywords: Solar modulation; Cosmic rays; Neutron monitor; Muon detector

1. Introduction

Measurements of top-of-atmosphere (TOA) cosmic-ray (CR) fluxes show a clear modulation related to solar activity (Usoskin, 2013). The imprint of the 11-year solar cycle is present in secondary particles created in the Earth atmosphere (Dorman, 1974; Dorman, 2004; Dorman, 2009), as seen in neutron monitor data (Simpson, 2000). Despite being an integral measurement (top-of-atmosphere fluxes folded by the atmosphere and instrument response), ground-based detectors have been providing monitoring of solar activity since the 50's, on a much finer timescale than balloon-borne and space experiments can achieve, even today.

In this work, we wish to provide a consistent description of modulation levels for cosmic-ray data. This is important in the context of galactic CR physics as clues on CR sources (Blasi, 2013) and constraints set on CR transport parameters (Strong et al., 2007) are based on modulated CR data. Similarly, dark matter indirect detection (Lavalle and Salati, 2012) involves low energy modulated antiproton and antideuteron fluxes. Unfortunately, the set of modulation levels provided for space or balloon-borne CR data (from the original publications) is not homogeneous and very patchy (Maurin et al., 2014): each value, when existing, is based on different assumptions regarding the IS spectrum (fitted to the experiment data, or resulting from different CR propagation models) and the modulation model (from force-field to sign-charge dependent drift models). This situation is inadequate and unsatisfactory.

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Providing homogeneous modulation levels for past and present CR experiments or providing $\phi(t)$ time series are complementary tasks. In the context of the force-field approximation (Gleeson and Axford, 1967, 1968), homogeneous monthly time series have been derived from NM data (Usoskin et al., 1999, 2002, 2005, 2011) since July 1936. Note however, that many experiments operate on a shorter timescale, during which solar activity can significantly depart from the monthly average. This is especially true during solar maximum periods. Moreover, in the last years, the PAMELA[1] (Adriani et al., 2011, 2013a,b) and AMS[2] (Aguilar et al., 2015a,b) experiments provided high precision proton and helium fluxes. The latter can be used to improve the IS flux description (Bisschoff and Potgieter, 2016; Corti et al., 2015; Ghelfi et al., 2016), and in a second step the accuracy of ϕ time series.

Our approach is based on Usoskin et al. (2011), with several differences. We build on our recent analysis of the uncertainties on ϕ reconstruction from ground-based detectors data (Maurin et al., 2015, hereafter Paper I). We also take advantage of our recent re-estimate of the interstellar (IS) proton and helium fluxes (Ghelfi et al., 2016). The robustness and consistency of ϕ time series from NM data (retrieved from the Neutron Monitor Data Base, NMDB[3]) are validated against GCR data ϕ values and compared to other ground-based detector data.

The paper is organised as follows. In Section 2, we recall how IS spectra are modulated and folded by the yield function of ground-based detectors, whose data are used to reconstruct ϕ time-series. In Section 3, we discuss the enhancement factor to account for heavy CR contributions to count rates. In Section 4, the procedure to calculate the correction factor of a NM station is detailed. In Section 5, we calculate and compare ϕ time-series (and their uncertainties) as obtained from NM, GCR, Auger scaler, or neutron spectrometer data. We conclude in Section 6. Along with the paper, we provide an online application to calculate, at any time in the past, ϕ values (for any time period) based on the methodology presented in this paper.

2. Solar modulation and count rates from ground-based detectors

Count rate detector calculations and measurements, and their dependence on the environment (geomagnetic field, meteorological effects, yield function, etc.) are presented in the comprehensive monographs of Dorman (1974, 2004, 2009). We briefly recall the ingredients of the calculation and our assumptions.

2.1. From count rates to modulation parameters

A ground-based detector $\mathcal{D}$ at $\vec{r} = (\varphi, \lambda, h)$ measures, at time t, a count rate $N^{\mathcal{D}}(\vec{r}, t)$:

$$N^{\mathcal{D}}(\vec{r}, t) = \int_0^\infty \mathcal{T}(R, \vec{r}, t) \times \sum_{i=\text{CRs}} \mathcal{Y}_i^{\mathcal{D}}(R, h)\, \frac{dJ_i^{\text{TOA}}}{dR}(R, t)\, dR, \tag{1}$$

where

- $\mathcal{T}(R, \vec{r}, t)$ is the transmission function in the geomagnetic field. In practice, it is very often approximated by an effective vertical rigidity cutoff R_c^{eff} (see, e.g., Cooke et al., 1991, for definitions), and this is the approach we follow here for simplicity. As discussed in Paper I, using the apparent cutoff rigidity or a sigmoid can lead to up to 50 MV differences on the reconstructed ϕ values (stations with $R_c^{\text{eff}} \lesssim 5$ GV are less sensitive to this effect).
- $\sum_{i=\text{CRs}}$ runs over all CR species. In practice, the He flux is rescaled by $(1 + s_{Z>2})$ in order to sum over $i = \text{H}, \text{He}$ only. The factor $s_{Z>2}$ accounts for the contribution of species heavier than He (Webber and Higbie, 2003; Usoskin et al., 2011; Maurin et al., 2015), relying on the fact that the yield function for a CR nucleus of atomic mass A is A/4 times that of a CR helium (Mishev and Velinov, 2011). The analysis presented here updates the discussion of Paper I, regarding $s_{Z>2}$ and its uncertainties.
- $\mathcal{Y}_i^{\mathcal{D}}(R, h)$ is the yield function, i.e. the detector response at altitude h in count m^2 sr to a unit intensity of primary CR species i at rigidity R. Yield functions are evaluated from the network of NMs (Nagashima et al., 1989, 1990; Caballero-Lopez and Moraal, 2012) or from Monte Carlo simulations (Clem, 1999; Clem and Dorman, 2000; Flückiger et al., 2008; Matthiä et al., 2009; Mishev et al., 2013; Cheminet, 2013). Our results are based on the Cheminet yield function (denoted C13) discussed in Paper I, but we also discuss how using other parametrisations (gathered in App. B of Paper I) affect the results. We underline that all Monte Carlo-based calculations used in this study take into account the geometrical correction factor discussed in Mishev et al. (2013), which better fit the latitudinal survey count-rates (see Paper I and Gil et al., 2015).
- dJ_i^{TOA}/dR is the top-of-atmosphere (TOA) modulated differential flux per rigidity interval dR for the CR species i in m^{-2} s^{-1} sr^{-1} GV^{-1}. TOA fluxes are obtained from a modulation model (and its parameters) applied to IS fluxes.
  - Modulation model: in this study, we use the force-field approximation (Gleeson and Axford, 1967, 1968), in which, for a given species i,

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[1] http://pamela.roma2.infn.it.

[2] http://www.ams02.org.

[3] http://www.nmdb.eu.

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