Assessment of Source and Transport Parameters of Relativistic SEPs Based on Neutron Monitor Data

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As part of the HESPERIA Horizon 2020 project, we developed a software package for the direct inversion of Ground Level Enhancements (GLEs) based on data of the worldwide network of Neutron Monitors (NMs). The new methodology to study the release processes of relativistic solar energetic particles (SEPs) makes use of several models, including: the propagation of relativistic SEPs from the Sun to the Earth, their transport in the Earth's magnetosphere and atmosphere, as well as the detection of the nucleon component of the secondary cosmic rays by ground based NMs. The combination of these models allows to compute the expected ground-level NM counting rates caused by a series of instantaneous particle releases from the Sun. The proton release-time profile at the Sun and the interplanetary transport conditions are then inferred by fitting NM observations with modeled NM counting rates. In the paper the used models for the different processes, the software and first findings with the new software are presented.

I. INTRODUCTION

The worldwide network of neutron monitors (NMs) together with the Earth's magnetic field acts as a huge spectrometer for cosmic rays (CRs) in the energy range ∼500 MeV to ∼15 GeV. The NM measurements are particularly useful for the quantitative investigations of energetic solar cosmic ray (SCR) events, so-called Ground Level Enhancements (GLEs). During the last decades NM data during GLEs were used to assess the characteristics of SCR near Earth, i.e. the transport in the interplanetary space was not included in these analyses and thereby no information about the SCR characteristics at the solar source could be derived.

As part of the HESPERIA Horizon 2020 project a new approach was developed, i.e. a software package for the direct inversion of GLEs based on NM data. With the new GLE inversion software it is possible to directly assess the release timescales of relativistic SEPs at the Sun and the characteristics of their transport in interplanetary space based on NM observations of the worldwide network. Goals of the new GLE inversion software are to learn about the high-energy processes that release high energy (>500 MeV) protons at the Sun and about the processes that affect their propagation in the interplanetary space up to the Earth orbit.

The procedure uses several models: propagation of relativistic SEPs in the interplanetary space from the Sun to the Earth, transport in the geomagnetosphere and in the Earth's atmosphere as well as the detection of the nucleon component of the secondary CRs by the NMs. The concept is summarised in Fig. 1.

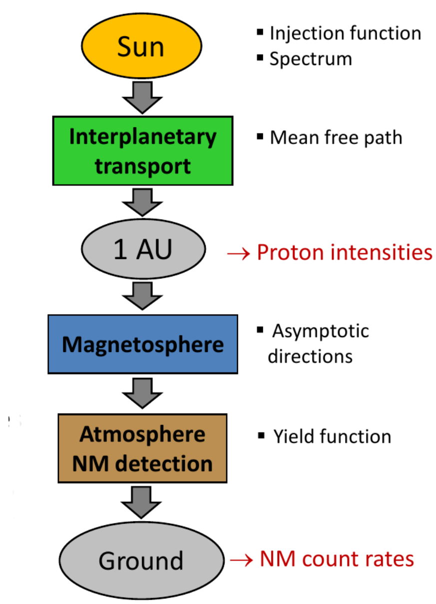

FIG. 1: Computation of the NM response to a particle release at the Sun.

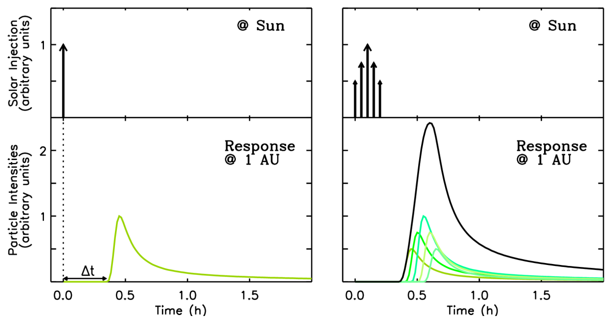

FIG. 2: Impulsive injection (delta function) at the Sun and the resulting response at 1 AU (left) and the superposition of impulsive injections and the corresponding response at 1 AU, i.e. the sum of series of impulse responses.

II. TRANSPORT FROM THE SUN TO THE EARTH

A. Injection of SEPs at the Sun and interplanetary transport of relativistic solar protons

The injection profile at the Sun is described by a superposition of impulsive (delta) injections of particles at a given starting time. It is assumed that the solar source spectrum of the released solar protons has the form of a power law in rigidity with spectral index γ ($dN/dR \propto R^{-\gamma}$). The duration and the dependence of the particle release process as well as γ is determined in the inversion procedure.

The interplanetary transport models provide the response of the system to an impulsive (delta) injection at the Sun, i.e. the Green's function of particle transport. Figure 2 shows an example of the output of the system (i.e. particle intensities at 1 AU from the Sun) for a well defined input such as a delta function at the Sun (left panel) as well as the superposition of impulsive injections (right panel).

In an unperturbed solar wind, the interplanetary magnetic field (IMF) can be described as a smooth average field, represented by an Archimedean spiral, with superposed magnetic fluctuations. In this case, the propagation of SEPs along the IMF is affected by both the effects of adiabatic motion along the smooth field and pitch angle scattering by magnetic turbulences. The quantitative treatment of the evolution of the particle's phase space density, $f(z, \mu, t)$, can be described by the focused transport equation [1]:

$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial z} + \frac{1-\mu^2}{2L}v\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = q(z,\mu,t) \qquad (1)$$

Here z is the distance along the magnetic field line, $\mu = \cos\alpha$ is the cosine of the particle pitch angle α, and t is the time. The systematic force is characterized by the focusing length, $L(z) = -B(z)/(\partial B/\partial z)$, in the diverging magnetic field B, while the stochastic forces are described by the pitch angle diffusion coefficient $D_{\mu\mu}(\mu)$. The injection of particles close to the Sun is given by $q(z, \mu, t)$. This simple form of the transport equation neglects convection and adiabatic deceleration (see [2] for the full equation), but for relativistic protons, this is typically a small effect. The effects of diffusion perpendicular to the average magnetic field and drifts [3] are also neglected. Instead, it is assumed that there is no variation across the magnetic field, and that the respective solutions are identical in neighboring flux tubes. A further limitation of the software in the present form is that it is not usable for the study of events that show bidirectional pitch angle distribution.

Analytical solutions of the focused transport equation are not known and numerical methods are applied to solve the focused transport equation. A Monte Carlo transport model [4] is used to compute the proton intensities expected at 1 AU assuming that the solar source is static at two solar radii, the particle release is instantaneous and that particles are hypothetically moving at the speed of light. These Green's functions of particle transport for $v = c$ can be scaled to provide the Green's functions for any other monoenergetic particles. As an example Fig. 3 shows the omni-directional intensities and pitch angle distributions expected at 1 AU for several rigidity values, assuming a solar wind speed of 400 km s^{-1}, a mean free path for pitch angle scattering $\lambda_0 = 0.2$ AU and a spectral index $\gamma = 3$ for the rigidity spectrum at the source.

B. Transport in the Earth's magnetosphere

In the geomagnetosphere, where the magnetic field (25-65 μT at the Earth's surface) is stronger than in the interplanetary space (typical 5 nT), CR particles are stronger deflected. The CR particle trajectories in the Earth's magnetic field are computed by numerical integration of backward trajectories in a model of the geomagnetic field, see e.g. [5]. Thereby the effect is used that the path of a negatively charged particle with mass, m, charge, q, and speed, v, in a static magnetic field, B, is identical to that of a positively charged particle but with reverse sign of the velocity vector. Therefore, the common method to compute CR trajectories in the geomagnetic field is to calculate the trajectory in the reverse direction, i.e. the starting point of the reverse trajectory calculation is above the observation location in question at an altitude of typically 20 km asl.

The asymptotic directions for all NM stations and for all historic GLEs, from GLE 1 through 71, were computed every 15 minutes using the software suite PLANETOCOSMICS [6]. The geomagnetic field is described by the IGRF model for the magnetic field

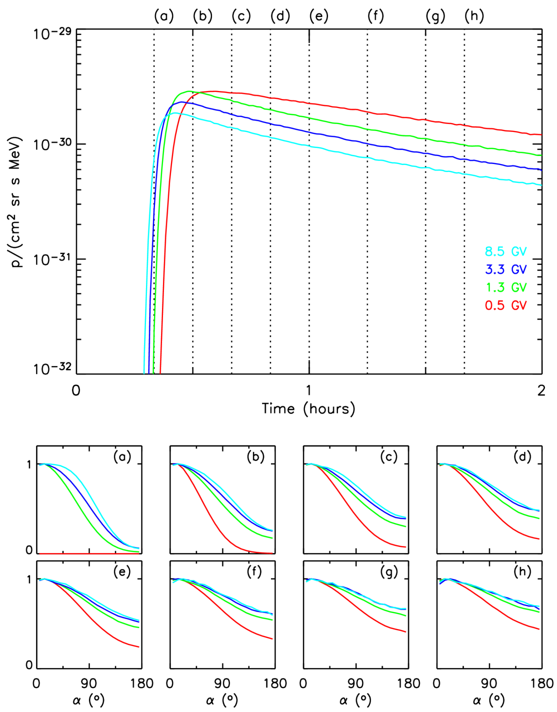

FIG. 3: Top: Proton omni-directional intensities at 1 AU for selected rigidities assuming v_{sw} = 400 km s^{-1}, λ_0 = 0.2 AU and γ = 3. Bottom: Corresponding pitch angle distributions for selected rigidities at eight different times (marked by the vertical lines in the top plot).

contributions caused by sources in the Earth's interior and the Tsyganenko 1989 model [7] describing the magnetic field caused by current systems within the geomagnetosphere.

C. Transport in the atmosphere and the detection of secondary cosmic rays by the neutron monitors

The transport of CR particles through the Earth's atmosphere and the detection of the nucleonic component of the secondary CRs are combined in the so-called NM yield function. Thereby the NM yield function can directly be used to determine the CR flux at the top of the Earth's atmosphere from the worldwide measurements of NMs.

In the current version of the GLE inversion software only the NM yield function for primary protons as determined by [8] is integrated. This yield function is based on Monte Carlo calculations with Geant4 [9] for the transport in the Earth's atmosphere as well as for the efficiency of the NM for nucleons.

The comparison of the results of different GLE analysis for a single GLE in the past have shown that the results may differ considerably [10]. The main reason for this behavior may be that different yield functions were used. Hence it is planned that also yield functions as published by other authors will be integrated in the GLE inversion software in the future.

III. SOFTWARE

The GLE inversion software suite, written in the programming language "Python", includes several stand-alone modules. To run this software, the user needs to consider two main blocks. The first one (Modules 1-3) concerns the storage of the data needed for the GLE inversion. The second block (Module 4) is the actual GLE inversion.

Module 1: To provide access to NM data using the NEST tool under the web page of NMDB (Neutron Monitor Data Base, http://www.nmdb.eu), allowing a direct retrieval from NMDB to the users computer.

Module 2: To download the asymptotic directions of NM stations for the selected time of the GLE under investigation from the HESPERIA webpage.

Module 3: To download OMNI magnetic field data in GSE coordinates and perform time averages to get an estimation of the predetermined axis of symmetry SCR angular distributions. This magnetic field direction is used to compute the pitch angles observed by each NM station, i.e. the angles between the magnetic field direction and the asymptotic directions of the NM station.

Module 4: To compute the count rate increases for each selected NM station based on the modeled intensities of CR particles and to perform the inversion using the data recorded by the selected NMs and the simulated count rates.

The following parameters are determined by the GLE inversion software: the series of instantaneous releases from the Sun, the source spectral index, γ, and the mean free path, λ_0.

IV. CASE STUDY: GLE ON 15 APRIL 2001

As a first case study the GLE inversion software was applied during the GLE on 15 April 2001 (GLE60). Figure 4 shows the injection profile at the Sun, the mean free path for scattering in the interplanetary space λ_0 = 0.12 AU, and power law index γ = 6 for rigidity spectrum at the source. These characteristics best fit the measured data of the selected NM stations Apatity, Calgary, Fort Smith, Irkutsk, Kerguelen, Kiel, Nain, McMurdo, Oulu, Rome, Terre Adelie, and Tixie Bay in the time interval 1345–1545 UT. In Fig. 5 the simulated and measured relative count rate

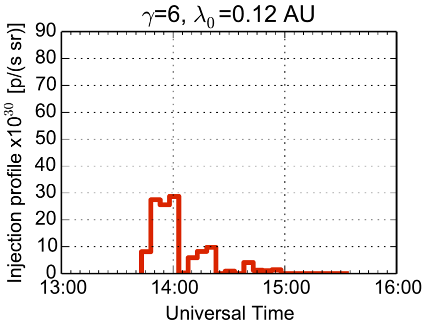

FIG. 4: Series of instantaneous releases at the Sun during the GLE on 15 April 2001 that best fits the measured data of the selected NMs with $\lambda_0 = 0.12$ AU and $\gamma = 6$ when applying the GLE inversion software introduced in this work.

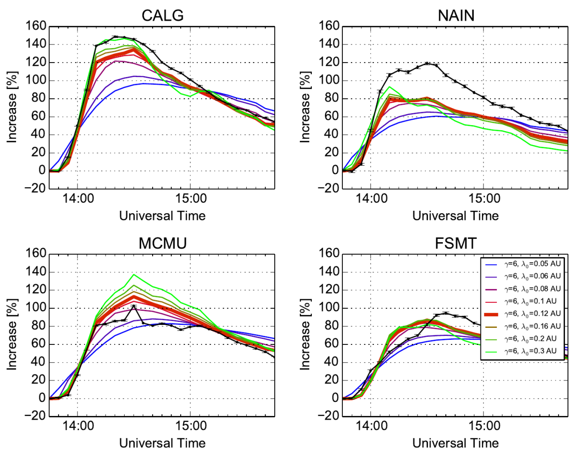

FIG. 5: Relative count rate increase during GLE on 15 April 2001 as measured by the NM stations with the largest observed count rate increases (Calgary, Nain, McMurdo, and Fort Smith, black curve) and as simulated for $\gamma = 6.0$ and different mean free path lengths for pitch angle scattering λ_0 (colored curves). The red bold curve corresponds to the best fit, i.e. injection profile as shown in Fig. 4, $\gamma = 6.0$, and $\lambda_0 = 0.12$ AU.

increases for the NM stations with the highest count rate increases are presented, i.e. with the injection profile shown in Fig. 4, $\gamma = 6$ and selected values for λ_0.

V. SUMMARY

Within the HORIZON 2020 project HESPERIA a new GLE analysis software was developed. Compared to former GLE inversion computer programs, which assessed the SCR characteristics near Earth, the current software determines the SCR characteristics at the Sun in one step, i.e. during the whole GLE (typically over one hour) as well as the characteristics of the transport between the Sun and 1 AU. There are made different assumptions and simplifications in the particle release at the Sun as well as in the transport in the interplanetary space. In addition, the transport in the Earth's magnetic field is based on magnetic field models which may show inaccuracies, and finally the used yield function differs somewhat from other published NM yield functions.

A first case study with the GLE on 15 April 2001 gives confident results. However, the GLE inversion software must be applied during further GLEs, e.g. GLEs with smaller count rate increases at the NM stations, GLEs with more complicate conditions in the interplanetary space or in the release proportion at the Sun. The software is available to the community from the HESPERIA webpage (http://www.hesperia-space.eu/index.php/results/inversion-software-tools).

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