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A comprehensive study of solar energetic particle propagation during the first ground-level enhancement of the solar cycle 24

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The first ground-level enhancement (GLE) of the 24th solar cycle was observed on 2012 May 17 by the ground-based neutron monitor network. Correspondingly, space-based high-energy particle detectors at the Earth orbit observed the typical signatures of a solar energetic particle (SEP) event. The SEP/GLE event occurred during the transit of a large-scale magnetic cloud. A comprehensive study of the event is presented here by analyzing both space- and ground-based high-energy particle measurements as well as by estimating the magnetic cloud configuration through the Grad-Shafranov reconstruction. In order to give an estimate of the GLE primary energy spectrum we use the neutron monitor based anisotropic GLE pure power law (NMBANGLE PPOLA) model and we compare results with spacecraft observations by using data gathered by the PAMELA experiment, which was in a favorable position with respect to the arrival directions of primary protons during the event main phase. The anisotropy of the particle flux during the SEP/GLE event is also investigated through the NMBANGLE PPOLA. Our results suggest that the large-scale magnetic cloud configuration played an important role in leading the high-energy particle propagation.

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1. Introduction

Ground-level enhancements (GLEs) are short-term increases in the cosmic ray intensity recorded by ground-based neutron monitors (NMs). They are produced by extreme solar energetic particle (SEP) events, when relativistic protons interact with the atmospheric nuclei generating a cascade of secondary particles down to the ground. GLEs represent one of the major hazard for human activities and health. Thus, understanding the physics of particle acceleration causing such extreme events as well as their propagation and forecasting are among the primary objectives of *Space Weather* studies [1]. Such extreme events are associated with both solar flares and coronal mass ejections (CMEs) at the source.

The first GLE of 24th solar activity cycle (GLE number 71 - GLE71) reached the Earth's environment on 2012 May 17. Different and extensive analyses of the GLE71 event were carried out by exploiting both satellite and ground-based observations pointing out that such an event was not a large one, neither in intensity nor in energy of the arriving solar protons [see 2, and references therein]. On the other hand, it was a complex and interesting event in many aspects. By inspecting solar wind data gathered by L1 orbiting spacecraft, it was shown that the arrival of the GLE event coincides with a disturbed period characterized by the transit in the near-Earth environment of an interplanetary coronal mass ejection (ICME) [3].

In this work we aim to retrieve the main characteristics of GLE71 event, such as primary spectrum and anisotropy, and to connect them with the passage of the ICME. This is carried out by performing independent data analysis using ground-based particle observations provided the global NM network as well as L1 solar wind and particle measurements (as described in Section 2). The model used to retrieve parameters of the GLE from ground-based NM observations is an updated version of the NM based anisotropic GLE pure power law (NMBANGLE PPOLA) model introduced by Plainaki *et al.* [2, 4] and is described in Section 3.1. Since the ICME event occurring in coincidence with the GLE contains a large coherent flux-rope structure, in order to analyze the main characteristic of such a transient event we use the Grad-Shafranov (GS) reconstruction presented in Section 3.2. Main results of this study are shown in Section 4 and conclusions are drawn in Section 5.

2. Overview of the GLE71 event

GLE71 was recorded by the worldwide NM network on 2012 May 17, starting at 01:50 UT at the Oulu NM station and reaching a maximum percentage increase of about 17% at 02:15 UT at the South Pole NM station. Some examples of the GLE intensity time profiles registered at polar and mid-latitude NMs are presented in Figure 1, left panel. In addition, the Energetic Proton, Electron and Alpha Detectors (EPEAD) on board the Geostationary Operational Environmental Satellites (GOES) recorded a sudden increase of proton intensity followed by a slow decay in four integral energy channels, as shown in Figure 1, right panel.

The onset of the GLE recorded by NM stations occurred during the transit of a large magnetic-cloud (MC) structure constituting part of the transient ICME disturbance. All the typical hallmarks of the magnetic cloud passage were present and many of them, as observed from the Wind spacecraft, are displayed in Figure 2. The presence of smoothly rotating magnetic field components

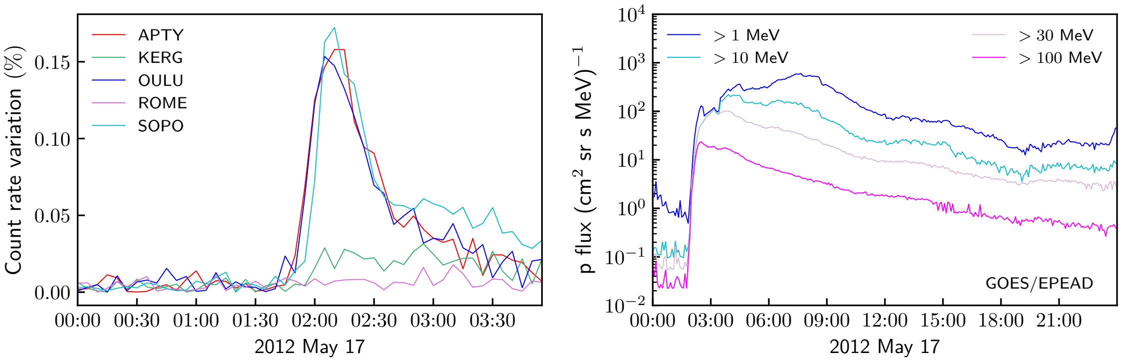

Figure 1: Left: Neutron monitor data during the onset of the GLE event. Right: High-energy protons as recorded by GOES/EPEAD at energies > 1, > 10, > 30 and > 100 MeV.

accompanied by low energy bidirectional electrons, stable flow speed, low plasma temperature and plasma beta allow us to identify the ICME start time (solid black line) and the magnetic cloud time interval (marked by the dotted black lines). The red vertical line of Figure 2 is reported as a reference and indicates the GLE onset time observed at the Earth. Rouillard *et al.* [3] by using CME data from the heliospheric imagers on board STEREO, SOHO and SDO showed that this ICME had originated by an Halo CME ejected in the vicinity of the NOAA active region 11476 at about 00:00 UT on 2012 May 12. Thereafter, active region 11476 moved westward, reaching the location N11° W76° on 2012 May 17 when it produced a M5.1 X-ray flare at 01:30 UT along with a partial-halo CME at 01:48 UT. This solar eruption can be associated with the acceleration of SEPs that caused the GLE71 event detected at the Earth shortly afterwards.

3. Methods

3.1 The Neutron Monitor Based Anisotropic GLE Pure Power-Law model

The model used in this work is an updated version of the NMBANGLE PPOLA introduced by Plainaki *et al.* [2, 4]. This model is meant for providing an estimation of the primary flux of particles at the top of the Earth's atmosphere by exploiting ground-based NM observations. The primary spectrum of solar particles is assumed to be a pure power law. The time variations ΔN of cosmic-ray count rates with respect to the background N, observed at the cut-off rigidity R_c at altitude h and time t are determined by the following expression [4, 5]:

$$\frac{\Delta N(R_c, h, t)}{N(R_c, h, t)} = \frac{\int_{R_c}^{R_u} dR\, W(R, h, t)\, A(R, t)\, b(t) R^{\gamma(t)}}{I(R_c, h, t)}, \tag{1}$$

where $W(R, h, t)$ is the coupling functions between secondary and primary high-energy particles at the top of the atmosphere introduced by Dorman [5] and

$$A(R, t) = \exp\left[-n_a(t)^2 \sin^2 \frac{\Omega(R, t)}{2}\right] \tag{2}$$

is the term accounting for anisotropic arrival of the solar particles at 1 AU, depending on the argument $\Omega(R, t)$ which indicates the distance between each individual NM angular location and

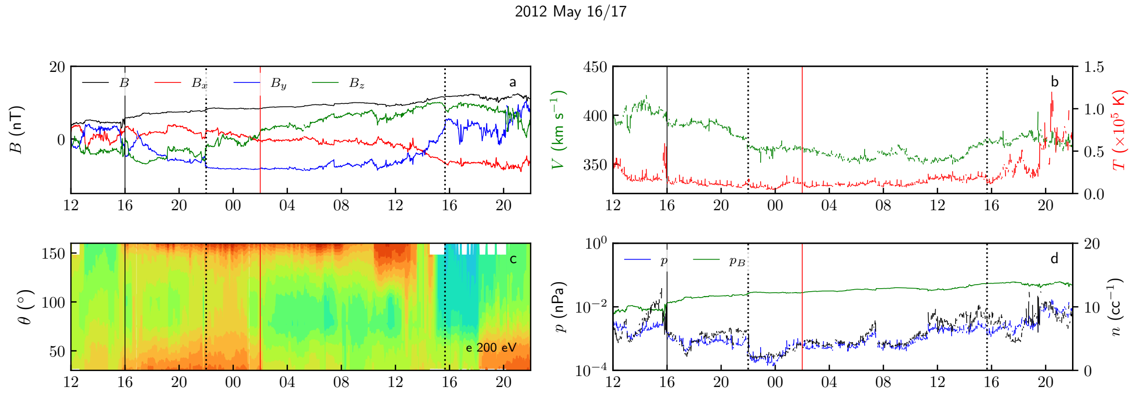

Figure 2: Magnetic field and plasma parameters of the 2012 May 16 MC event as observed by Wind. Panel (a) shows the magnetic field components in Geocentric Solar Ecliptic (GSE) coordinates along with the magnitude; panel (b) displays flow speed and temperature; in panel (c) is depicted the logarithmic electron intensity as a function of the pitch-angle θ; panel (d) contains kinetic and magnetic pressure and solar wind number density. Vertical black lines indicate the ICME start time (solid) and the MC transit interval (dotted). The red vertical line marks the GLE event onset time.

the direction of the anisotropy. Finally, the term

$$I(R_c, h, t) = \int_{R_c}^{+\infty} dR\, W(R, h, t)\, J_{GCR}(R, t) \tag{3}$$

is the integral background cosmic-ray flux, being $J_{GCR}(R, t)$ the primary cosmic-ray energy spectrum. From the operational point of view, the NMBANGLE PPOLA model performs the Levenberg-Marquardt optimization in order to minimize a cost function defined by the squared difference between the observed count rate variation (l.h.s. of Equation 3.1) and the corresponding model predictions (r.h.s of Equation 3.1). The optimization procedure retrieves some key parameters of the GLE such as the location of the anisotropy, the width of the particle beam, which is modeled through the anisotropy parameter $n_a(t)$, and the primary spectral index $\gamma(t)$.

3.2 Grad-Shafranov reconstruction of interplanetary magnetic clouds

One of the most powerful techniques aiming to retrieve the configuration of interplanetary MCs by using single spacecraft data is the GS reconstruction, which provides a 2.5-D magnetic flux rope configuration under axial symmetry condition [6]. This technique is based on the GS equation

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{d}{dA}\left(p + \frac{B_z^2}{2\mu_0}\right) \tag{4}$$

which, in this form, describes a 2D plasma structure which is invariant along the z direction, where A is the vector potential, p is the plasma pressure and μ_0 is the vacuum magnetic permeability. The fit of the transverse pressure $P_t = p + B_z^2/2\mu_0$ as a single valued function of A through a suited optimization procedure, allows us to identify the best invariant axis of the MC [6]. In this framework, magnetic field lines wrap around this direction, constituting the core of the MC. Such a helical configuration is retrieved through a Taylor expansion of A on the transverse plane assuming Equation (4) to be valid.

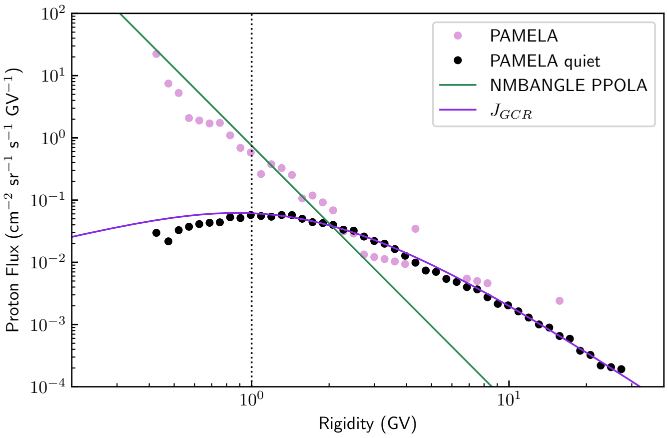

Figure 3: Differential rigidity spectrum measured by PAMELA in the time bin 02:15 - 02:20 UT (purple circles). The black circles show the PAMELA background spectrum along with the parametrization J_{GCR} used in the model (violet line). The green line indicates the GLE primary spectrum retrieved through the NMBANGLE PPOLA model.

4. Results

The free parameters of the NMBANGLE PPOLA model have been optimized by using 29 NM observations as described in the previous work by Plainaki *et al.* [2]. Data used in this study are available at the web page `http://www.nmdb.eu/`. In this discussion we focus our attention on two parameters of the model: the anisotropy index n_a and the spectral slope γ. Their values at four different times from the GLE71 onset to the main phase are reported in Table 1. The anisotropy index of the NMBANGLE PPOLA model gives an estimate of the incoming particle beam width. Results indicate that the particle beam is narrower at the GLE onset time, i.e., higher value of n_a, and becomes wider overcoming the main phase of the event. Concerning the spectral slope, the NMBANGLE PPOLA model predicts a fairly stable value, slightly decreasing as a function of time. In order to test model predictions, in this work we use the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) observations [see 7, and references therein]. PAMELA was placed on board the Russian satellite Resurs DK1 and during the GLE71 was able to record the primary particles at energies above 80 MeV. In Figure 3, black circles indicated the quiet spectrum recorded by PAMELA before the GLE onset and used to parametrize the $J_{GCR}(R, t)$ term appearing in Equation (3, violet line). Such a parameterization, carried out by using the model by Gleeson and Axford [see 8, and references therein], represents an update with respect to previous versions of

Table 1: Values of the anisotropy index n_a and the primary spectrum exponent γ retrieved through the NMBANGLE PPOLA model as a function of time.

	1:55	02:05	02:15	02:25	02:35
n_a	5.59 ± 1.28	7.18 ± 2.36	1.76 ± 0.27	2.00 ± 0.26	0.97 ± 0.14
γ	−3.43 ± 0.71	−4.39 ± 1.62	−4.15 ± 0.68	−4.15 ± 0.82	−4.46 ± 0.79

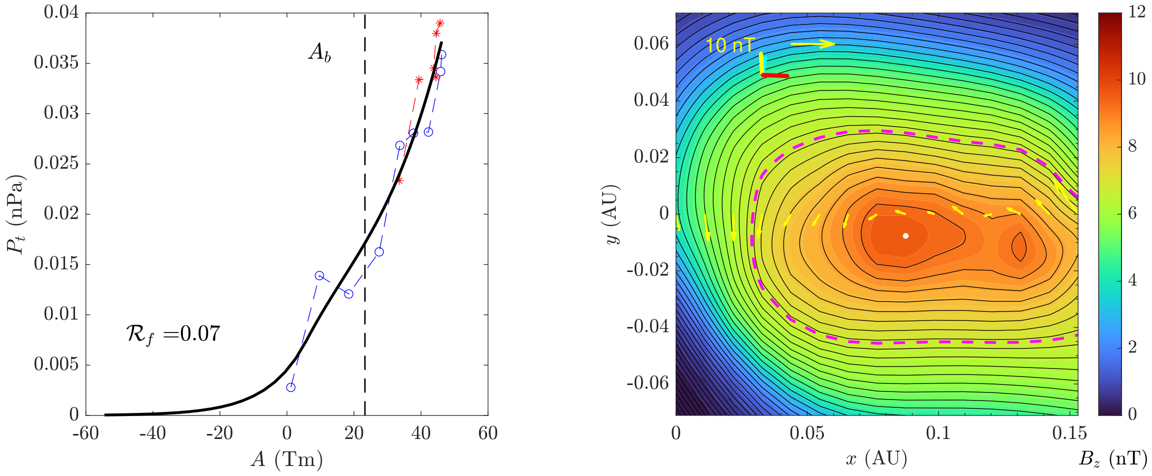

Figure 4: Left: transverse pressure P_t as a function of the potential vector A (stars). The solid line indicates the fit with a residue of 0.07. Right: GS reconstruction result. The colormap shows the intensity of the axial magnetic field B_z whereas black curves are the isopotential lines. Yellow arrows display the transverse magnetic field vector along the Wind path and the reference frame reported in the upper left corner is the GSE (x in red, y in cyan and z in yellow).

the NMBANGLE PPOLA model [2, 4]. The differential proton flux observed by PAMELA within the time interval 02:15 - 02:20 UT (purple circles) is compared with the NMBANGLE PPOLA model prediction (green line). The rigidity spectrum thus retrieved is quantitatively consistent with PAMELA observations, returning a reduced $\chi^2 < 0.1$ at rigidity > 1 GV.

The analysis of the MC observed by the Wind spacecraft is carried out through the GS reconstruction and main results are summarized in Figure 4. The left panel show the fit of the transverse pressure P_t as a function of A and the right panel contains the reconstruction. The axial magnetic field B_z in the reconstruction reference frame is shown along with the contour lines of the potential vector (black lines) and the GSE reference frame is reported in the upper left corner of the figure to show how the MC is oriented. The Wind spacecraft, and thus the near-Earth environment, were crossed by the structure at $y \sim 0$, i.e., they experienced the innermost region of the MC where the contribution of the axial magnetic field is largest. The orientation of the MC axis is found to have a longitude of $-86.5°$ GSE and a latitude of $38.7°$ GSE. We aim to test if this constitutes a preferential direction for high-energy particles propagation in the ICME by using the NMBANGLE PPOLA model, which relies on ground-based observations. A comparison between the direction of the MC axis and the anisotropy function of Equation (2), obtained in the time interval 02:00 - 02:05 UT corresponding with the GLE main phase, is shown in Figure 5. The MC axis orientation is indicated by the white cross and presents a remarkable agreement with the direction of the anisotropy obtained through the model, i.e., $-91.2 \pm 3.9°$ GSE longitude and $41.5 \pm 4.0°$ GSE latitude, which is representative of the arrival direction of the primary high-energy particle beam (>1 GV) at the beginning of the GLE event.

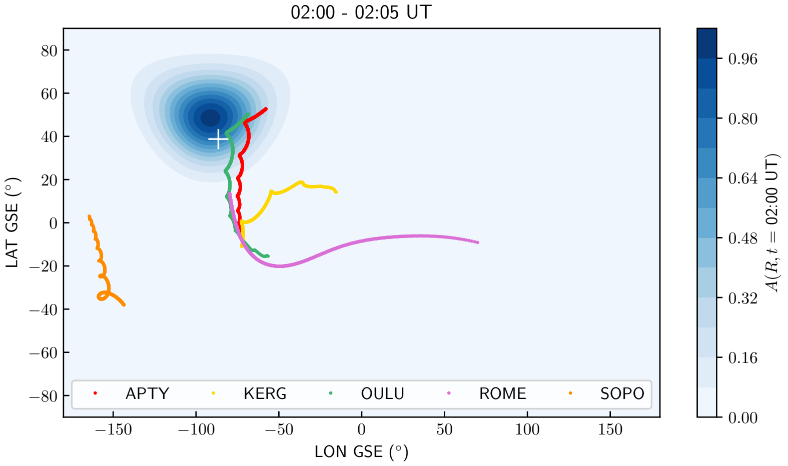

Figure 5: Contour plot of the anisotropy function $A(R,t)$ for the time bin 02:00 - 02:05 UT obtained from the NMBANGLE PPOLA model. Colored circles indicate the asymptotic directions of viewing of five NM stations. The white cross indicates the orientation of the MC axis retrieved through the GS reconstruction.

5. Discussion and Conclusions

The GLE71 event has several puzzling aspects. A CME left the Sun on 2012 May 12 and crossed the near-Earth environment between 2012 May 16 and 17. On May 17 around 02:00 UT, when the Earth was surrounded by a large scale MC, the sharp increase in NM count rates of the GLE71 event took place. The primary spectrum retrieved through the NMBANGLE PPOLA model presents a remarkable agreement with PAMELA observations during the main phase of the event. By including the PAMELA cosmic-ray background in the model, we obtain softer spectral indices with respect to previous findings by Plainaki *et al.* [2], which are in agreement with results by Bruno *et al.* [9]. Furthermore, our results are compatible with those of Mishev *et al.* [10] in terms of the change in the slope over time, e.g., predicting progressively softer spectra during the event. However, differences in the index numerical values between these two models are a consequence of the different function used to parametrize the primary spectrum. The analysis of the MC shows that the near-Earth environment was connected with the innermost part of the MC during the main phase of the GLE71. The strong agreement between the MC orientation and the anisotropy function of the NMBANGLE PPOLA model supports a scenario in which SEPs producing the GLE71 were injected at the footpoints of the MC and propagated through it, which therefore provided the necessary magnetic connection between Earth and Sun during the event. Moreover, the small spread around the preferred direction and the short arrival time suggest that SEP propagation was almost scatter free and thus the cross field transport, accounting for the penetration of high-energy particles inside the MC, may represent a minor contribution.

Acknowledgements

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