Probing energetic particle transport through spectrum and anisotropy evolution during GLE77

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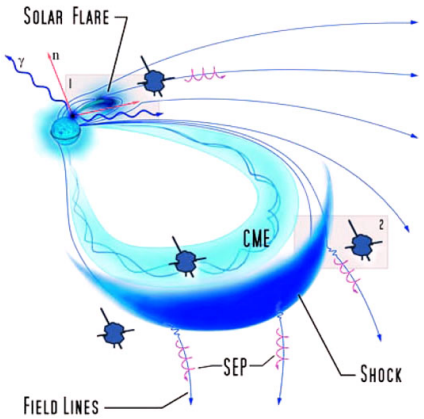


Outline

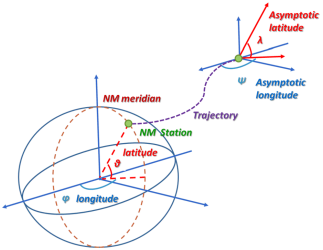
- Introduction to **Ground-Level Enhancements** (GLEs) and the GLE77 event
- Observations and Solar Origins (Flare, CME)
- The problem of **SEP transport**
- Modeling the time evolution of **GLE spectrum and anisotropy**
- Insights on **solar energetic particle transport** (SEP) from ground-based **neutron monitor** (NM) data

The problem of SEP transport

- **SEPs** are injected into the heliosphere following intense solar events, such as flares and coronal mass ejections (CMEs) $\longrightarrow$ **impulsive** vs **gradual events**
- During their propagation, the evolution of the particle distribution is governed by different competing mechanisms $\longrightarrow$ **adiabatic focusing** and **turbulent pitch-angle scattering**
- Observations from ground networks frequently show **structured anisotropic patterns** characterized by early impulsive peaks and late gradual phase
- **Challenge** $\longrightarrow$ understanding whether these gradual peaks are the result of prolonged solar injection or interplanetary transport effects



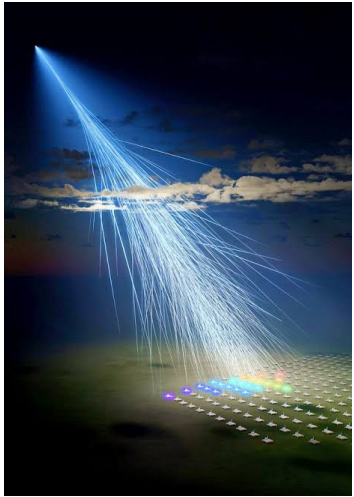
What are ground-level enhancements (GLEs)?



McCracken, et al., JGR 1962

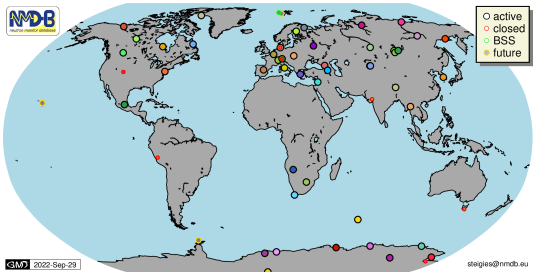
- **Ground-Level Enhancement** $\longrightarrow$ near-time coincident and statistically significant enhancements of the count rates of at least **two differently located neutron monitors**, including at least one neutron monitor near sea level and a corresponding enhancement in the proton flux measured in space

Poluianov, et al., SolPhys 2017

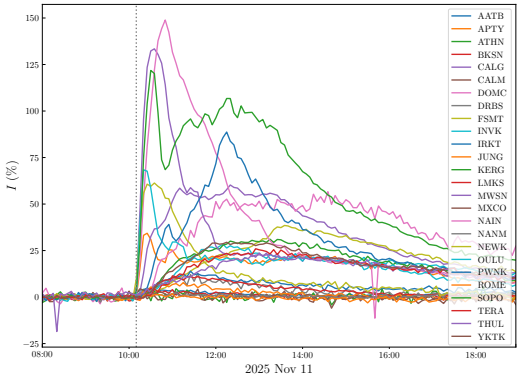


The Neutron Monitor network

- Each detector is connected with a specific region of the interplanetary space at a given time, depending on its **geographic location** and on the **configuration of the geomagnetic field**
- The worldwide network of neutron monitor detectors can be used to infer important information about **energy dependence** and **angular anisotropy** of the incoming particle fluxes



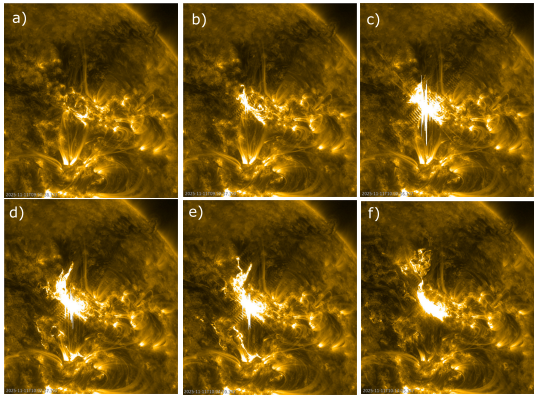
The case of GLE 77



- **GLE77** occurred on November 11, 2025 at 10:10 ⟶ **strongest event registered in the last 36 years** since **GLE42** in September 1989
- The impulsive phase (10:10 - 10:50 UT) was detected by high-cutoff stations up to 12 GV ⟶ very **hard initial particle spectrum**
- The **gradual phase** was predominantly recorded by high- and mid-latitude stations with cutoff rigidities below 5 GV ⟶ **softer spectrum**

Data summary : the solar source

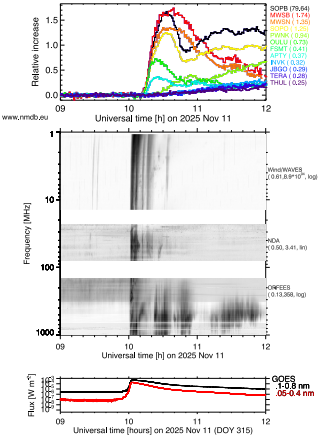
- The event originated from an **intense solar flare** in the active region NOAA 14274
- Extreme ultraviolet images at 17.1 nm from SDO/AIA showed a J-shaped ribbon geometry, indicating **magnetic reconnection and the dynamic build-up of a flux rope**
- SOHO/LASCO coronagraphs detected a **halo CME** propagating with an estimated three-dimensional speed of approximately 2100 km s^{-1}



Mishev, et al., ASR 2026

Data summary : X-rays and radio waves

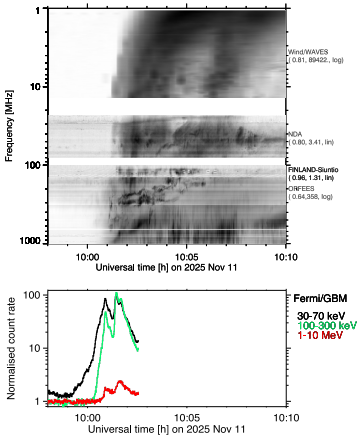
- Radio dynamic spectra from ORFEES, NDA, and Wind/WAVES revealed multiple signatures ⟶ **Type IV** continuum, **Type II**, and **Type III** bursts
- Type II radio bursts **driven by a shock wave** ⟶ located in the direction of the erupting flux rope progression
- Type III radio bursts ⟶ **outward-traveling electron beams** along open magnetic field lines
- The event was associated with a **strong X5.1 soft X-ray burst** that started at 09:49 UT and reached its peak at 10:04 UT



Mishev, et al., ASR 2026

Data summary : X-rays and radio waves

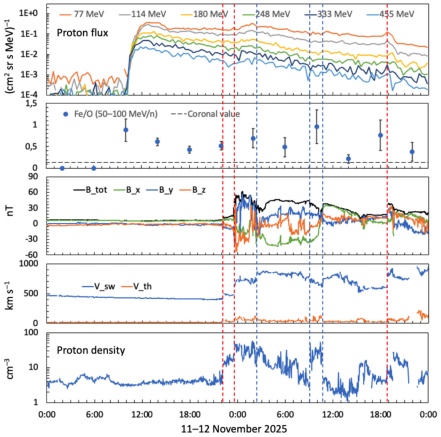
- Fermi/GBM detected initial peaks in **X-rays** (30-70 and 100-300 keV) and **gamma-rays** (1-10 MeV) around 10:00 UT and 10:01 UT
- **Gamma-ray emission** $\longrightarrow$ relativistic electrons and protons at deka-MeV energies
- The first particle release to the high corona $\longrightarrow$ **second stronger peak** of the hard X-ray and gamma-ray emission



Mishev, et al., ASR 2026

Data summary : s/c data, composition and related ICME

- SEP space observations ⟶ typical **gradual profile**
- Despite the gradual nature of the SEP event, Fe/O ratio was above the nominal coronal value of 0.134 Reames, ASR 1995 ⟶ **flare-accelerated SEP component** or suprathermal seed particles
- Interplanetary magnetic field and plasma parameters ⟶ the **ICME shock** arrived at 23:32 UT on 2025 Nov 11 and is likely the one driven by the CME related to the GLE event



Mishev, et al., ASR 2026

Modeling GLE spectrum and anisotropy

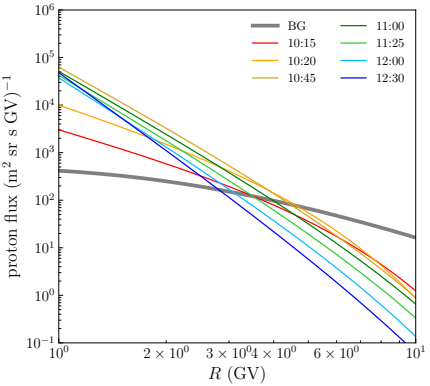
- Analysis of the time evolution of the primary proton spectrum and spectral index during the event

$$\frac{\Delta N}{N}(t) = \frac{\int_{R_c} dR\, J_{sep}(R,t)\mathcal{A}(\alpha,t)Y(R,h)}{\int_{R_c} dR\, J_{bkg}(R)Y(R,h)}$$

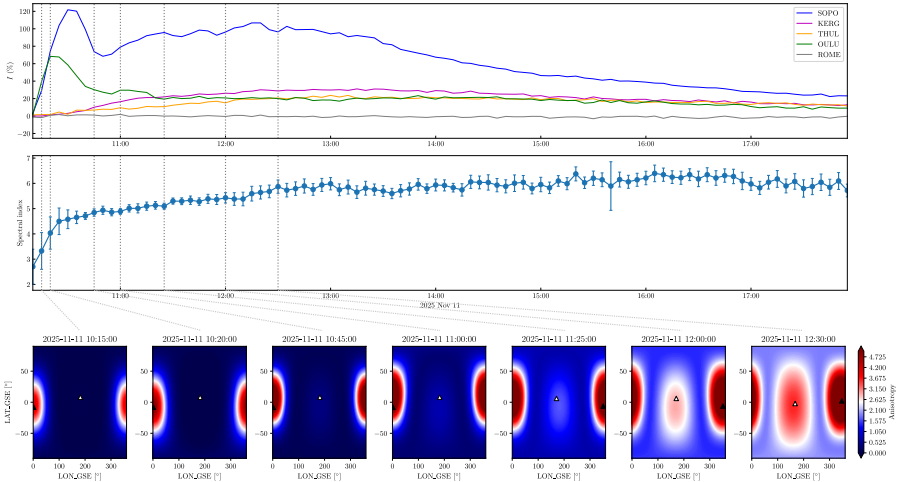
- $J_{sep}(R) = J_0 R^{-[\gamma+\delta\gamma(R-1)]} \longrightarrow$ modified **power-law spectrum**
- $\mathcal{A}(\alpha) = a_1 e^{-(\alpha^2/\sigma_1)} + a_2 e^{-((\pi-\alpha)^2/\sigma_2)} \longrightarrow$ geomagnetic field, **TSY01 + IGRF** (OTSO) Larsen, et al., JGR 2023
- $Y(R,h) \longrightarrow$ NM **yield function** accounting for secondary production in the atmosphere Mishev, et al., JGR 2020

Time evolution of the primary spectrum

- **Impulsive phase** (10:15 - 10:45 UT) $\longrightarrow$ **hard rigidity spectrum**, solar proton flux exceeds the GCR background even at high R
- **Gradual Phase** (from 11:00 UT) $\longrightarrow$ **softer spectrum**, high fluxes at low rigidities but rapidly dropping below the background around 3, 4 GV
- Transition from a **highly energetic initial injection** to a **prolonged, lower-energy** particle flux

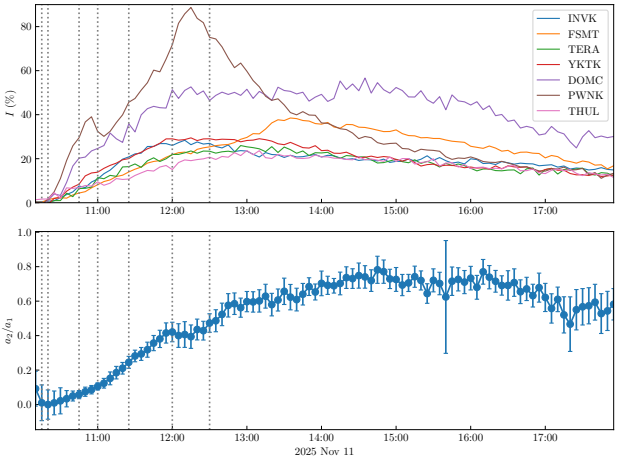


Time evolution of spectral index and anisotropy



Time evolution of the bidirectional anisotropy

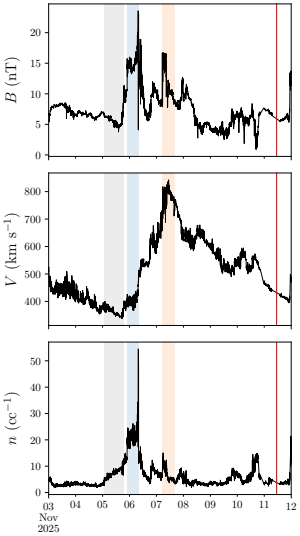
- **Impulsive peak** recorded by high- and low-latitude NMs (e.g., SOPO, MWSN, JUNG, MXCO)
- A **pronounced gradual second peak** $\sim$ **1-2** hours
- SOPO, INVK, THUL, FSMT, PWNK, and more NMs observe **peak intensity** during this second phase
- Qualitative agreement with a_2/a_1 ratio fitted on the world-wide NM network $\longrightarrow$ possible role of **counter-streaming high-energy particles**?



Corotating interaction region : possible magnetic mirroring ?

- "Second peak H" $\longrightarrow$ relativistic protons travel outward along the Parker spiral and mirror at a **corotating interaction region** (CIR) compression front
- **CIR observed at 1 au** on 2025 November 5 at 21:45 UT
- **CIR properties** from 1 au in situ data $\longrightarrow$
  - $V_{CIR} = (n_u v_u + n_d v_d)/(n_u + n_d) = 496$ km s^{-1} $\longrightarrow$ GLE particle **timing**
  - Compression ratio $R_{CIR} = B_{max}/B_u \approx 4.2$ $\longrightarrow$ GLE **reflected flux**
- Conservation of the first adiabatic invariant ($\mu_M = p_\perp^2/2mB = \text{const}$) $\longrightarrow$ critical pitch angle threshold for mirroring

$$\alpha_c = \arcsin\left(\frac{1}{\sqrt{R_{CIR}}}\right) \sim 29^\circ$$



Corotating interaction region : possible magnetic mirroring ?

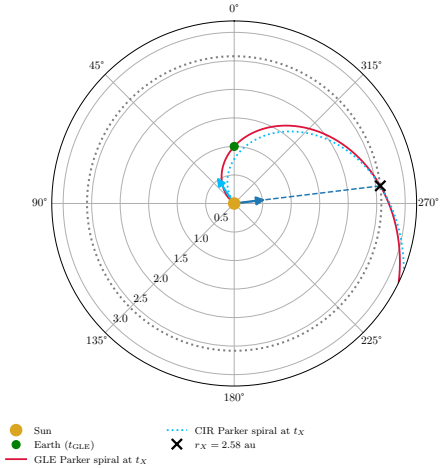
- **Ballistic propagation** of the CIR observed at Earth with radial speed V_{CIR}

$$\Delta t = t_{GLE} - t_{CIR}, \qquad E_p = 1 \text{ GeV}$$

$$r_X = r_0 + V_{CIR}\Delta t \approx 2.58 \text{ au}$$

$$\Delta s = s(r_X) - s(r_0) \approx 3 \text{ au}$$

$$\Delta t_p = 2\Delta s / v_p \approx 58 \text{ min}$$



Focused transport equation and regimes

- The focused transport equation describes the evolution of the particle distribution due to **adiabatic focusing** and **turbulent pitch-angle scattering**

  Earl, ApJ 1976; Bieber, Evenson, JGR 1986

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

- Stationarity $\partial f/\partial t \sim 0 \longrightarrow$ asymptotic solution $f(\mu) \propto \exp\left(\frac{\lambda}{L}\mu\right) \longrightarrow$ ratio λ/L is constant in time

  - $\lambda/L \ll 1$: **diffusive regime** $\longrightarrow$ strong scattering, nearly isotropic distribution
  - $\lambda/L \gg 1$: **focusing regime** $\longrightarrow$ weak scattering, particle beam is collimated along B
  - $\lambda/L \sim 1$: **intermediate regime** $\longrightarrow$ exponential anisotropy due to the interplay between focusing and scattering

Linking fitted anisotropy to particle transport

- Pitch-angle distribution $\longrightarrow$ connecting **fitted** and **transport** parameters

$$f(\mu) \propto \exp\left(\frac{\lambda}{L}\mu\right) \approx \exp\left(-\frac{\alpha^2}{\sigma_1}\right) \implies \frac{\lambda}{L} = \frac{2}{\sigma_1}$$

- By assuming that adiabatic focusing and pitch-angle scattering are **balanced during the propagation**

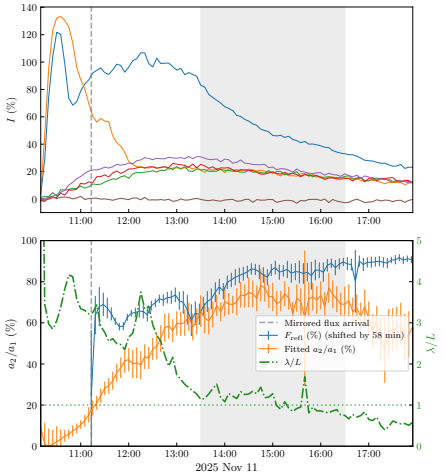
$$\frac{a_2}{a_1} \text{ (2nd to 1st Gaussian amplitude ratio)} \approx F_{refl} \text{ (first Gaussian width)}$$

- Fraction of **CIR reflected protons**

$$F_{refl} = \exp\left(-\frac{\alpha_c^2}{\sigma_1}\right)$$

Possible evidence for CIR mirroring

- 1 GeV protons
- Ideal arrival of **mirrored protons** after a **58** min round-trip path
- High λ/L indicates **ballistic propagation** dominated by solar injection and magnetic focusing ($\partial f/\partial t \gg 0$)
- Transport parameter tends towards $\lambda/L \approx 1$ $\longrightarrow$ stationary **focusing/scattering balance**
- This quantitative argument supports the second peak as a **counter-streaming particle flux** from the CIR boundary at $r_X \approx 2.58$ au $\longrightarrow$ needs for **numerical models** to support this conclusion! :)



Summary

- **GLE77** (November 11, 2025) was the strongest event in 36 years, triggered by an intense X5.1 solar flare and a fast halo CME
- NMs recorded an early impulsive peak followed by a **pronounced delayed phase** 1-2 hours post-onset
- We investigate the possible origin of the late second peak in terms of **adiabatic mirroring** at a CIR boundary located at $r_x \approx 2.58$ AU
- **Expected timing** is consistent with data $\longrightarrow$ arrival of 1 GeV mirrored protons after a $\approx$ **58** minute corresponds to the **rising phase of the second gradual peak**
- **Stationary transport regime** $\longrightarrow$ High initial λ/L values indicate ballistic propagation, which then tends towards $\lambda/L \approx 1 \longrightarrow a_2/a_1 \approx F_{refl}$ … *…with a little imagination*
- Next **ideal** step $\longrightarrow$ global modeling of **CIR evolution** and **SEP transport**

Thank you for your attention

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