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

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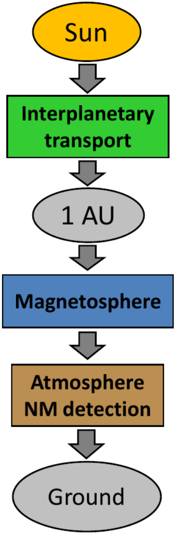
Motivation

- The worldwide network of neutron monitors (NMs) is a huge spectrometer for cosmic rays in the energy range $\sim$500 MeV to $\sim$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 the GLE characteristics near Earth were determined, 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

New approach

- Within the Horizon 2020 project HESPERIA, we are developing a software package for the direct inversion of GLEs based on NM data
- The new methodology to study the release processes of relativistic solar energetic particles (SEPs) at the Sun makes use of several models



Propagation of relativistic SEPs from the Sun to the Earth I

- In an unperturbed solar wind, the interplanetary magnetic field (IMF) can be described by an Archimedean spiral with superposed magnetic fluctuations
- In this case, the propagation of SEPs in the interplanetary space is determined by:
  - adiabatic motion along the smooth magnetic field, i.e. gyration around and streaming along IMF, focusing and mirroring
  - pitch-angle scattering by magnetic turbulences, i.e. diffusion in pitch-angle $\Rightarrow$ spatial diffusion

Propagation of relativistic SEPs from the Sun to the Earth II

Quantative description of the particle's phase space density, $f(z, \mu, t)$, by the focused transport equation (Roelof 1969):

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

Quasi-Linear Theory (QLT) (Jokipii 1966):

pitch-angle scattering at small irregularities $\Rightarrow$

discribed by pitch-angle diffusion coefficient $D_{\mu\mu}$ $\Rightarrow$

parallel scattering mean free path $\lambda_{\|}$

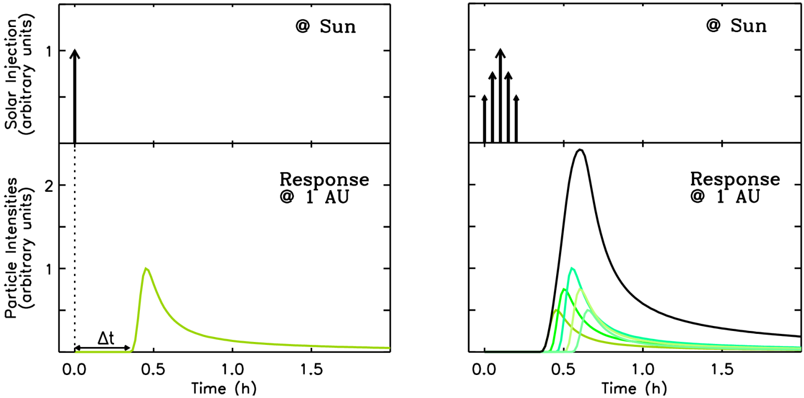
Propagation of relativistic SEPs from the Sun to the Earth III

Simplifications / neglects:

- This simple form of the transport equation neglects:
  - convection and adiabatic deceleration
  - effects of diffusion perpendicular to the average magnetic field and drifts

- Assumption that there is no variation across the magnetic field and that respective solutions are identical in neighboring flux tubes

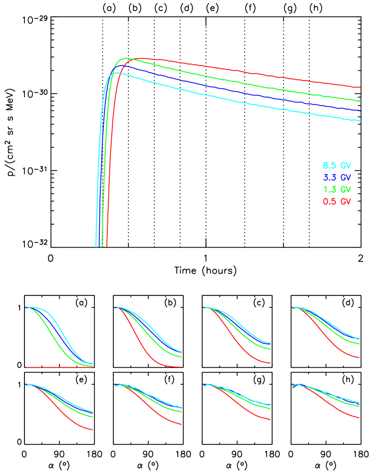
From injection to observation at 1 AU



Impulsive injection (delta function) at the Sun → response at 1 AU

Superposition of impulsive injections → corresponding response at 1 AU = sum of series of impulse responses

SCR characteristics at 1 AU



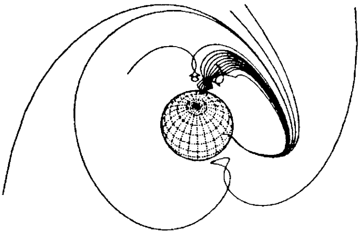
Expected proton intensities at 1 AU

for selected rigidity values, assuming v_{sw} = 400 km/s, λ_0 = 0.2 AU and γ = 3 ($I(R,t) \propto R^{-\gamma(t)}$)

and pitch-angle distributions

at eight different times

Transport in the Earth's magnetosphere



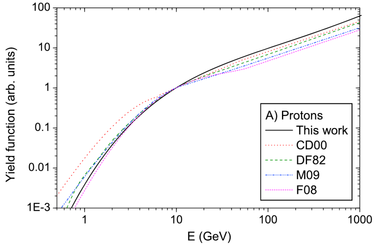
Trajectories of charged particles with different energies in the Earth's magnetic field

Smart et al., 2000, Space Science Reviews, 93, 305

Computation of cosmic ray trajectories by using IGRF and Tsyganenko89 field models for different times and with different levels of disturbance of the geo-magnetic field

Computed asymptotic directions are stored in a database

Transport in the atmosphere and the detection of secondary CRs by the NMs



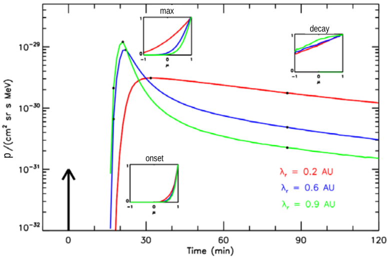
Calculated yield functions of sea level NM64 NM for isotropically incident protons into the Earth's atmosphere

Mishev, Usoskin, and Kovaltsov, JGR, 118, 6, 2013

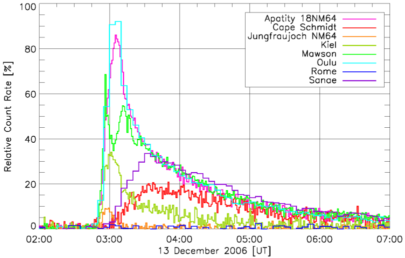
Transport of CR particles in the Earth's atmosphere and the NM detection efficiency for secondary cosmic ray particles are combined in the NM yield function

In the program it is possible to select from different yield functions as published by different authors

GLE inversion – Fitting NM data



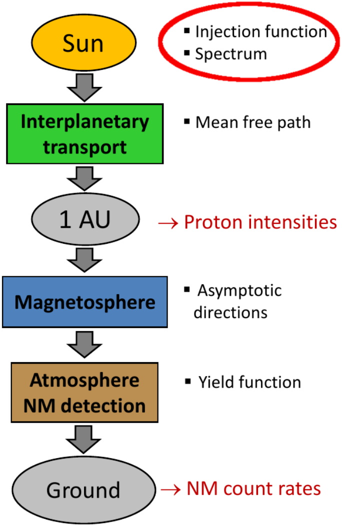
SCR characteristics at 1 AU vs. time



Relative NM count rate increase vs. time

Determination of SCR characteristics at the Sun in one step, i.e. during the whole GLE (typically over one hour)

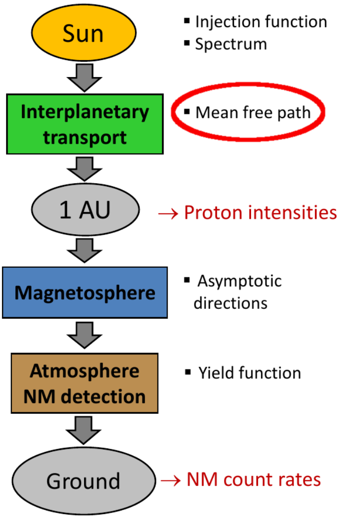
GLE inversion



Model parameters:

- a series of instantaneous releases from the Sun
- source spectral index, γ

GLE inversion



Model parameters:

- solar wind speed, v_{sw}
- mean free path, λ_r

Summary

- Development of software for the direct determination of the SCR injection characteristics at the Sun based on NM data
- Only the standard Archimedean spiral configuration of the IMF and pitch-angle scattering at small irregularities are considered for the transport in the interplanetary space
- The software will be available to the community end of 2016

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