HelMod: a Comprehensive Treatment of the Cosmic Ray transport through the Heliosphere

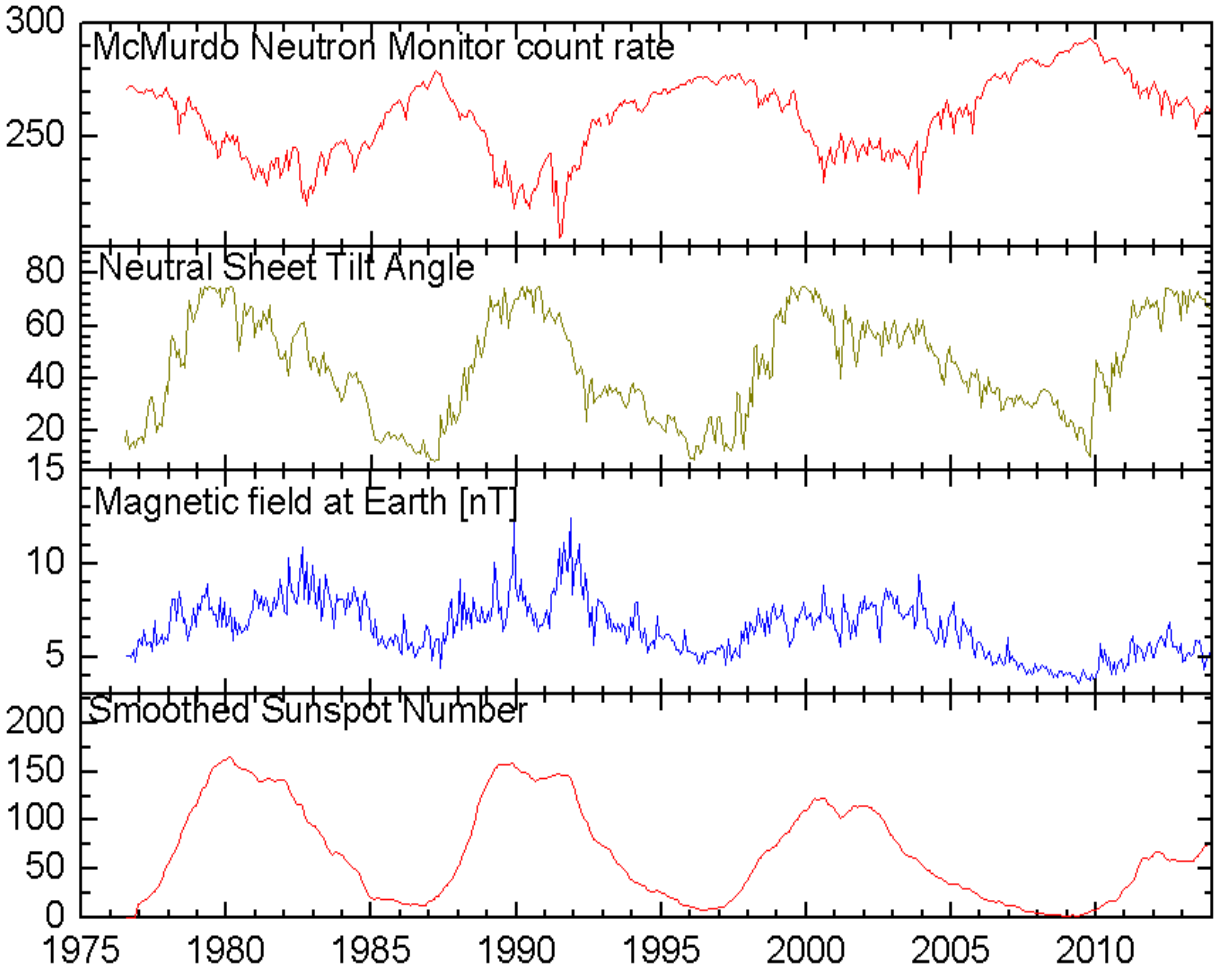
S. Della Torre, M. Gervasi, **D. Grandi**, G. Johannesson, G. La Vacca, N. Masi, I. V. Moskalenko, E. Orlando, T. A. Porter, L. Quadrani, P. G. Rancoita and D. Rozza

Outline

- Solar Modulation introduction
- The HelMod Monte Carlo Model
- HelMod results in conjunction with GALPROP Local Interstellar Spectra.
- Online calculator

Solar modulation - Introduction

The Cosmic ray measured at Earth orbit is affected by Solar modulation at rigidity <10-30 GV



The Cosmic rays intensity varies with time

The variation is related to solar activity: greater is the activity, less is the cosmic rays intensity

Solar modulation - Introduction

Cosmic Rays diffusion is described by Parker equation (1965)

$$\frac{\partial U}{\partial t} = -\nabla \cdot (U\mathbf{V}) + \nabla \cdot \left[\vec{K} \cdot \nabla U\right] + \frac{(\nabla \cdot \mathbf{V})}{3} \frac{\partial}{\partial T} (\alpha_{rel} T U)$$

U Cosmic Rays number density per unit interval of kinetic energy

$$\frac{\partial f}{\partial t} = -\nabla \cdot (f\mathbf{V}) + \nabla \cdot \left[\vec{K} \cdot \nabla f\right] + \frac{(\nabla \cdot \mathbf{V})}{3p^2} \frac{\partial}{\partial p} \left(p^3 f\right)$$

f Cosmic Rays omnidirectional distribution function

Diffusion

Small Scale Magnetic Field irregoularity

Convection

Presence of the solar wind moving out from the Sun

Drift

Large Scale structure of magnetic field (e.g. gradients)

Energetic Loss

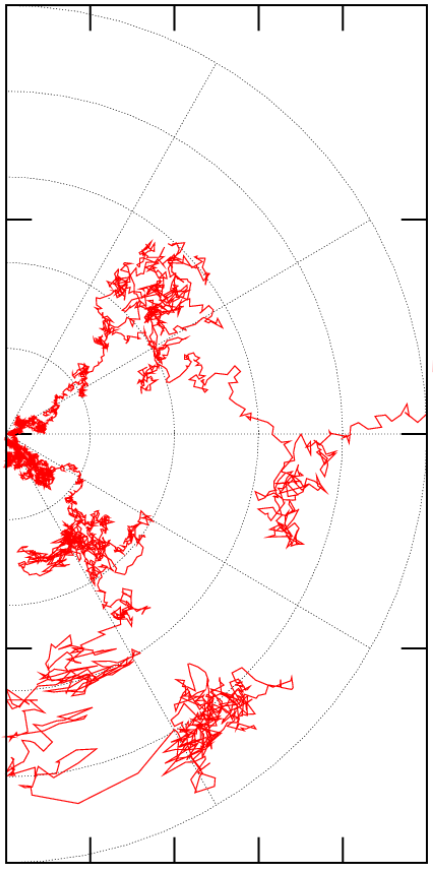
Due to adiabatic expansion of the solar wind

Monte Carlo Approach

Fokker Planck Equation

Ito's lemma, see e.g. Gardiner, 1985

$$\frac{\partial Q}{\partial t} = -\sum_i \frac{\partial}{\partial x_i}[A_{F,i}(t,x)Q] + \frac{1}{2}\sum_{i,j}\frac{\partial^2}{\partial x_i \partial x_j}[C_{F,ij}(t,x)Q] - L_F(t,x)Q + S$$



Quasi-particle evolution

Stochastic Differential Equations (SDE)

Deterministic **Stochastic**

$$dx_i(t) = A_{F,i}dt + B_{F,i,j}dW_j(t)$$

Convection+ Drift

Diffusion $C_F = B_F B_F^T$

L allows to "increase" (or "decrease") the quasi particles weight at an exponential rate as function of time propagation [see, e.g., Zhang, 1999]

Details of the SDE approach can be found in *Bobik et al. JGR. 2016, 121(5)*

HelMod Monte Carlo Code For low activity - Parameters

Diffusion

Small Scale Magnetic Field irregoularity

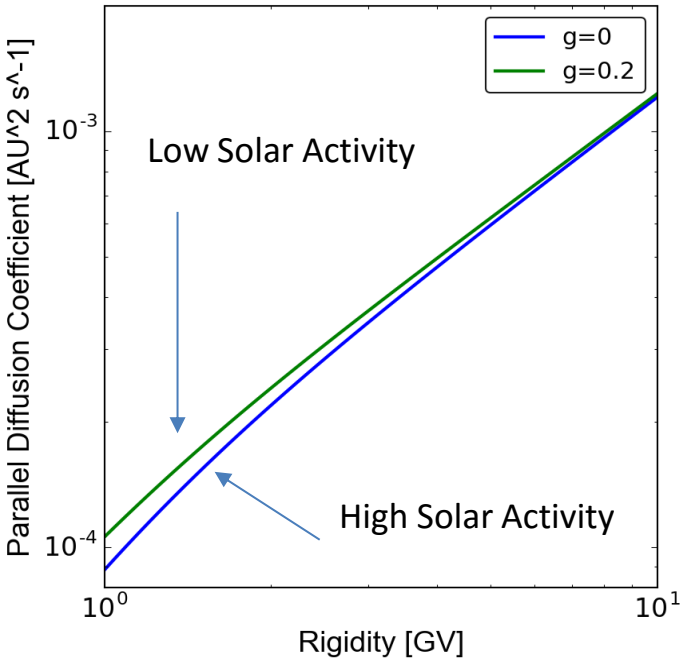
The Diffusione process is described by *diffusion tensor:*
In the *magnetic field line reference* this is

$$K_{ik} = \begin{vmatrix} K_{\perp r} & -K_A & 0 \\ K_A & K_{\perp\theta} & 0 \\ 0 & 0 & K_{||} \end{vmatrix}$$

$$K_{||} = \frac{\beta}{3} K_0 \left[\frac{P}{1\mathrm{GV}} + g_{low}(t) \right] \left(1 + \frac{r}{1\ \mathrm{AU}} \right)$$

$$K_{\perp,i} / K_{||} = \rho_i$$

The linear dependence of parallel diffusion was corrected at lower rigidity depending for solar Activity



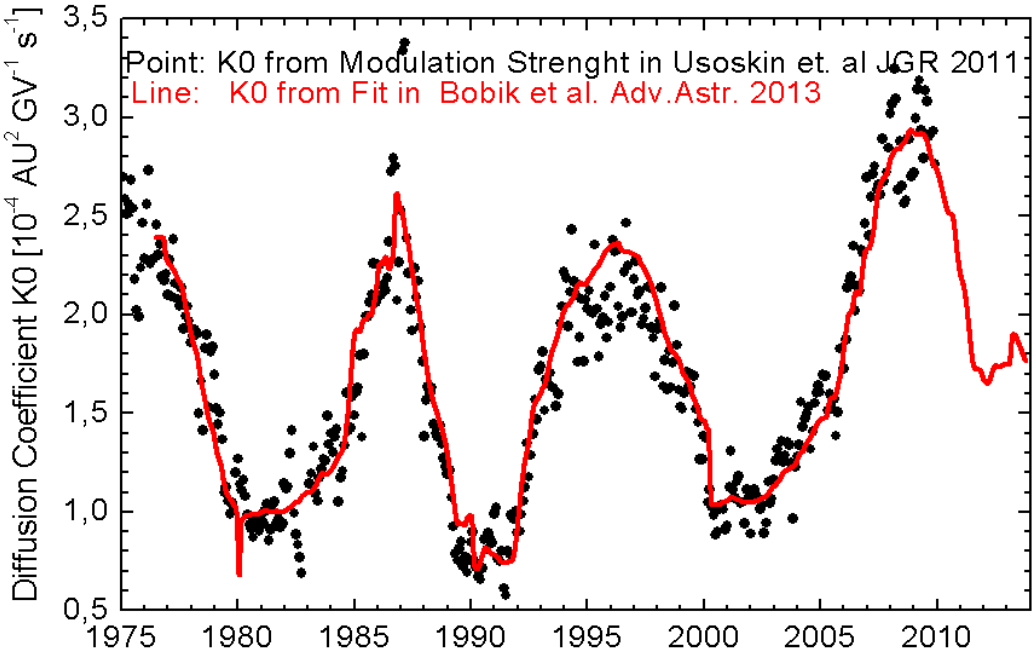
HelMod Monte Carlo Code Parameters

Diffusion

Small Scale Magnetic Field irregoularity

$$K_{||} = \frac{\beta}{3} K_0 \left[\frac{P}{1\mathrm{GV}} + g_{low}(t) \right] \left(1 + \frac{r}{1\ \mathrm{AU}} \right)$$

$$K_{\perp,i} / K_{||} = \rho_i$$



K0(t) Is the modulation parameter obtained using cosmic ray flux > 2 GV

K0(t) fitting procedure use a practical relationship between K0 from modulation strength and Solar activity evaluated using both Smoothed Sunspot Numbers and Neutron Monitor Counting Rate. *This act like a time scaling factor for the diffusion process*

see [Bobik et al, Adv.Astr. 2013]

HelMod Monte Carlo Code Parameters

Convection

Presence of the solar wind moving out from the Sun

Energetic Loss

Due to adiabatic expansion of the solar wind

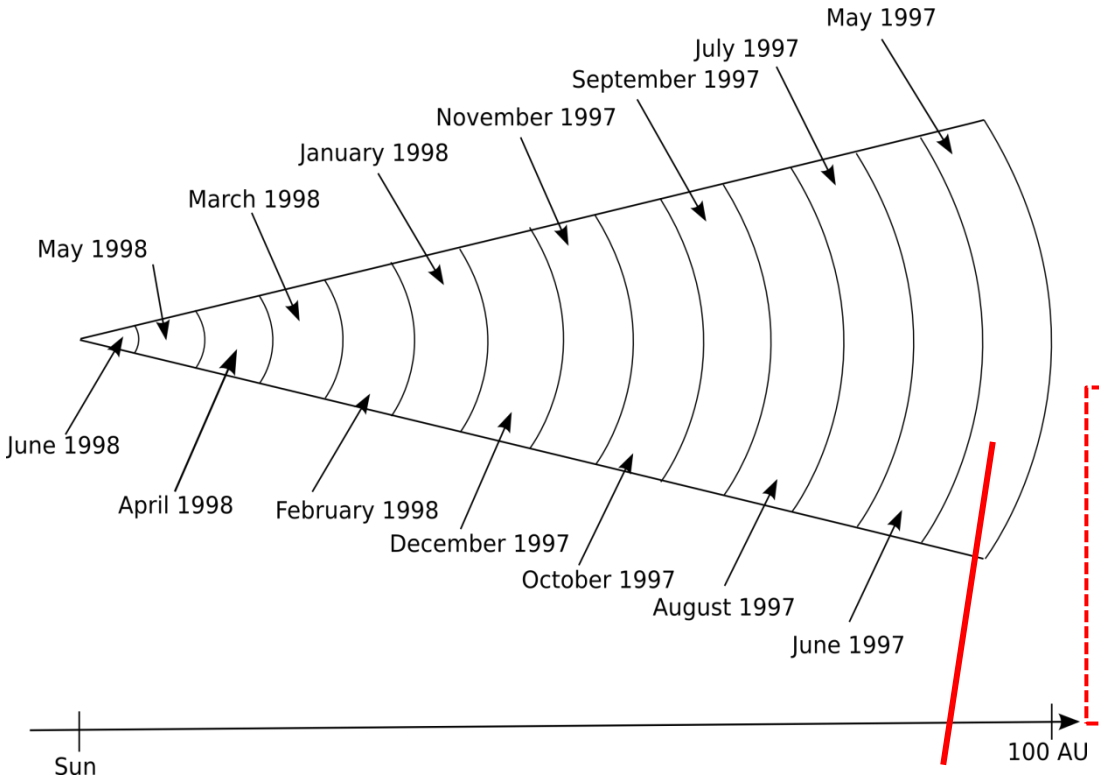
Solar Wind speed is obtained by in-situ measurements available in omniweb.gsfc.nasa.gov database

Drift

Large Scale structure of magnetic field (e.g. gradients)

We use the model described in
Potgieter & Moraal, ApJ 1985
The model depends on Tilt angle of the Neutral Sheet (computed monthly by http://wso.stanford.edu using the so called "L" and "R" model) and Magnetic Field Magnitude at Earth (available in omniweb.gsfc.nasa.gov database)

HelMod Monte Carlo Code Parameters



We divide the Heliosphere in 15 regions.

each one equivalent to the average of solar activity in periods before the experiment

Details of the model can be found in

Bobik et al. Ap.J. 2012 745:132

Bobik et al, Adv.Astr. 2013

Proc. ICRC 2013

www.helmod.org

Parameters in each region are

- *Diffusion parameter*
- *Tilt angle of the Neutral Sheet*
- *Magnetic Field Magnitude at Earth*
- *Solar Wind Speed*

The modulated spectrum is obtained combining unmodulated spectrum (J_{LIS}) with Monte Carlo normalized probability function G

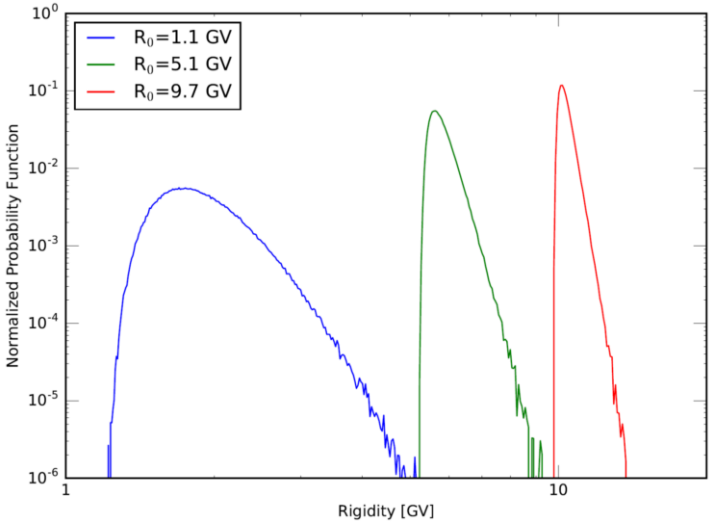
$$J_{mod}(R_0) = \int_0^{\infty} J_{LIS}(R) G(R_0|R) dR.$$

In present approach, the Local Interstellar Spectrum is an additional parameter that need to be tuned on data

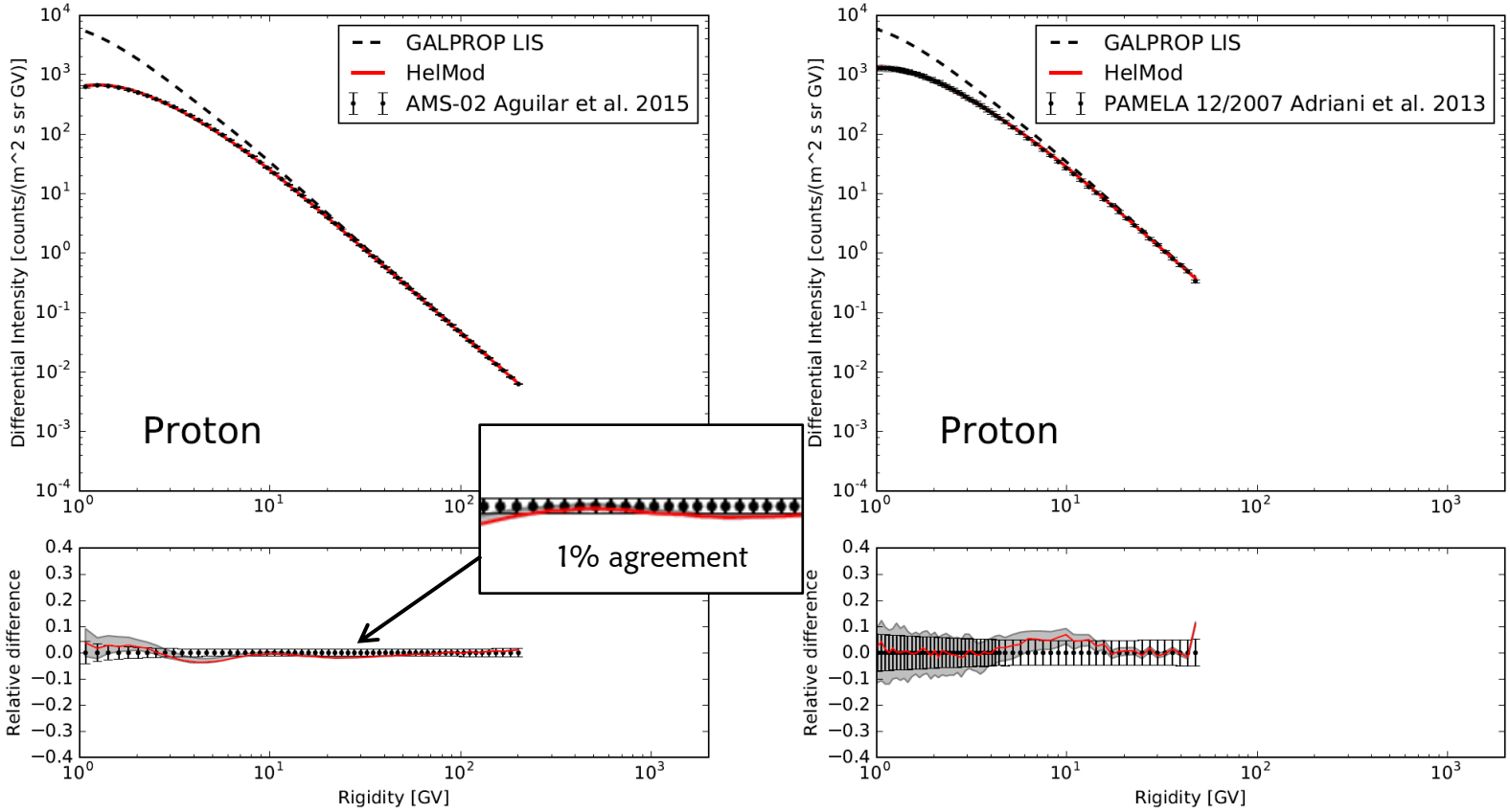
We developed a procedure that tune LIS from GALPROP to reproduce experimental data during both Solar Cycle 23 and 24

See N. Masi talk, id 8 Parallel Session 5b On September, 7

Normalized probability function that a particle with Rigidity R at 100 AU reach 1 AU with Rigidity R_0. Evaluated via Monte Carlo Simulation

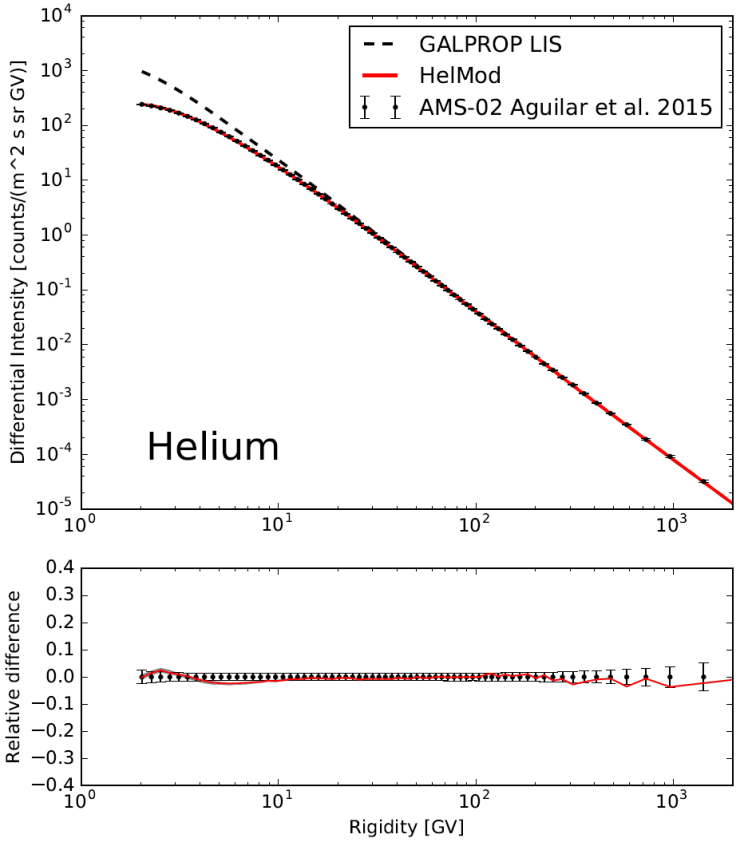


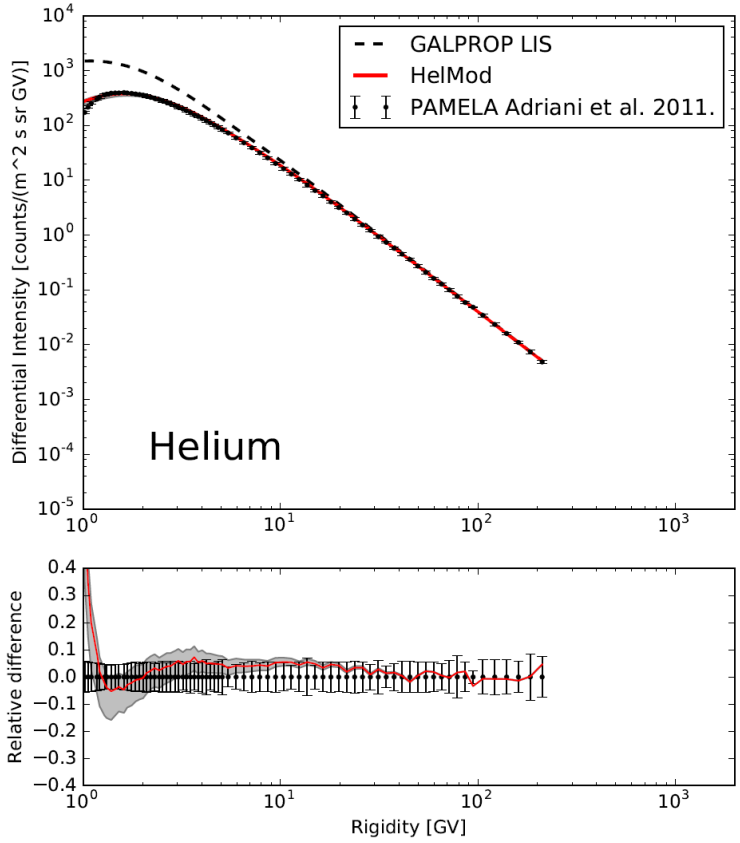
The model was able to reproduce both Low and High Solar activity Modulated Proton Spectra



The error bars comes from data and the grey area account for parameter uncertainties.

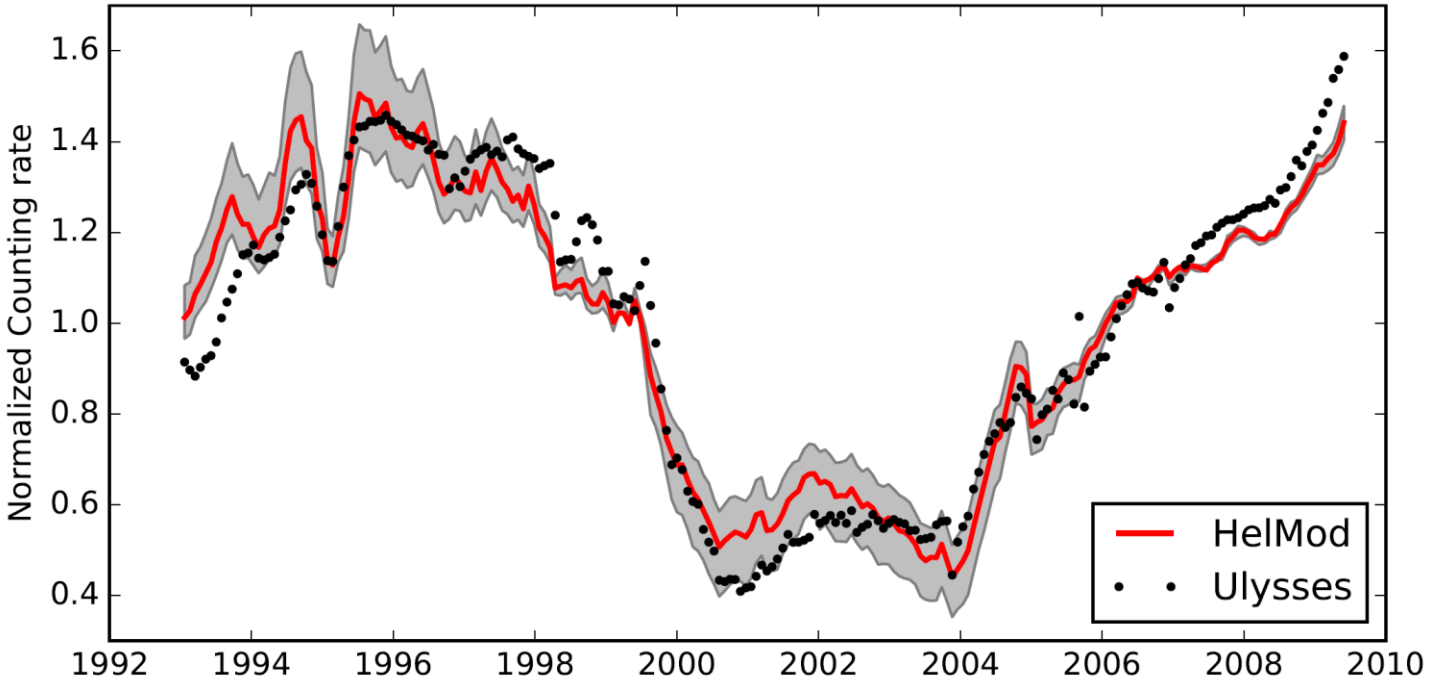
The model was able to reproduce both Low and High Solar Activity Modulated Helium Spectra





The error bars comes from data and the grey area account for parameter uncertainties.

The model was able to reproduce the normalized proton Counting rate measured by Ulysses at ~2 GeV



Ulysses spacecraft explored the heliosphere outside the ecliptic plane up to ±80° of solar latitude at a solar distance from ~1 up to ~ 5 AU

HelMod: The Modulation Model for Heliosphere

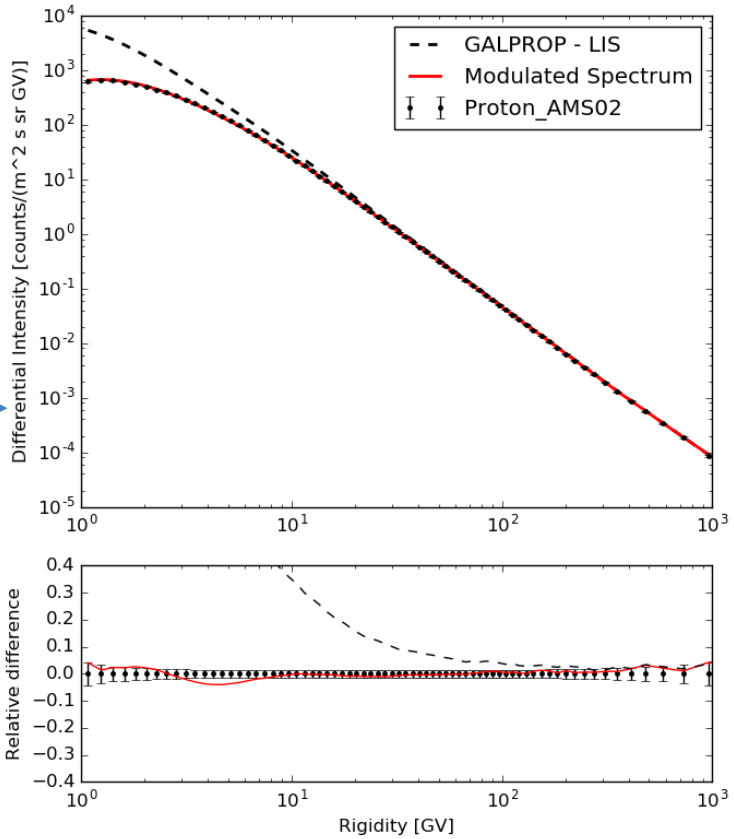
Online Calculator
(version 3.0.0)

The released online tools for solar modulation
http://www.helmod.org

Using the *online calculator* it is possible to modulate GALPROP spectrum and compare with relevant experiment during solar cycle 23 and 24

Online Calculators

Galactic Cosmic Rays particle species	Proton
Experiments datasets	AMS02
LIS-GALPROP Fits File	Sfoglia... Nessun file selezionato.
	Submit



Using the *Solar Modulator* it is possible to modulate GALPROP spectrum for an arbitrary period during solar cycle 23 and 24.

HelMod:
The Modulation Model for Heliosphere
Online Calculator
(version 3.0.0)

Istituto Nazionale di Fisica Nucleare

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The Modulation Model for Heliosphere
Online Calculator
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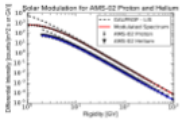

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Website Search

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HelMod Long Write Up

- The HelMod Model
- Monte Carlo Integration
- Magnetic Field
- Diffusion tensor
- Current and History of default parameters

HelMod Web Calculators

- HelMod Online Calculator
- HelMod Solar Modulator
- Stand-Alone Module for GALPROP

Propagation of Galactic Cosmic Rays through the Heliosphere with HelMod

Website latest update on September 1, 2016

Welcome to the HelMod Website. In these pages you can find information about the Solar Modulation Model for the propagation of Galactic Cosmic Rays through the Heliosphere from the Termination shock down to Earth.

HelMod is a 2D Monte Carlo model to simulate the solar modulation of galactic cosmic rays. The model is based on the Parker's transport equation which contains diffusion, convection, particle drift and energy loss. Following the evolution of the solar activity in time, we are able to modulate the local interstellar spectra (LIS) of cosmic ray species, assuming their isotropy beyond the termination shock, down to the Earth's location inside the heliosphere.

In the present website version, a solar modulation calculator is available for Cosmic Rays experiments carried out during solar Cycle 23 and 24.

In the 2D-HelMod code version 1.0 the standard Parker field without drifts was implemented;

From version 1.2 the dependence on the particle drift was added;

From version 1.4 the Parker magnetic field was modified in polar regions.

From version 1.5 the Solar Wind description was revisited for high and low activity periods, the Heliosphere was divided in regions related to spatial propagation of turbulence from Sun. Introduced the possiblity to evaluate solar modulation for electrons and positrons.

From version 2.0 the heliospheric magnetic field was modified in polar regions to accounts for different latitudinal gradients in opposite solar polarities

Conclusions

- We presented the HelMod Model for the propagation of Cosmic rays through the heliosphere that is able to reproduce the observed spectra during solar cycle 23 and 24, both at high and low solar activity using GALPROP LIS's.
- HelMod is in agreement at the 1% level for AMS-02 Protons.
- It was able to reproduce the observed spectra by Ulysses outside the ecliptic plane (between +80° and -80° of solar latitude) and from 1 to 5 AU
- The HelMod Model is available online (for GALPROP LIS's) at *www.helmod.org* to evaluate modulated spectrum for Proton, Helium, Antiproton and Electron for an arbitrary period during solar cycle 23 and 24, as a function of the Carrington Rotations.
- The forthcoming features to the web model are: Nuclei modulation spectra and the possibility to use a generic LIS.

Thank You for Your Attention!