Inferring the diffusion coefficient in the heliosheath by time spectra simulations of GCRs in the HelMod framework

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HelMod is a code describing the modulation of *Galactic Cosmic Rays* (GCRs) through the heliosphere, which is a spheroidal structure around the Sun shaped by the outwards flowing *Solar Wind* (SW). The main focus of this work is on the characterization of the *Heliosheath* (HS), an extremely turbulent region extending for ~ 30 AU from the so called *Termination Shock* (TS) at ~ 90 AU to the ~ 120 AU heliospheric boundary, the *Heliopause* (HP). The HS, in particular for low energy particles, is responsible for a significant part of the modulation. Indeed, when *Cosmic Rays* (CRs) travel in the heliosphere, they undergo convection, adiabatic loss and, most importantly, diffusion [1]. All these processes are described by the so called *Parker Transport Equation* (PTE). HelMod approaches the problem with a 2D Monte Carlo procedure, solving the PTE through a set of Sto*chastic Differential Equations* (SDEs) in a backward in time fashion [2]. This means that the pseudo particles simulating the GCRs move from a specific position inside the heliosphere up to the HP with the SW flowing inwards. Then, for a given *Local Interstellar Spectrum* (LIS), provided by the GALPROP numerical code, the output for the chosen simulated particle is a modulated energy (or rigidity) spectrum at a specific position in the heliosphere.

The solar modulation is the process causing the energy spectrum of CRs to drop below ~ 1 GeV/nucleon with respect to the power law behaviour observed at higher energies [3] . The shape of the modulated spectrum is very much dependent on the solar activity.

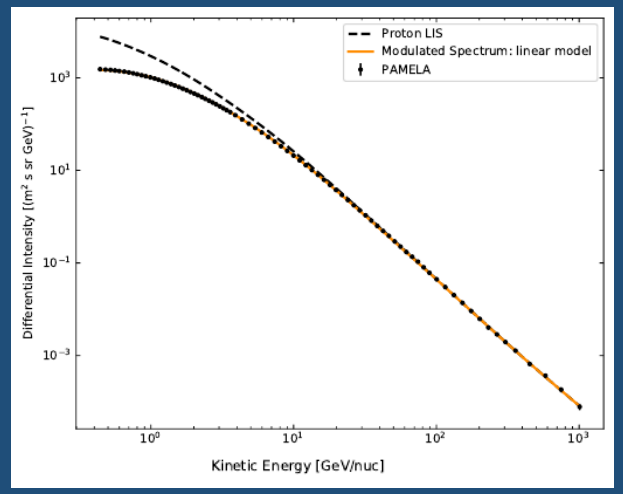

Figure 1: HelMod proton modulated spectrum with respect to the PAMELA data averaged between 14 July 2006 and 1 April 2008. The proton LIS is shown as well.

In this work, HelMod is used to compute time modulated spectra for H, He, O, C, Mg and Si ions. Voyager 1 is exploited as the target element in the backward in time procedure to compute the modulated spectra at each position along its trajectory in the heliosphere.

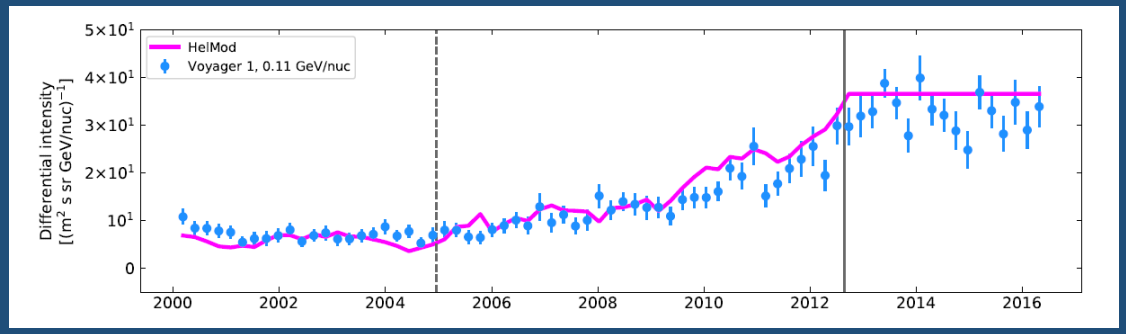

Figure 2: temporal spectrum for 0.11 GeV/nucleon energetic O ions over the 2000-2016 period travelled by the Voyager 1 probe. The model is compared to the extracted Voyager 1 data.

References
[1] Moraal, "Cosmic-ray modulation equations", Space Science Reviews
[2] Boschini, Della Torre, Gervasi, La Vacca and Rancoita, "The HELMOD model in the works for inner and outer heliosphere: From AMS to Voyager probes observations", Advances in Space Research
[3] Schrijver, Bagenal, Bastian, Beer, Bisi, Bogdan, Bougher, Boteler, Brain, Brasseur et al., "Principles of heliophysics: a textbook on the universal processes behind planetary habitability" , arXiv:1910.14022

The diffusion coefficient derived from this work presents a linear dependence with rigidity: $K = (0.47 + 1.37P)10^{-5}\ \beta\ AU^2\ s^{-1}$.
Then, from the figure below the mean free paths for particles scattering alongside the magnetic field lines are of the order of 1 AU.

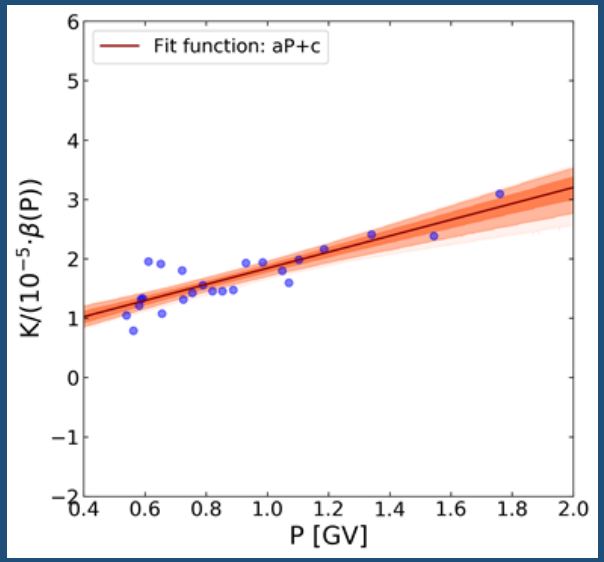

Figure 3: inferred diffusion coefficient behaviour in the HS with respect to the rigidity.