PROCEEDINGS OF SCIENCE

Predicting galactic cosmic ray intensities in the heliosphere employing the HELMOD-4 model

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Cosmic ray intensity variation has become a classic heliospheric physics problem that can be addressed through space radiation models. In this scenario, the HELMOD-4 model is a more-than-good compromise between the need for a comprehensive theory of particle propagation and an easy-to-use numerical model capable of assessing the solar modulation contribution in various heliospheric scenarios. The HELMOD-4 model can assess and forecast the long-term variations of the galactic cosmic ray (GCR) ion spectra making it suitable also for space mission radiation hardness mitigation studies. In the model, a Monte Carlo approach is used to solve the Parker transport equation to evaluate the effect of the solar modulation on the local interstellar spectra of GCRs during high and low solar activity periods, as well as at different distances from the sun and outside the ecliptic plane. In this work, we present the updated parametrization of the HELMOD-4 model, focusing on the descending phase of the solar cycle 24, employing a data-driven approach using the latest high-precision data from AMS-02. We will also present how the broader space community could benefit from the model using dedicated web tools.

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1. Introduction

In the space radiation environment, Galactic Cosmic Rays (GCRs) are particularly hazardous to electronic components because their high energies make them extremely penetrating, with a high rate of energy deposition. This makes GCRs an important contributor, for example, to single-event effects (SEE) especially in deep space. Therefore, planning future missions are required to rely on a good description and forecast of the GCR component in order to correctly assess the radiation risk.

The joint effort from GALPROP and HelMod-4 provides a complete cross-tuned model framework that is validated using state-of-art GCR measurements in space, *e.g.,* from AMS-02 [1] and Voyagers [2]. The GALPROP-HelMod-4 framework [3, 4] derived the Local Interstellar Spectra (LISs) for particles with the atomic number $Z \leq 28$ [5–10]. In this way, the Model showed a better capability of reproducing high-precision data with respect to other solar modulation models commonly employed by the space community [11]. HelMod-4 includes a forecasting tool that is able to predict the GCR fluence for future space missions with uncertainty of ~5–15% up to 11 years [12]. More recently, the HelMod-4 algorithm has been ported to GPU architecture using the CUDA programming language, thus achieving significant speedup without losing in precision compared to the CPU implementation [13, 14]. Finally, the model is available through an easy-to-use web interface on its website[1] and is embedded in the so-called SR-NIEL framework[2].

2. GCR fluences with HelMod-4

The determination of the total GCR fluence faced by a probe in deep space has to take into account the different physical processes that are involved in the particle's propagation from the source (*i.e.,* in the galaxy) to the inner heliosphere. These effects are related to the level of solar activity intensity, and the solar magnetic field polarity, and are energy- and charge-sign-dependent. The global effect is the reduction of the particle fluence at lower energies that additionally depends on the Sun's distance and helio-latitude. All these processes are included in the HelMod-4 model: a Monte Carlo code, based on the Parker Equation, that is currently capable to reproduce the observed modulated spectra since solar cycle 22 [3–10, 15–19] with and accuracy of the level of actual experimental uncertainties (i.e. few percent for AMS-02 integrated spectra). The details of the model are described in [18, 19].

The heliosphere in HelMod-4 has a complex structure, based on hydro-dynamical considerations, providing the long-term variation of the distance to the termination shock and the heliopause as a function of time, generally consistent[3] with observations by deep-space spacecraft [19]. Furthermore, as discussed in [18], the diffusion parameter K_0 sets the normalization of the parallel component of the symmetric part of the diffusion tensor. In HelMod-4 it varies with time through a practical relationship as a function of the monthly smoothed sunspot numbers (SSN) which has been updated including data up to the end of 2022 (see Table 1 in [21]), using the procedure discussed

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[1] `https://www.helmod.org/`

[2] `https://www.sr-niel.org/`

[3] Recently, the observation of the heliopause position provided by Voyager 2 showed that the spacecraft is at present in the very local interstellar medium [20]. Therefore, a practical correction has been implemented to keep the Voyager 2 trajectory outside the heliopause from the crossing point up to the current date. This correction is approximately within one standard deviation with respect to the averaged heliopause predicted by the model.

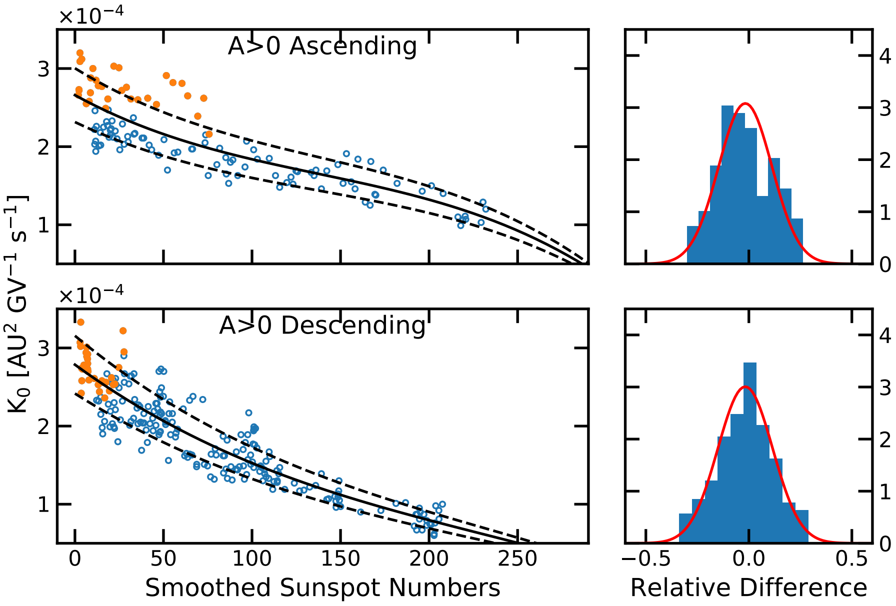

Figure 1: The estimated diffusion parameter K_0 for the ascending (upper row) and descending (lower row) phases of the solar activity for the positive polarity periods. On the left panels, the blue (orange) points represent the K_0 values before (after) 2017 as a function of SSN; the continuous black lines are the fit results with the error band (dashed lines). The right panels show the distribution of the residuals.

in Section 2.1 of [15]. As shown in Fig. 1 the so-obtained relationship shows an overall agreement with K_0 values.

As reported in [18], the magnetic drift is suppressed during high-activity periods at rigidities below few GV through a time-dependent suppression factor related to solar activity as discussed in [22]. In order to match the latest AMS-02 proton and electron data in the positive polarity minimum, drift term is suppressed at high energy (above 10–15 GV) by means of a logistic function where the plateau at higher rigidities is a function of the tilt angle, assuming positive values lower than 1.

3. Comparison with observations

The Model has been tuned using proton and electron data, along more than two solar cycles, both at 1 AU and larger distances from the Sun, up to the border of the heliosphere, as well as outside the ecliptic plane. The same parametrization has been then applied to all GCR ions [3–10].

In Fig. 2 the available data sets from BESS [23], SOHO/EPHIN [24], PAMELA [25–28], and the monthly means of the AMS-02 daily fluxes [29–31] for proton, helium nuclei, and electron GCR are reported. The period covers more than the last two solar cycles up to the end of 2022. In particular, the AMS-02 data include the descending phase to the minimum of the solar cycle 24 with a positive polarity which has been observed for the first time with such high accuracy.

The Model already showed to be able to reproduce the latitudinal gradient observed by the Ulysses spacecraft outside the ecliptic plane [15] and the radial gradient measured by Voyager 1 and Voyager 2 probes inside the heliosphere [18].

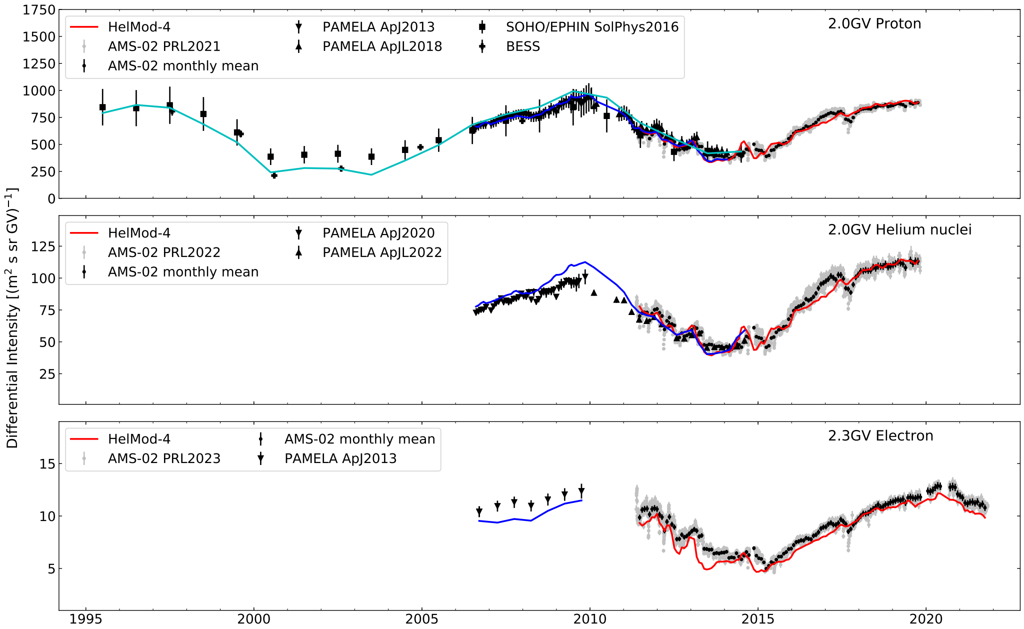

Figure 2: HelMod-4 solutions at ~2 GV (solid lines) for protons (top panel), helium nuclei (central panel), and electrons (bottom panel). Line colors indicate the simulations for different data sets within their own period and cadence: cyan for the yearly SOHO/EPHIN data, blue (red) for the monthly PAMELA (AMS-02) data. In the same plot, measured fluxes from EPHIN, BESS, PAMELA, and AMS-02 are reported.

4. Transfer orbit fluence calculator

When space probes travel in deep space to their target, they follow a transfer orbit to move the spacecraft from one stable orbit to another. During the time spent on the transfer orbit, the spacecraft experiences exposure to the GCR fluence without the natural shield due to the geomagnetic field. Thus, the full amount of solar-modulated spectra interacts directly with the probe components. HelMod-4 could provide a precise estimation for the space radiation environment due to GCR that resides both along the transfer orbit and at the target-specific celestial body.

In Fig. 3 we reported the case of the Cassini transfer orbit. The differential intensity (top panel) shows a decrease as long as the space probe travels into deep space during the rising phase of solar activity. The GCR intensity observed by the probe can be therefore ascribed to a combination of solar activity and solar distance that cannot be easily disentangled. The GCR fluence (middle panel of Fig. 3), obtained by integrating the flux from 10 MeV to 30 GeV, can be calculated by means of dedicated numerical simulations that must be evaluated for each Carrington rotation at the corresponding spacecraft average position.

In order to provide a reliable tool (within the model uncertainties), that can make these simulations accessible even for non-expert users, we implemented a web-based *transfer orbit fluence calculator* available at `https://www.helmod.org/`. Owing to the HelMod-4 forecast tool, this calculator can be used to predict the GCR fluence experienced by spacecraft during future missions. The calculator interpolates the GCR fluence using pre-calculated simulations at selected solar distances allowing for a fast response. This approach relies on the assumption that, on the

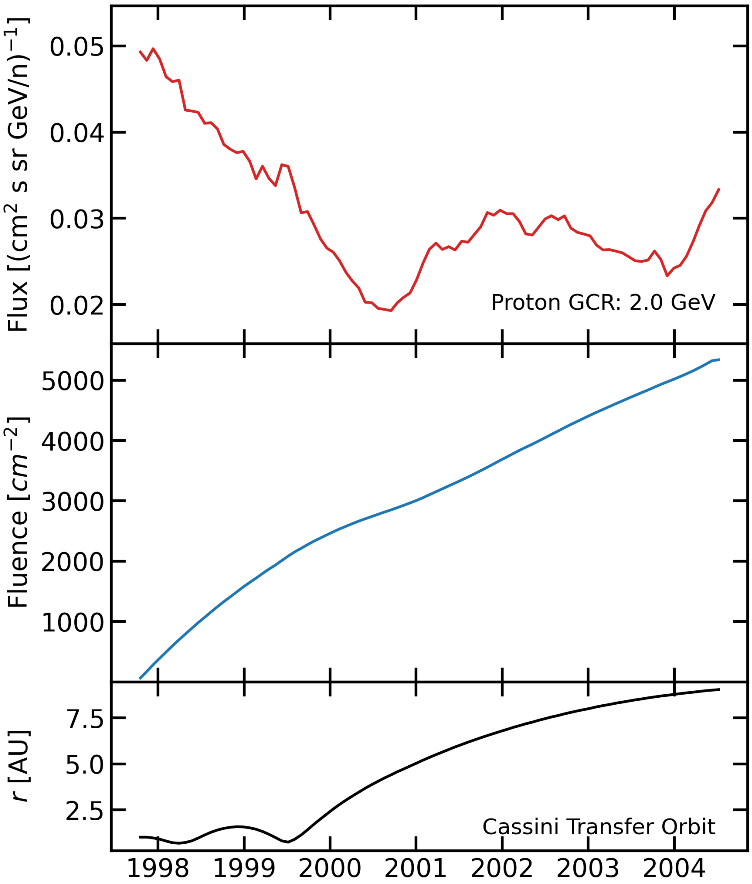

Figure 3: Top panel: computed proton differential intensity at 10 MeV along the Cassini transfer orbit. Middle Panel: computed proton fluence integrated from 10 MeV to 30 GeV. Bottom panel: radial distance of the Cassini transfer orbit.

orbital plane, the radial profile of GCR intensity can be described as $J_{sp} = J_E \cdot e^{G_r \cdot \Delta r}$ where J_{sp} is the GCR intensity at spacecraft distance, J_E is the GCR intensity at reference distance, Δr is the radial distance from spacecraft and the reference distance where J_E is evaluated, and, finally, G_r is the radial gradient computed between two reference solar distances.

A systematic comparison of fluences calculated within the mission time using dedicated simulations at the proper orbital distance and the web-based calculator has been carried on over six transfer orbits namely: Cassini, Juno, Mars Express, Mars Science Laboratory, Rosetta, and the SpaceX-Roadster. These missions are representative of the possible transfer orbits for exploration purposes in the inner part of the heliosphere, with different duration, covering different solar activity periods and final target distances. Averaging over all the tested transfer orbits we found that the two methods have a relative difference of $0.14^{+0.34}_{-0.31}\%$, where errors are evaluated considering the 68% C.L. interval.

5. Conclusion

In this work, we presented the updated parametrization of the HelMod-4 model during the descending phase of the solar cycle 24, regarding both the diffusion coefficient and the drift modelization, employing a data-driven approach. In this way, we were able to improve the agreement with the latest high-precision data from AMS-02. The HelMod-4 model, embedded in the so-called SR-NIEL framework, provided with a precise forecast tool and the transfer orbit fluence calculator, is aiming to support the space community with the most advanced and accurately predicted GCR fluences for precisely assessing the occurrence of SEEs during long-duration deep-space missions.

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