Research area: FORMAL MODELS, DATA ANALYSIS AND SCIENTIFIC COMPUTING

ERC sector: PE6

1) State of art

Many sensitive, future ESA and NASA space missions will be forced to benefit of models that will allow us to predict variations of interplanetary parameters (magnetic field (IMF) and solar wind (SW) speed) and energetic particle fluxes impacting on the efficiency of on-board instruments due to missing *in situ* measurements (the ESA Laser Interferometer Space Antenna (LISA) mission is an example). Some of these models have been developed thanks to an increasing cooperation between physicists and computer scientists that benefitted of data gathered in space on board the ESA LISA Pathfinder (LPF) mission and the NASA ACE and Wind satellites (Armano et al.; ApJ, 2018,2019; Grimani et al.; ApJ, 2020; Grimani et al.; A&A, 2021). As an example, I have developed an artificial neural network model to predict the galactic cosmic-ray (GCR) flux short-term variations (< 1 month) observed on board LPF. Such model used as input variables time series of hourly observations of IMF intensity and SW speed. This model represents an improvement of the one described in my master's thesis, for which a different training/test set splitting was performed. My thesis work was focused on the extraction of interpretable rules out of such neural network, so I picked random samples from the whole data set to create a test set, thus causing an on purpose over-fitting situation. Conversely, the goal of this project is to obtain real predictions of GCR flux short-term variations using only data of cosmic rays and interplanetary parameters gathered in advance to build the model. My preliminary model shows that supervised machine learning approaches cannot reproduce single GCR recurrent variations with a mean prediction error smaller than 2-3%, too large for sensitive space missions.

2) Objectives

I aim to develop a new model to predict GCR flux short-term recurrent variations associated with the passage of high-speed solar wind streams from coronal holes of the Sun by considering a Monte Carlo approach. There is a major lack of similar work reported in the literature since only very recently the LPF mission allowed to study recurrent GCR variations with percent uncertainties on hourly binned data. A deep investigation based on different methods considered to carry out analogous studies revealed that an analytical approach, for instance, applied to a specific depression allows to reproduce the decay phase of the depression while the constant, depressed flux phase and the recovery phase showed a very poor agreement with observations. These studies are of interest of the LISA mission, among others, that in order to detect gravitational waves will require a detailed monitoring of the space weather conditions of the interplanetary medium without possibly carrying dedicated instruments, even though ESA is still evaluating if a particle monitor dedicated to cosmic rays shall be placed on board the three LISA satellites. Presently, I have a scientific association to the INFN Bologna Section within the LISA experiment and I already contribute to the mission research program. The heart of my project is the development of a dedicated Monte Carlo program that will incorporate GCR diffusion and convection processes from the outer heliosphere through the point of observations.

3) Methodology

I will simulate the cosmic-ray particle propagation in the near inner heliosphere after taking into account the effects of the long-term solar modulation from the heliopause to the point of observations at the transit of high-speed solar wind streams. In particular, changes of the IMF intensity and SW speed will be considered to calculate the variations of the GCR flux. The Larmor radius of GCR particles propagating in the interplanetary magnetic field undergoing the Lorentz force and convection in the solar wind are the two processes affecting the cosmic-ray propagation that will be implemented in the Monte Carlo simulation. The effects of the convection in the solar wind will be implemented, in particular, as continuous energy losses of the particles. Tentative correlations between GCR variations and interplanetary magnetic field and solar wind speed separate increases will be set to evaluate if GCR variations may be inferred from models without particle detectors flown on the LISA spacecraft. These simulations are expected to require quite long execution time. I plan to explore different solutions to optimize the execution time involving programming languages (Python, Fortran, etc…) and the Monte Carlo design architecture. A pivotal objective of this project will be to assess the complexity of the simulation intended as its scalability with respect to both the number of simulated particles and the available computing power (i.e., the number of available cores), by assuming to have designed and implemented a Monte Carlo simulation executable in parallel. I plan to carry out theoretical estimates and then exploit some benchmarks to establish the algorithm complexity. This will be useful to evaluate if the present technology is already mature to execute the optimal version of the simulation or, otherwise, to estimate the gap between the present context and the required conditions. The optimal version of the program will be made available to the LISA Collaboration.

4) Expected results

Monte Carlo simulations of short-term galactic cosmic-ray variations observed on board LPF are expected to be reproduced with an overall particle flux uncertainty on a daily basis smaller than 1%. On the basis of lessons learned with LPF data, I will spot to which extent it will be possible to estimate the GCR flux variations on the basis of interplanetary magnetic field intensity obtained from LISA platform magnetic field measurements and with no solar wind speed measurements carried out on the LISA spacecraft. The final goal of this work is to estimate if Monte Carlo simulations of cosmic-ray variations will be sufficient or if it will be mandatory to fly a particle detector on board LISA dedicated to galactic cosmic rays in addition to the ESA Next Generation Radiation Monitors optimized for harsh radiation environments and in particular for short-forecasting and monitoring the evolution of solar energetic particle events. I plan to obtain these results that may impact on the mission design before its launch expected in 2035.