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Solar physics between the 24th and 25th solar cycles: observations and results from the High-Energy Particle Detector (HEPD-01) onboard the CSES-01 satellite

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Galactic cosmic rays, as well as particles accelerated to high energies either at the solar surface or in the interplanetary medium, are subject to a wide variety of phenomena that can modify their energy distribution, intensity and composition over different time-scales. These effects are greater in the low-energy portion of the spectrum, and it is crucial to have instruments that are able to monitor energy intervals as low as possible and for a prolonged period of time. After the seminal results of successful space-borne missions, past (PAMELA) and present (AMS-02), the China Seismo-Electromagnetic Satellite (CSES-01) mission - in particular the High-Energy Particle Detector (HEPD-01) - aims to continue such studies, well into the 25th solar cycle and beyond. HEPD-01, launched in February 2018, is a light and compact payload suitable for measuring electrons (3-100 MeV), protons (30-250 MeV), and light nuclei (up to a few hundreds of MeV) with a high energy resolution and a wide angular acceptance. The very good capabilities in particle detection and identification, together with the Sun-synchronous orbit, make this instrument very well suited for low-energy studies; moreover, being HEPD-01 just the first of a network of similar detectors that will be lunched in the forthcoming years, the evolution of particles inside the Sun-Earth environment is going to be fully investigated. The latest results on the long-term solar modulation of protons and helium nuclei and on impulsive phenomena like Solar Energetic Particle (SEP) events and Forbush decreases, are presented.

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1. Introduction

It is well-known that the interplanetary space, vast as it is, is not empty nor is it static over time nor uniform. Galactic cosmic rays (GCRs) are originated outside the solar system and then accelerated by energetic processes in the interstellar medium, showing a time-independent and isotropic distribution when arriving at the heliopause [1, 6, 7, 10]. However, after entering the interplanetary space, their energy distributions are modified by the turbulence in the solar wind - a plasma of ionized gas which is continuously expanding from the corona of the Sun at supersonic speed [20] also carrying an embedded magnetic field which generates the heliospheric magnetic field (HMF). Moreover, changes in galactic particle fluxes show a very clear time-dependence (e.g., Heber [12], Potgieter [24]), directly related to the periodical activity of the Sun [31] - of which the number of visible sunspots is one of the most used proxies [26]. During a period of minimum activity, the solar magnetic field structure is regular and spatially ordered, while, during maximum phases, it assumes a more chaotic configuration. This phenomenon is referred to as *solar modulation* [11, 21]. Furthermore, during maxima of solar activity, the near-Earth environment is disturbed by powerful emissions of particles coming from the Sun itself - the so-called Solar Energetic Particles, or SEPs. After decades of studies, it is now accepted that such SEPs are accelerated by both flares and shocks driven by coronal mass ejections (CMEs); they can be classified into impulsive and gradual events [8, 9, 14], based on their properties, acceleration source and particle composition. The difference between these categories is not sharp [4, 18, 25] and numerous studies are still ongoing to better understand such aspects. The overall shape of a solar particle spectrum during SEPs is crucial to shed more light on the mechanisms of production and acceleration, but this spectrum may exhibit a combination of signatures, linked to different processes, usually complex to disentangle. Furthermore, the transport of energetic particles inside the interplanetary space may play an important role [32]. For all these reasons, data from space-borne experiments like HEPD-01 - together with the information gained from other spacecrafts - could allow for a better understanding of the plethora of processes that charged particles (produced inside the heliosphere or coming from the interstellar space) undergo during their travel.

2. Limadou Mission and the HEPD-01 detector

The CSES-01 satellite [27] was launched on February 2, 2018, and is currently flying on a sun-synchronous polar orbit at ~507 km altitude, 97° inclination, and 5-day revisiting periodicity. It is the first of a network of multi-instrument satellites scheduled for launch in a few years. The mission objectives include monitoring of the electromagnetic field, plasma, and particle perturbations in the ionosphere and magnetosphere, either due to natural sources, like earthquakes, or artificial emitters. The orbital characteristics of CSES-01 allow for a detailed investigation of the high-latitude regions of the Earth - the ones more sensitive to the influence of the Sun, despite the fact that all payloads are switched off at ±65° of latitude (now increased to ±70°). The High-Energy Particle Detector - completely designed and integrated in Italy in the framework of the CSES/Limadou project - is one of the nine instruments on board the satellite and it is a light and compact payload (40.36 cm × 53.00 cm × 38.15 cm, total mass ~45 kg), made up of a series of sub-detectors: from the top of the detector, two double-sided silicon microstrips planes providing tracking information, a single layer of EJ-200 segmented plastic scintillator, a range calorimeter for energy measurement, composed of a stack (TOWER) of 16 plastic scintillators, P_1...P_{16}, and, finally, a 3×3 matrix of Lutetium-Yttrium Oxyorthosilicate (LYSO) inorganic scintillator crystals. The instrument is surrounded - laterally and at the bottom - by 5 plastic scintillators which reject out-of-acceptance particles or that do not deposit all their energy inside the detector (VETO). The payload is optimized to measure electrons in the 3-100 MeV energy range, and protons between ~30 and 300 MeV, as well as light nuclei. The HEPD-01 capabilities for various Space Weather topics have already been assessed in [5], Martucci et al. [16], [19], Piersanti et al. [23] and Martucci et al. [17]. More technical details can be found in [2, 3, 22, 28].

3. Data Analysis

The selection of galactic/solar protons in HEPD-01 is described in detail in dedicated papers [5, 15] and just a summary description is given here. After a valid trigger is acquired by the detector, only protons fully contained (e.g. those that stop inside the TOWER+LYSO sub-detector) are included in the final flux sample, while particles generating signal in one of the VETO planes are discarded. The discrimination between protons and other particle populations is performed using the P_1 signal distribution as a function of the total energy released inside the TOWER+LYSO sub-detector, as shown in Figure 1 (left). Regarding the geomagnetic selection applied to discriminate between protons coming from outside the magnetosphere and the under-cutoff re-entrant populations, we made use of a static map - reported in Figure 1 (right) - obtained using the AACGM (Altitude-Adjusted Corrected Geomagnetic) coordinates reference frame [29]. In this way, we corrected the estimation of the McIlwain parameter L obtained through the International Geomagnetic Field Reference (IGRF) model [30]; we selected only portions of the CSES-01 orbit that were above a value of the L-parameter greater than 7, to assure that all coming protons with energy >40 MeV were of cosmic origin (i.e. above the cutoff threshold). Of course, the same geomagnetic selection was applied to the estimation of the Live Time of the instrument for consistency purposes. A dedicated GEANT4 MonteCarlo simulation was used to estimate the geometrical factor, the various selection efficiencies and all the systematic uncertainties.

4. Some Results

The time-dependence in the GCRs is reported in Figure 2 (upper panel). Here, the time profiles of GCR protons measured by HEPD-01 in 10 energy intervals from ~0.050 to ~0.250 GeV between August 2018 and March 2022 are depicted. In the bottom panel, the sunspot number (blue) and Heliographic Current Sheet or HCS (red) tilt angle [13] are shown. The former is taken from `https://www.sidc.be/silso/datafiles`, while the latter - obtained with radial boundary conditions - is taken from the Wilcox Solar Observatory at `http://wso.stanford.edu/26`. The HCS tilt angle represents the misalignment of the magnetic dipole axis of the Sun with respect to the solar rotational axis and is one of the best proxies for modulation of charged particles in cosmic rays because its time variations are related globally to the solar magnetic field. A deep discussion on these results can be found in Martucci et al. [17].

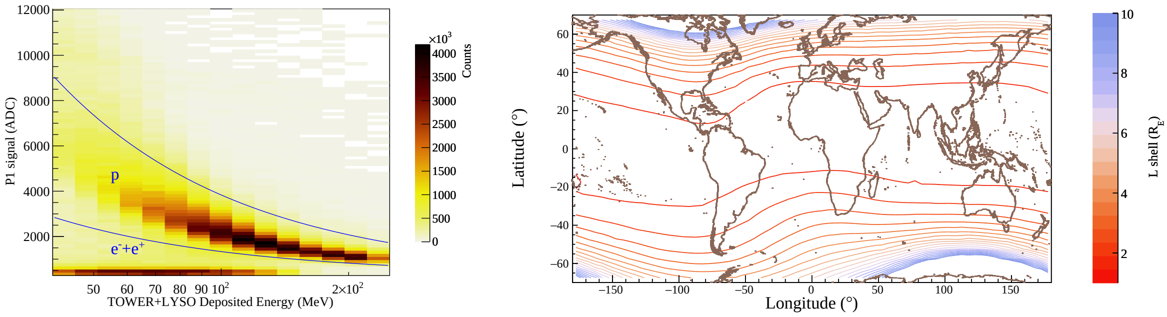

Figure 1: (Left) Proton and electrons+positrons signal on plane P_1 as a function of the total energy deposited inside the calorimeter (TOWER+LYSO). To better visualize the separation in the plot, only vertical particles have been selected. The blue curves identify the selection employed to discriminate between protons and other populations. (Right) Map of the distribution of L shell as a function of geographic longitude and latitude, obtained using the AACGM approach.

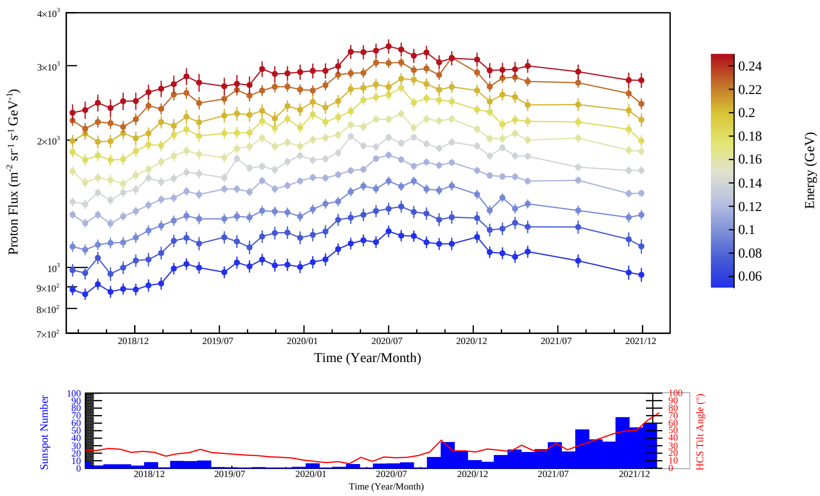

Figure 2: Time-profile of GCR protons measured by HEPD-01 in 10 energy intervals (upper panel) between 2018 and 2022. Error bars take into account both statistical and systematic uncertainties. Sunspot number - blue - and HCS tilt angle values - red - as a function of time, in the same period (bottom panel).

Figure 3 shows the time-profiles (scaled for a better visualization) of HEPD-01 galactic proton data between August 2021 and July 2022, a period in which ~9 medium-to-high SEP events took place. These SEPs are well visible in the plot, as peaks of various height, which are more pronounced at lower energies (~50 MeV) than at higher energies (~200 MeV). Each of these SEPs present some peculiar characteristics that have been studied to form a first catalog of solar events before entering the solar maximum. A comprehensive study of one of these events - the one of October 28, 2021 - has been carried out and published in Martucci et al. [16]

More results will be presented during the conference.

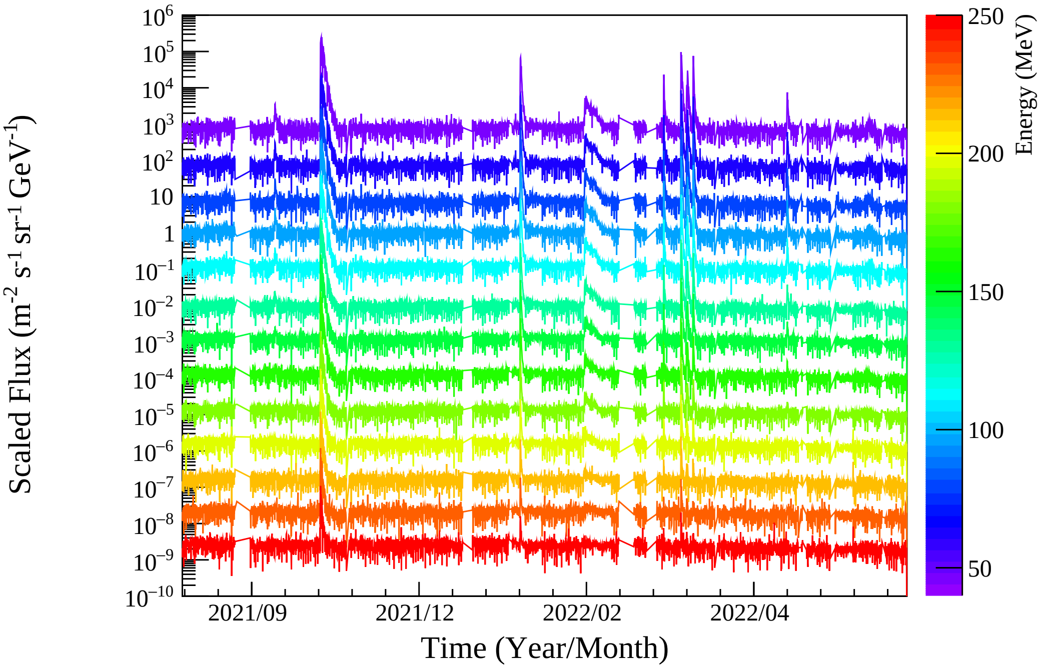

Figure 3: Time-profile (scaled for a better visualization) of GCR protons measured by HEPD-01 in 13 energy intervals from ~50 MeV to ~250 MeV. Spikes appearing over the background represent solar proton injections linked to the SEPs of the period 2021-2022.

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