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Solar Energetic Particles within the STEREO era: 2007-2012

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Abstract: STEREO (Solar TErrestrial RElations Observatory) recordings provide an unprecedented opportunity to analyze the evolution of Solar Energetic Particles (SEPs) at different observing points in the heliosphere, which is expected to provide new insight on the physics of solar particle propagation and acceleration as well as on the properties of the interplanetary magnetic field that control these processes. In this work, two instruments onboard STEREO have been used in order to identify all SEP events observed within the declining phase of solar cycle 23 and the rising phase of solar cycle 24 from 2007 to 2012, namely: the Low Energy Telescope (LET) and the Solar Electron Proton Telescope (SEPT). A scan over STEREO/LET protons within the energy range 6-10 MeV has been performed for each of the two STEREO spacecraft. We have tracked all enhancements that have been observed above the background level of this particular channel and cross checked with available lists on STEREO/ICMEs, SIRs and shocks as well as with the reported events in literature. Furthermore, parallel scanning of the STEREO/SEPT electrons in order to pinpoint the presence (or not) of an electron event has been performed in the energy range of 55-85 keV, for all of the aforementioned proton events, included in our lists. We provide the onset of all events for both protons and electrons, time-shifting analysis for near relativistic electrons which lead to the inferred solar release time and the relevant solar associations from radio spectrographs (Nanay Decametric Array; STEREO/WAVES) to GOES Soft X-rays and coronal mass ejections spotted by both SOHO/LASCO and STEREO Coronagraphs

1 Introduction

The Solar TErrestrial RElations Observatory (STEREO) was launched on October 25, 2006, on a Delta II rocket from Cape Canaveral Air Force Station on Florida, USA. It employs two nearly identical space-based observatories – one ahead of Earth in its orbit (STEREO-A: STA), the other trailing behind (STEREO-B: STB) – aiming at providing the first-ever stereoscopic measurements of the Sun [2]. STEREO incorporates four instrument suites, namely: SECCHI (Sun-Earth-Connection and Heliospheric Investigation), SWAVES (STEREO Waves), IMPACT (In-Situ Measurements of Particles and CME Transients) and PLASTIC (Plasma and Suprathermal Ion Composition)[2].

Solar Energetic Particle (SEP) events can be recorded and analyzed in great detail once utilizing the STEREO measurements from an armada of instruments onboard the aforementioned suites. The perspective that has been made possible through STEREO is clearly unprecedented. Currently, the detection of SEP events can take place at three different locations within the heliosphere (including L1), with high time resolution and directional information over the energy range from 10's of keV to 100 MeV.

SEPServer is a three year collaborative project (started in December 2010) funded under the seventh framework programme (FP7-SPACE) of the European Union. The basic objective of SEPServer is to provide an internet server that will give access to a large number of SEP datasets from different instruments on-board several missions, to electromagnetic (EM) observations related to the events indentified from the SEP data, and to state-of-the art analysis tools that can be used to infer the solar SEP emission time profiles and interplanetary transport conditions prevailing during the SEP events. Furthermore, the project will provide analysis results on the events in the form of comprehensive SEP event catalogues that list key properties of the events. Currently, the first SEPServer catalogue of SEP events based on SOHO/ERNE ≈ 68 MeV protons with complementary information from SOHO/EPHIN protons and electrons and ACE/EPAM electrons (including anisotropy information) and a statistical treatment of the results has been published [4], another catalogue based on Ulysses/COSPIN/KET protons (both of high $125 < \mathrm{E} < 250$ MeV and low $32 < \mathrm{E} < 125$ MeV energy) with complementary information on near relativistic electrons from Ulysses/HISCALE and lower energy protons from Ulysses/COSPIN/LET has been constructed. A first example of this Ulysses catalogue, together with the plan for its further exploitation has been presented in [1]. Furthermore, SEPServer presents two catalogues for Helios-A and Helios-B, resulting in the third and fourth catalogue of the SEPServer project. Both Helios catalogues are based on the systematic scan of the integral proton channel above 51 MeV. In parallel also the intensities of 37 MeV protons as well as > 2 MeV electrons were analyzed. Within the catalogues results of the scientific analysis has been tabulated: Onset time determination, detailed associations to the EM emissions have also been performed and presented using Observatory Solar Radio Astronomy (OSRA) data if available for the events. It is noteworthy that these two catalogues for the first time provide an easy access to SEP events that were recorded in the 70s at distances close to the Sun ranging from 0.3 to < 1 AU. All of the aforementioned catalogues have already been released to the scientific community through SEPServer at: `http://server.sepserver.eu` and it is foreseen that all of the material and the results presented in these, already four, catalogues will be freely utilized by the community.

In this work we briefly present the establishement of the last two catalogues to be released by SEPServer based on STEREO recordings observed within the declining phase of solar cycle 23 and the rising phase of solar cycle 24 from 2007 to 2012.

2 Instrumentation, Motivation and Implementation

Since our worked focused on SEP events we have utilized two of the instruments on-board the IMPACT suite at both spacecraft. STEREO is a 3-axis stabilized spacecraft pointing to the center of the Sun, with the IMPACT suite pointed along the nominal IMF field direction, 45° to the west of the Sun. We have primarily based our analysis on the Low Energy Telescope (LET) that measures low energy protons from 1.8–10(15) MeV, He within the energy range 4–10(15) MeV/n and heavier ions (for details see `http://www.srl.caltech.edu/STEREO/Level1/LET_public.html`). We have also utilized the Solar Electron Proton Telescope (SEPT) which records electrons ranging from 0.065–0.43 MeV and ions from 0.084–6.5 MeV (`http://www2.physik.uni-kiel.de/STEREO/index.php`). Our intention was to create comprehensive SEP event catalogues based on STEREO recordings.

Concerning the implementation, as noted here above, we have scanned the LET measurements of 6–10 MeV protons from 2007 to 2012. We have recorded all enhancements above the background of this channel (2×10^{-5} particles / cm^2 sr s MeV) and did not apply any other intensity threshold so that even small in magnitude events would be taken into account. Then we performed cross-checks with lists of Corotating Interactive Regions (CIRS) interplanetary shocks and Interplanetary Coronal Mass Ejections (ICMEs) (available at: `http://www-ssc.igpp.ucla.edu/forms/stereo/stereo_level_3.html`) with the aim to identify the solar origin of the initial enhancements. In parallel near relativistic electron measurements from SEPT were scanned, whereas the recordings of higher energy protons from the High Energy Telescope (HET) within the energy range 40 MeV $< E <$ 100 MeV were also taken into account to pin-point the SEP events in the catalogues that could potential have a space weather impact.

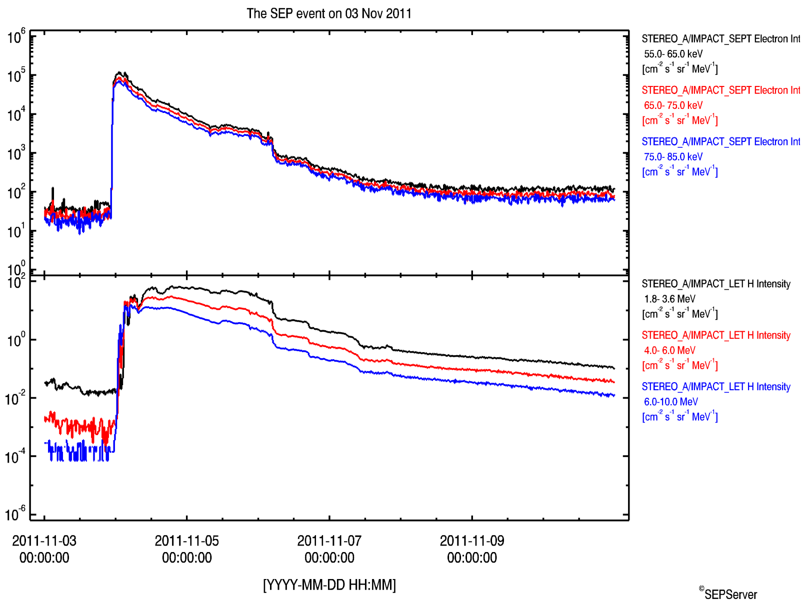

Figure 1: The SEP event on 03 November 2011, as this was recorded by electrons onboard SEPT ranging from 55–85 keV (upper panel) and LET protons ranging from 1.9–10 MeV (bottom panel). This figure was produced with the online available tool of SEPServer: http://server.sepserver.eu

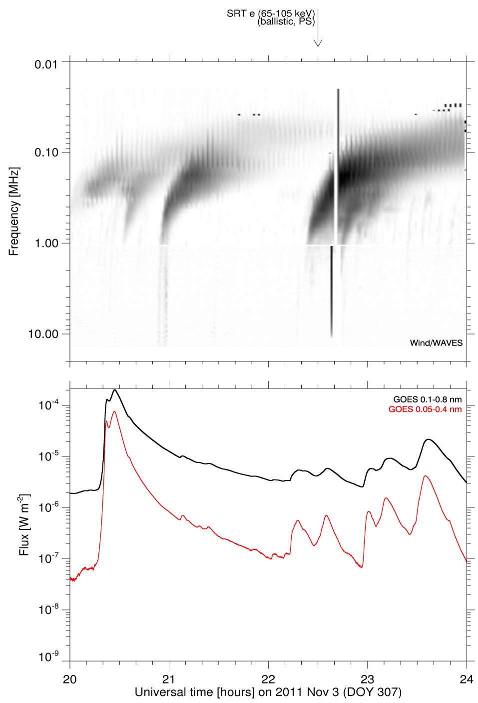

Figure 2: The relevant solar associated data for the 03 November 2011 SEP event as provided by the online SEPServer catalogue

3 Analysis and Released Information through SEPServer

For each event of the SEPServer STEREO catalogues, time-shifting analysis (TSA) was performed [4] in order to pinpoint the latest possible release (solar release time) of the particles at the Sun that is consistent with the determined onset time at each STEREO spacecraft.

For the first arriving particles we assume scatter-free propagation and we calculate the expected release time of the relativistic electrons, $t_{\rm release}$, adding 8.33 min for comparison with ground based EM observations (*e.g.* radio burst), as:

$$t_{\rm release} = t_{\rm onset} - \frac{L}{u} + 8.33 \text{ (min)}. \tag{1}$$

the nominal length of the Parker spiral L is computed based the solar-wind speed $u_{\rm sw}$ observed during the events, using the formula:

$$L = z(\approx 1\text{AU}) - z(R_{\rm s}) \tag{2}$$

with $z(r)$ expressed as:

$$z(r) = \frac{a}{2}[\ln(\frac{r}{a} + \sqrt{(1 + r^2/a^2)} + \frac{r}{a}\sqrt{(1 + r^2/a^2)}] \tag{3}$$

and $\alpha = u_{\rm sw}/\Omega$, given that Ω corresponds to the sidereal rotation period (i.e. $2\pi/\Omega = 24.47$d). We have used the, $u_{\rm sw}$ measured by the STEREO/PLASTIC instrument for each event in our lists (available at `http://aten.igpp.ucla.edu/forms/stereo/level2_plasma_and_magnetic_field.html`).

This timing was used as an input for the establishment of the relevant solar associations based on soft X-rays (GOES), radio data (from Wind/WAVES, SWAVES on both STEREO and ground based facilities such as ARTEMIS-IV) as well as with hard X-rays (HXRs).

An example of an SEP event recorded by STA on 03 November 2011 is presented in Fig.1. In the online version of the STEREO Catalogues though the SEPServer server at: `http://server.sepserver.eu` the user can retrieve such plots, onset and peak time for each particle species, start and end time of the relevant solar related data (see Fig.2) as well the position of the spacecraft (in degrees) and its distance (in AU). Multiple levels of information include HXRs recordings and the apparent solar source derived from RHESSI data wherever possible, TSA results for each event and combined electron and proton plots for each of the identified multi-spacecraft events [3].

4 Results

Our scanning has led to a total of 130 events for STA and 113 events for STB, with a much smaller subset of events being recorded onboard both spacecraft fulfilling the multi-spacecraft scheme [3]. One should note that SEP catalogues are a vital part of SEP research as those include crucial information on the event (i.e. basic characteristics, energy channels used in the analysis) as well as observational data accompanying the parent solar activity. To this end SEPServer project greatly facilitates this need, releasing six catalogues of SEP events recorded at distances of 0.3 AU to > 5 AU in and out of the ecliptic, including data driven analysis and the relevant solar associations.

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