SEPServer solar energetic particle event catalogue in and out of the ecliptic; a Ulysses COSPIN/KET, COSPIN/LET and HISCALE particle data driven study

B. Heber¹, N. Agueda², D. Heynderickx³, K.-L. Klein⁴, O. E. Malandraki⁵, A. Papaioannou⁵, B. Sanahuja², and R. Vainio⁶

¹Christian-Albrechts-Universität zu Kiel, Germany, ²Departament d’Astronomia i Meteorologia, Universitat de Barcelona, Barcelona, Spain, ³DH Consultancy BVBA, Leuven, Belgium, ⁴LESIA-Observatoire de Paris, CNRS, UPMC Univ Paris, ⁵Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, Greece, ⁶Department of Physics, University of Helsinki, Finland

heber@physik.uni-kiel.de

Abstract: SEPServer is a three-year collaborative project funded by the seventh framework programme (FP7-SPACE) of the European Union. The objective of the project is to provide, among other things, access to state-of-the-art observations and analysis tools for the scientific community on solar energetic particle (SEP) events. The study of SEPs at different latitudes and under different conditions provides useful information about energetic particle propagation and acceleration, and is one of the focus areas of the project. The Ulysses mission, launched in 1990, explored the three dimensional heliosphere during different solar activity conditions until the spacecraft was finally switched off on June 30, 2009. The mission has been the only one that allowed us to study the characteristics of SEPs at low and high latitudes. In this work, the Cosmic Ray and Solar Particle Investigation (COSPIN) Kiel Electron Telescope (KET) data of 38 to 125 MeV has been used to identify a number of 40 events SEPs observed in and out of the ecliptic plane over solar cycle 23. Using electron observations from the Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies (HISCALE) and proton intensities from the COSPIN Low-Energy Telescope (LET), different characteristics of these events have been determined and compared with simulation based analysis and remote sensing data from radio and optical observation. The event catalogue presented in this paper will be available to the community for further analysis through http://server.sepserver.eu.

Keywords: Solar energetic particles, Analysis tool, Latitudinal distribution

1 Introduction

SEPServer (www.sepserver.eu) is a collaborative project of eleven European partners funded by the European Union’s Seventh Framework Programme. The project was launched in December 2010 and will run for three years. The main objective of the project is to develop an Internet server facilitating access to solar energetic particle (SEP) data and related electromagnetic observations and to browsing tools and state-of-the-art analysis methods. The database will contain SEP observations from a number of spacecraft at L1 and from HELIOS, Ulysses and STEREO. Electromagnetic observations from ground-based radio observatories and from Earth-orbiting and interplanetary observatories will also be included. The server will be released to the community in November 2013. In addition, the project will perform a preliminary analysis of the SEP events observed by several spacecraft and provide these results to the community in form of event catalogs. The results are available online (server.sepserver.eu) in a reusable form and the community is encouraged to make use of the results in further studies.

The first SEPServer event catalogue [22] is based on SOHO/ERNE observations of ~68 MeV proton intensities and contains 115 SEP events from 1996–2010 observed at L1. The focus of the project is now on spacecraft observations of missions at other locations, i.e., STEREO, HELIOS and Ulysses. In order to establish such a catalogue of high-energy SEP events at different helio latitudes we visually scanned through Ulysses/KET [20] data for the time period from May 1996 till the end of the mission. Intensity enhancements of protons in the energy range 38-125 MeV (average energy 68.3 MeV) were searched for. From that data we derived a catalogue of 40 proton events. From these 16 SEP events were obtained at polar latitudes above 60°. One of them is the Novem-
2 Observations

Ulysses, launched in October 1990, began its second out-of-ecliptic orbit in September 1997. In 2000/2001 the spacecraft passed from the south to the north polar regions of the Sun. In contrast to the first rapid pole to pole passage in 1994/1995 close to solar minimum, Ulysses experienced solar maximum conditions. Figure 1 displays from top to bottom the count rate of 38-125 MeV protons as measured by the Kiel Electron Telescope [20], Ulysses’ heliographic latitude and radial distance, the observed solar wind speed and the longitude of the footpoint of the nominal Parker spiral using the measured solar wind speed of panel 4 from [6] during Ulysses’ solar maximum fast latitude scan [6]. A series of SEP events were detected at high southern heliographic latitudes (July 14, 2000 (#03), September 12, 2000 (#04) and November 9, 2000(#06)), close to the ecliptic plane (January 21, 2001, April 1 and 3, 2001 (#08 09&10), June, 15 (#16)) and at northern polar latitudes (August 16, 2001 (#19), September 24, 2001 (#20), November 4, 2001 (#21), November 23, 2001 (#22), December 26, 2001 (#24), and April 21, 2002 (#27)). The start times of the SEP events are indicated by dots in the figure.

In what follows we discuss the November 4, 2001 SEP event: The time profiles of 0.18 to 0.3 MeV and ~7 MeV electrons measured by Ulysses/HISCALE (blue curve, [11]), ACE/EPAM (brown curve, [9]), Ulysses KET (red curve) and SOHO/EPHIN (black curve, [18]) as well as the 38-125 MeV and 8 to 19 MeV protons, measured by the KET (black curve) and the Low Energy Telescope (blue curve) together with the SOHO/ERNE 80 to 101 MeV (red curve, [21]) and the SOHO EPHIN 7.8 to 25 MeV protons (brown curve) are shown in Figure 2. The event was observed by Ulysses when it was at high-northern heliolatitudes (77°), at a radial heliocentric distance of 2.2 AU, and embedded in a fast solar wind flow from the northern polar coronal hole (see Figure 1 and Table 1), where only an inward magnetic field polarity was observed [16]. On the other hand, ACE and SOHO were in orbit around the L1 Sun-Earth libration point and embedded in a slow solar wind stream. Although a forward shock is marked on November 8, 2001 at 06:53 UT at Ulysses [4] and an interplanetary coronal mass ejection (ICME) is present from November 8, 2001 at 14:40 UT until November 10, 2001 at 15:20 UT [7], the onset of the event can be considered as clear. The onset and time of maximum of the event, as summarized in Table 1, were observed several hours later at Ulysses than at ACE or SOHO. While the maximum intensity were lower at Ulysses the decay phase is characterized by identical intensity time profiles, indicative for the reservoir effect [17, 14]. The analysis by [12] shows stronger antisunward anisotropic flows during the onset at ACE than at Ulysses.

1. http://www3.imperial.ac.uk/portal/pls/portallive/docs/1/719930.TXT
3 Solar release time determination

One possibility to determine the solar release time is the so-called velocity dispersion analysis (VDA) of an SEP event \([22]\). It is based on the determination of the onset times of the event at various energies and the presentation of these onset times as a function of the inverse velocity of the particles at the respective energies. The linear fitting of the onset times as a function of the corresponding inverse velocity, estimates both the release time and the apparent path length of the particles. We apply this method for both Ulysses/COSPIN/KET and LET proton measurements, thus ranging between 1.8–250 MeV.

3.1 Onset time determination

Onset time determination for COSPIN/KET measurements based on two methods: the Poisson-CUSUM \([10]\) and the Fit one, hereafter labeled as method A and B, correspondingly. Method A is analogous to a statistical quality control scheme deciding whether or not a process is in control, and if not, gives the time when the failure happened. In our case, the failure is an SEP event causing intensities to rise above the pre-failure background. According to method B, the user applies an exponential fit to the recorded counting rate of the channel involved in the analysis. The corresponding function is \(C(t) = C_0 + C_1H(t_1)e^{\alpha t}\), with \(H(t_1)\) being 0 when \(t \leq t_1\) and 1 in case \(t > t_1\). At COSPIN/LET as well as on HISCALE measurements, we have applied another algorithm, labeled as method C, which aims to an objective identification of the onset time for each energy channel. It compares the counts of the detector of a specified time window with the data just ahead of it. The main steps can be summarized as follows: Firstly, the algorithm determines the average intensity \((\langle I \rangle)\) and the standard deviation \(\sigma\) inside the specified time window, following that, it compares the data just ahead of this window with a threshold \(\langle I \rangle + n \cdot \sigma\), where \(n\) can be chosen by the user (typically \(3 \cdot \sigma\) are used). When a number \(m\) of consecutive points fulfills such condition, the onset is defined as the time stamp of the first point above the threshold\([15]\).

The results of the different methods for the onset time identification have been tabulated in the Ulysses SEP Catalog found under http://server.sepserver.eu. A snapshot of the Ulysses Catalog is shown at Table \([1]\). As can be seen in Table \([1]\), SEPServer aims at facilitating and testing different analysis methods. Table \([1]\) provides the date of the event in column 1, the onset time determined under each method (i.e. A, B, C): for KET 38–125 MeV protons (columns 2 and 3), 125–250 MeV protons (columns 4 and 5); for HISCALE near relativistic electrons (column 6), the position of Ulysses i.e. distance (in AU at column 7), heliolatitude and heliolongitude in (°) in columns 8 and 9. Column 10 gives the solar wind speed during the onset of the event (in Km/s) and column 11 the length of a Archimedian spiral from the Sun to Ulysses (in AU).

3.2 VDA results

Figure \([3]\) presents the onset times of the proton events in both KET and LET channels with respect to the soft x-ray onset (SXR) at 16:03 UT as a function of the inverse velocity of the mean energy of each channel. Applying the VDA, combining the results of methods A & C (noted by red and green color in Fig. \([3]\)) we obtained an apparent path length \(L = 2.6\) AU that is in reasonable agreement with the one in column 10 of Table \([1]\) and a solar release time \(t_0 = 20.47\) UT. The application of the VDA using the results of methods B & C (noted by blue and green color in Fig. \([3]\)) provides an apparent path length \(L = 4.7\) AU that overestimates the path length and a solar release time \(t_0 = 17.40\) UT. Comparing the release times the VDA results based on A & C with the one based on B & C yields even longer delay of the SRT compared to the onset of the SXR associated flare \([5, 6, 4]\).

4 Simulation-based analysis

In a recent study \([4]\), the modeling results for the near-relativistic electron events observed on 2001 November 4 by the ACE/EPAM and the Ulysses/HI-SCALE experiments were presented. This study could be taken as an example on how to apply the Green’s function provided by SEPServer for an SEP event study. These functions describe the pitch angle distribution (PAD) of near relativistic electrons at certain location in the inner heliosphere. They were calculated by using the particle transport model of \([11]\) to simulate the propagation of these electrons along a given Parker magnetic tube. This model is based on the focused transport equation \([19]\) and computes these PADs for a delta injection close to the Sun \([3]\). For simplicity, \([4]\) isotropic pitch-
angle scattering is assumed. Thus the only free parameter is the radial mean free path $\lambda_r$ that is assumed to be constant [8], describes the degree of pitch-angle scattering processes undergone by the energetic particles.

In order to be able to invert spacecraft observations as provided by SEPServer, it is necessary to fold the simulated Green’s function with the angular response of each experiment in order to derive the corresponding Green’s intensities [1, 2]. Then, the inversion problem was solved and the best fit injection function was determined using the observations to constrain the problem. SEPServer will make a large database of Green’s functions available on line, as well as inversion tools for several spacecraft experiments including Wind, ACE, Ulysses and STEREO.

According to [4], the events observed on 2001 November 4 by ACE and Ulysses were consistent with a value of $\lambda_r$ of 0.24 AU and 0.27 AU, respectively. The similar $\lambda_r$ values suggested comparable interplanetary transport conditions for the NR electrons observed at high and low heliolatitudes. The best-fit electron Green’s function peaks 0.6 h (2.6 h) after release at the ACE (Ulysses) location. The omni-directional peak intensity is 7 times larger at 1 AU than at 2.2 AU and the peak pitch-angle distribution is more isotropic at the Ulysses location; 58° (130°) wide at 1 AU (2.2 AU).

The event catalogue provides also information about the electromagnetic emission if possible. Thus following [4], the inferred electron release times shifted by the travel time of solar electromagnetic emission to 1 AU was determined to be 16:27 UT and 18:08 UT in the flux tube connecting ACE and Ulysses with the Sun, respectively. While the time at low latitudes and at 1 AU is 30 min before the peak in SXR emission, 3 min before the beginning of the reported type II radio emission and 8 minutes before the CME was first observed in the C2 coronagraph at 4R$_S$, the values at Ulysses are $\sim$1.5 hours delayed. In addition the injection time is much more extended at Ulysses (>3 h) w.r.t. the Earth (≈2 h) and the maximum injection rate for Ulysses is about two orders of magnitude smaller than for ACE.

5 Summary

We have performed a scan of 38–125 MeV proton fluxes observed by Ulysses KET in 1996 to the end of the mission. A total of 40 SEP events were identified from this time period. Here we performed a VDA on the November 4, 2001 proton event, using KET and LET observations in several energy channels between 1.8–250 MeV and different methods of onset time determination, to get estimates of the solar release time and the apparent path length in the interplanetary medium of the firstarriving protons. In order to compare the event characteristics at two location in the inner heliosphere a study using the Greens function delivered by SEPServer has been summarized [4].

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References