

The role of large scale solar magnetic field for distribution of SEP in the 3D Heliosphere

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Abstract. Large scale structures of the solar magnetic field may play a crucial role for propagation of the solar energetic particles (SEP) to the observer. Here we investigate this question using an example of SEP observations in different points of the heliosphere in December 2006. The active Region 10930 rotating with the Sun from its East to West limb produced four X-class flares on December 5, 6, 13 and 14. The particle signature of these events were observed close to Earth and 70 degree South above the ecliptic by the Ulysses spacecraft, which was at a heliocentric distance of 2.8 AU at that time. Comparable SEP fluxes were detected by Ulysses and GOES on December 5. On December 6 SEP flux was significantly larger at Earth, than at Ulysses. The SEP fluxes from the parent flares on December 13 and 14 were substantial near the Earth, but were practically invisible above the KET/Ulysses background.

Using the Potential Field Source Surface model we develop a preliminary technique to simulate magnetic field inside the spherical coronal shell $1.5 R_{\odot}$ above the photosphere and to test magnetic connection of the parent flares sites with the spacecrafts' Parker spiral footpoints on the Source Surface. It is shown that the quasi-stationary model coronal magnetic field can qualitatively explain the peculiarities of the December 5, 13, 14 SEP events. The model does not work properly for the December 6 observations near the Earth, possibly due to CMEs reconfiguration of the coronal and/or the interplanetary magnetic fields. Further analysis of three additional SEP events on 14 July and 12 September 2000, and 4 November 2001 leads to the conclusion that the coronal magnetic field can arrange a "magnetic path" for the SEP propagation from flare sites to distant heliolatitudes and heliolongitudes.

Keywords: model coronal magnetic field; solar energetic particle release from the corona

I. INTRODUCTION

One of the scientific goal of the Ulysses mission to the high heliolatitudes for the Cosmic ray and Solar Particle Investigation (COSPIN) instrument was to determine the role of coronal magnetic fields for the storage and propagation of SEP, the importance of emission of energetic particles from regions other than solar flares [1]. Since the SEP source might not be extended similarly

in latitude as in longitude and the theoretical ratio of the cross and along field diffusion coefficients is rather small, it has been questioned before the Ulysses mission whether SEP would be detectable at polar latitudes in the heliosphere. However SEP were detected both during the solar maximum south (August-December 2000) and north polar (August-December 2001) passes. The authors of [2] found that for almost all large SEP events, significant particle increases both near Earth and at Ulysses were observed. Therefore their detection is independent of the spacecraft positions relative to the location of the flare and CME. The SEP events at highest latitudes are characterized by 1) a delay of the event onsets, 2) a longer rise time towards maximum, and 3) significant smaller maximum intensities when compared to measurements near the Earth.

The SEP release time from the solar source derived from the high latitude measurements is between 100 and 350 min later than the release time derived from in-ecliptic measurements [3]. They showed that the parameter, which best orders this characteristic, is the difference in latitude between the associated flare and the spacecraft. If shock acceleration is of some importance it is expected that the delay and the inverse speed of the corresponding interplanetary shock should be correlated. This was, however, not observed. The model of SEP acceleration by coronal mass ejections driven shocks does not account for the Ulysses observations according to [4]. During the rising phase of a solar particle event an efficient cross-field diffusion close to the observer can be excluded, since the particle flow direction during the rising phase of the events is essentially field aligned [5]. They found no evidence for any net flow across the field lines for the events, which occurred in the high-latitude high-speed solar wind (the north polar pass in August-December 2001).

Analysing eight large SEP events of 2000-2001 the authors of [6] have noticed that during the rising phase, the first 30 hours, the time histories for the high latitude events at Ulysses are the same within a factor of ≈ 3 similar, in contrast with near Earth observations of the same events. This excludes the cross-field diffusion of SEP as dominant particle transport from the ecliptic to high latitude regions and rather requires a direct particle injection at high latitudes from a region very close to the Sun. Since SEP acceleration at high solar latitudes is very unlikely we need investigating other possibilities of their transport from active region to high latitudes.

Here we investigate a role of large solar magnetic field structures for SEP propagation to the observer using an example of SEP observations in different points of the heliosphere in December 2006 (Section II) jointly with coronal magnetic field modeling (Section III). Preliminary analysis of the KET/Ulysses observations at high latitudes in December 2006 was done in [7].

II. OBSERVATIONS

Fig. 1 summarizes solar proton observations during the December 2006 activity period at polar latitudes (Ulysses) and near Earth (GOES, STEREO). We compare in logarithmic scale proton intensities measured aboard these three spacecraft within similar energy bands of 38-250, 40-80, 40-60 MeV respectively and show KET data from the 250-2000 MeV proton channel in linear scale. A simple inspection of Fig. 1 shows that three proton intensity increases related to the solar events on December 5, 6 and 13 are observed in the 38-250 MeV range both by Ulysses and STEREO and additionally one more near the Earth on December 14. First two events are merged together within lower energies, but they are clearly distinguishable within 250-2000 MeV at the Ulysses location. We underline three issues: 1) comparable proton intensities measured in both locations on days 339-340; 2) the sudden intensity increase observed at 20:30 UT on day 340 near the Earth; 3) relatively small proton intensity increase observed by Ulysses on days 347 and 348. Below we will try to resolve these issues modeling magnetic connection between flare site and footpoint-region of spacecraft interplanetary magnetic field lines on the Source Surface.

III. MAGNETIC FIELD MODELING

We suppose that the structured quasi-stationary magnetic field of the solar corona is globally potential and can guide accelerated charged particles through the corona. Indeed, the Larmor radius of 100 MeV protons is ~ 1 km in 10 gauss field, which is much less than the observed width of the most common coronal structures: e.g., coronal loop width is ~ 1 Mm [8] and polar coronal plume width is ≈ 25 Mm [9]. To qualitatively verify the assumption we implement special technique, which combines magnetic field simulation in the coronal volume using the Potential Field Source Surface (PFSS) model [10] with determination of the footpoint-region of the spacecraft's nominal Parker spiral for the interplanetary magnetic field on the Source Surface. This region, we believe, can act as an "open window", through which SEP can be injected into the interplanetary magnetic flux tubes connecting spacecrafts and the solar corona.

Below we describe a preliminary technique, which we have developed and implemented to each SEP event from Table I. Three extra SEP events, observed in the ecliptic plane and in high heliolatitudes, are added for the analysis, in addition to four December 2006 events. The technique is illustrated by the December 5 SEP event (Fig. 2).

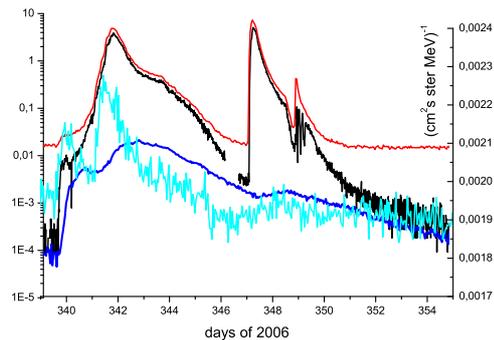


Fig. 1: Time profiles of hourly averaged proton intensities measured by KET/Ulysses during the December 2006 flare series: 250-2000 MeV - cyan (right linear Y-axis) and 38-250 MeV - blue; GOES: 40-80 MeV - red; HET/STEREO: 40-60 MeV protons - black (left log Y-axis).

- 1) To simulate magnetic field within the current-free (potential) approximation in the spherical coronal shell $1.5R_{\odot}$ above the photosphere we use PFSS model developed and embedded into the SolarSoftWare as PFSS-package by Schrijver and DeRosa [10]. As the lower boundary condition the routines of field calculation use the synoptic magnetic field maps calculated with the evolving surface flux model [11]. When available, full-disk photospheric line-of-sight magnetograms from the Michelson Doppler Imager (MDI) onboard the SOHO satellite are assimilated into the field model. After the assimilation process the model continuously evolves magnetic flux patterns over the photosphere standardly producing magnetic maps with the linear pixel size 1° every 6 hours. Magnetic field is assumed to be radial directed on the upper boundary, i.e., on the Source Surface (red grid on Fig. 2) due to action of the solar wind.
- 2) From the mathematical point of view the easiest way to describe magnetic field configuration is to use field lines (FL) described by a system of ordinary differential equations: $dx/B_x = dy/B_y = dz/B_z$. As generally accepted, FL that reach the Source Surface radially directed we call "open", and FL that have a pair of photospheric footpoints of different magnetic polarities we call "closed".
- 3) We assume that the accelerated charged particles could be guided through the corona mainly by these FL. At the present time we totally neglect charged particle pitch-angle scattering by the self-generated MHD waves, Coulomb collisions or, say, magnetic field turbulence in the hypothetical current-sheets.
- 4) Using the PFSS model we simulate 10000 open and closed FL (only 10 of them are plotted on Fig. 2 by thin blue lines for clarity) starting from

TABLE I: Parent solar flares of the analysed SEP events; Ulysses position in the Heliosphere; Ulysses and Earth Parker spiral footpoint position on the Source Surface (SS); features of the model magnetic connection of the flare region with the observer's Parker spiral footpoint-region on the SS. See Section III-A for the notations description.

SEP event	14.07.2000	12.09.2000	04.11.2001	05.12.2006	06.12.2006	13.12.2006	14.12.2006
Day of year	196	256	308	339	340	347	348
H α flare position	N22W07	S12W18	N06W18	S07E79	S06E63	S06W24	S06W46
Soft X-ray flare onset, UT	10:03	11:31	16:03	10:18	18:29	02:14	21:07
Ulysses coords (Heliogr)	S62E116	S71E163	N78W63	S73W120	S73W119	S74W115	S74W114
Ulysses distance, [R_{\odot}]	3.2	2.8	2.2	2.8	2.8	2.8	2.7
Ulysses coords (Heliogr) on SS	S62W10	S71E04	N78W137	S73E158	S73E156	S74E168	S74E157
Earth coords (Heliogr) on SS	S00W37	S00W61	S00W73	S00W72	S00W49	S00W36	S00W32
Ulysses $\Delta\Lambda$, [deg]	84	61	90	80	85	100	99
Ulysses $\Delta\Phi$, [deg]	39	13	58	41	11	39	32
Ulysses $\Delta\Psi$, [deg]	1	1	14	1	26	12	11
Ulysses $\Delta\Theta$, [deg]	0	1	21	0	-	14	9
Earth $\Delta\Lambda$, [deg]	37	44	55	150	112	13	15
Earth $\Delta\Phi$, [deg]	0	0	23	64	35	0	0
Earth $\Delta\Psi$, [deg]	0	0	0	18	16	0	0
Earth $\Delta\Theta$, [deg]	0	1	1	25	16	0	9

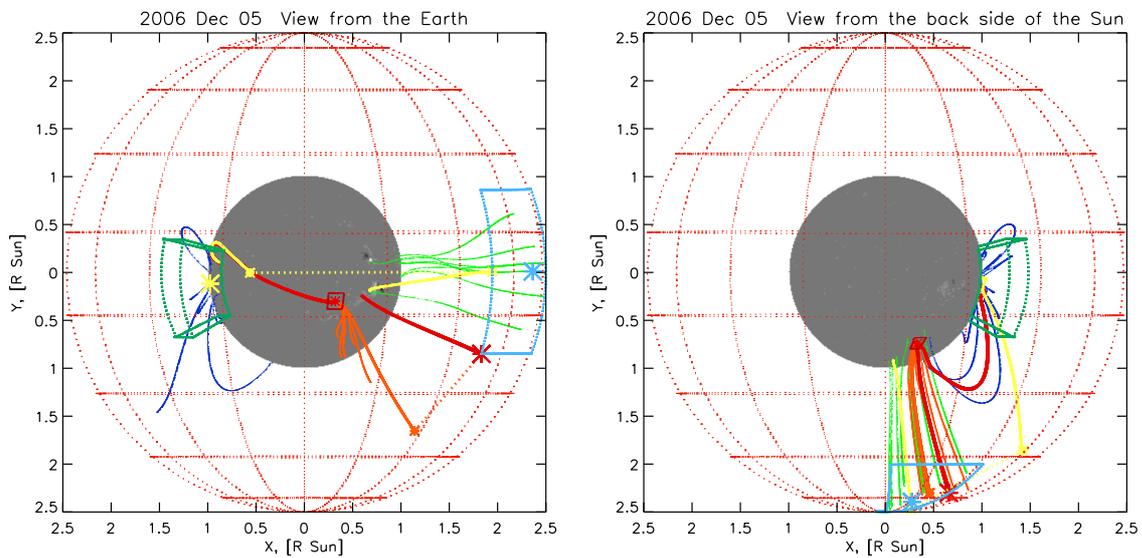


Fig. 2: Magnetic connection of the parent flare region (thick green-grey box) with the spacecraft's Parker spiral footpoint-region (thick cyan polygon) on the Source Surface (thin red grid) by field lines of the model magnetic field for the 5 December 2006 SEP event. *Left*: Earth connection. *Right*: Ulysses connection. Grey solar disk is the low-resolution equivalent of a full-disk magnetogram. See notations in Section III-A.

the random-generated points inside the coronal volume (thick green-grey box on Fig. 2) of $\pm 20^\circ$ around and $0.5R_{\odot}$ above the nominal soft X-ray flare position (large yellow asterisk on Fig. 2) reported in the *Solar Geophysical Data*. We call these FL “flare”. We emphasize that this volume is very model-dependent. We assume that charged particles can be accelerated in this volume, but we do not refer to the special physical mechanism of particle acceleration, whether this is some flare or shock acceleration.

- We simulate about 400 open coronal FL (only 8 of them are plotted on Fig. 2 by thin light green lines) starting from the equally-spaced points of the region (thick cyan polygon on Fig. 2) $\pm 20^\circ$ around the nominal footpoint (large cyan asterisk on Fig. 2) of the spacecraft's Parker spiral for the interplanetary magnetic field on the Source

- Surface. We call these light-green FL “spacecraft”.
- To calculate the Earth's and Ulysses's Parker spirals we use solar wind speed data obtained with the SWEPAM/ACE and the SWOOPS/Ulysses instruments, respectively. Note, we generate the large footpoint-region by hands just to include possible ambiguity of the Parker spiral reconstruction method due to the solar wind speed irregularity and diffusion of the magnetic field lines in the interplanetary medium. For example, it was shown by [12] that the longitudinal scattering of the Parker spirals' footpoints on the Sun due to random walk in the interplanetary medium can achieve $\pm 10^\circ$.
- Thus, we know coordinates and magnetic field vector in each point of each simulated FL,

quantity of which we consider sufficient for our purposes. Firstly, we try to find the direct magnetic connection of the flare region with the spacecraft's footpoint-region on the Source Surface. To do this, we find the nearest open “flare” and “spacecraft” FL (Fig. 2; two thick yellow lines) by finding the minimum angular distance $\Delta\Phi$ between their footpoints on the Source Surface (Fig. 2; small yellow asterisks). See Table I.

- 8) Secondly, we try to find the magnetic connection of the flare region with the “spacecraft” FL via the closed “flare” FL. To do this, we firstly find the nearest “flare” closed and “spacecraft” open FL (Fig. 2; two thick red lines) by finding the minimum angular distance $\Delta\Psi$ between their footpoints on the photosphere.
- 9) After this step, we simulate 500 FL (only small amount of them are shown on Fig. 2; thin orange lines) starting from the randomly generated photospheric points inside the rectangle (Fig. 2; thin red rectangle) $\pm 5^\circ$ around the footpoint of the “flare” closed FL found at the previous step.
- 10) Finally, we find the nearest thin orange and open “spacecraft” FL (Fig. 2; two thick orange lines: one of them coincides with thick red line on the left panel, and they are merged together on the right panel) by finding the minimum angular distance $\Delta\Theta$ between their footpoints on the Source Surface.

We emphasize here, that the technique developed in this work is still very rough. It must be considered as the first “iteration” for more sophisticated methods, which are under development at this time. In this work we just start to investigate, whether there is a tendency to reduce the angular distance $\Delta\Lambda$ (between the flare position and the spacecraft's Parker spiral footpoint on the Source Surface), which the observed SEP have to overcome, by FL of the model coronal magnetic field.

IV. MODEL RESULTS AND CONCLUSIONS

Table I contains the main model parameters ($\Delta\Phi$, $\Delta\Psi$, $\Delta\Theta$), which quantitatively indicate different types of magnetic connection of the flare region with the observer's Parker spiral footpoint-region on the Source Surface by the model FL. In the frame of our model it is clear that:

- 1) FL of the model coronal magnetic field significantly reduce the nominal angular distance $\Delta\Lambda$ between possible region of SEP acceleration and the observer's Parker spiral, facilitating the way of SEP to the observer.
- 2) Magnetic connection of the Ulysses's Parker spiral with the parent flare site via FL was much better on 5 and 6, than on 13 and 14 of December that can qualitatively explain why Ulysses observed larger SEP fluxes in the first two SEP events.
- 3) Magnetic connection of the Earth with the parent flare site via FL was practically the same on December 5 and 6 (although a bit better on December 6), while the maximal SEP flux on GOES was significantly larger in the December 6 event. This suggests that the model magnetic field is inadequate in this case, possibly due to CMEs action.
- 4) From our modeling it is not evident why SEP fluxes were comparable at Ulysses and at GOES on December 5.

We emphasize that the model parameters ($\Delta\Phi$, $\Delta\Psi$, $\Delta\Theta$), although giving some qualitative understanding of the magnetic connection in most analysed events, are still rough and not allowed to make conclusions on the quantitative level. The developed technique of the magnetic connection finding should be significantly improved even in frames of the used not perfect PFSS model (it was shown by [13] that the PFSS model reconstructs coronal magnetic field significantly deviating from the observed one in many active regions). Moreover, the role of dynamic processes, such as CME, on reconfiguration of coronal and/or interplanetary magnetic fields remains unclear.

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