# The Effects of Magnetic Boundary on the Uniform Distribution of Energetic Particle Intensities Observed by Multiple Spacecraft

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## Abstract

In the decay phase of solar energetic particle (SEP) events, particle intensities observed by widely separated spacecraft usually present comparable intensities (within a factor of 2–3) that evolve similarly in time. The phenomenon of SEP events is called a reservoir, which could be observed frequently in intensive gradual SEP events. In this work, we find the effects of the magnetic boundary could help to form the reservoir phenomenon in energetic proton and electron events. In the 1978 January 1 and the 2000 November 8 SEP events, we find the effects of the magnetic boundary associated with the reservoir phenomenon were observed simultaneously in the sheath of magnetic cloud/interplanetary coronal mass ejection. Based on the observations, we suggest that the effects of the magnetic boundary could help to form the reservoir phenomenon in both the energetic proton and electron events in some large SEP events.


## The Energetic Proton Event on 1978 January 1

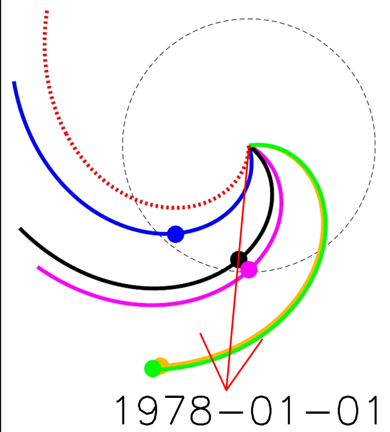


Figure 1. The locations of Helios 1, Helios 2, IMP 8, Voyager 1, and Voyager 2 are indicated by the blue, black, pink, green, and yellow dots, respectively. To use a Parker solar wind model with a speed of 400 km s$^{-1}$, the longitudinal coordinates of the spacecraft magnetic footpoint are shown in the figure. The nominal Parker field line that originates from the solar flare is represented by the dotted red spiral and the longitude of the flare is indicated by the arrow. The orbit of the Earth is represented by the circle.

As shown in the Figure 1, during the period of 1978 January 1 to 7, Helios 1 was near 1 au, Helios 2 and IMP 8 were close to one another near 1 au, and Voyager 1 and Voyager 2 were close to one another near 2 au. In the event, Burlaga et al. (1981) analyzed the plasma data from five spacecraft (Helios 1, Helios 2, IMP 8, Voyager 1, and Voyager 2). They found a systematic configuration of the magnetic field and named it "magnetic cloud (MC)". Figure1, it is shown that Helios 1 was well connected with the flare by the magnetic field lines; but the magnetic field line through Voyage 1 was far away from the flare.

In Figure 2 one can see the following during the rising phase of the event. The SEP intensities observed by Helios 1 rose quickly and they were the most intense. At the same time, the SEP intensities observed by Voyager 1 increased more slowly and they were much smaller than that observed by Helios 1. The prompt increases of the SEP intensities observed by Helios 1 indicate the good magnetic connection between the source and the Helios 1. According to the 4–13 MeV protons, the SEP intensities observed by Helios 1 decreased gradually after the peak time before 1978 January 3 and they suddenly dropped by a factor of 10 in several hours since 06 UT on 1978 January 3. The sudden drops of SEP intensities were also observed by Helios 2 at 06 UT on 1978 January 4 and IMP 8 at 09 UT on 1978 January 4. At the same time, the reservoir phenomenon was observed by Helios 1, Helios 2, and IMP 8. The sudden drops of SEP intensities observed by IMP 8 were also accompanied by a Forbush Decrease (FD) as shown in the counting rates of neutron monitor.

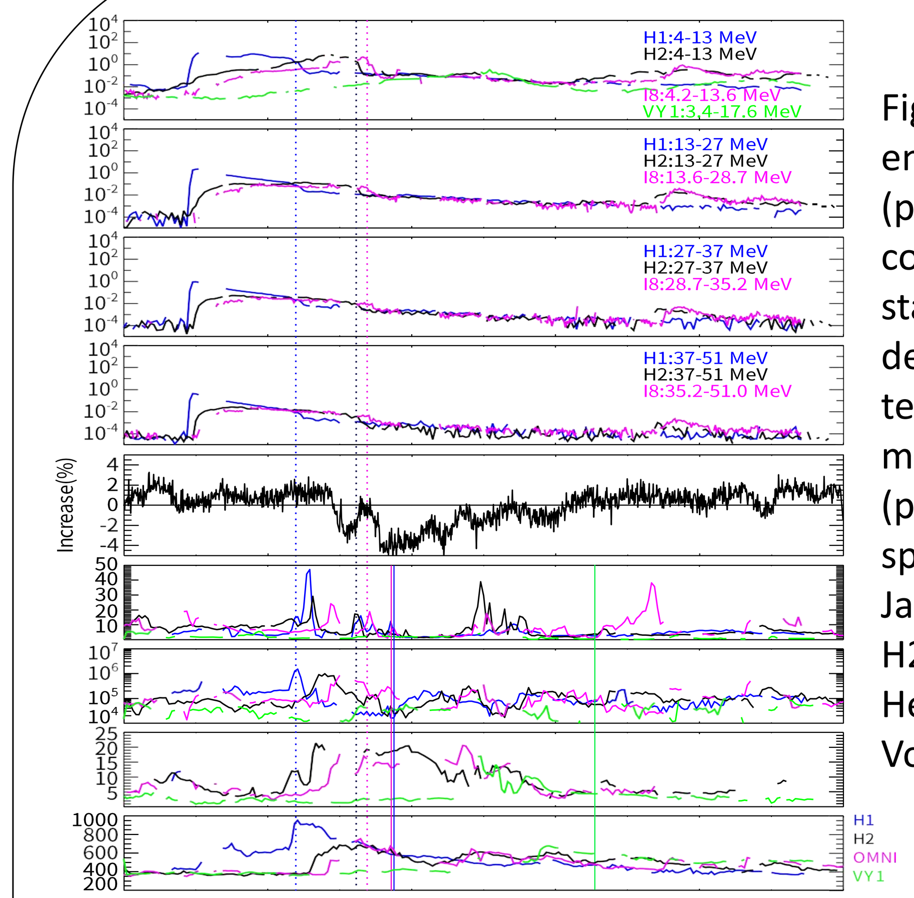


Figure 2. From top to bottom: energetic proton intensities (panel 1–4), neutron monitor count rates from OULU station (panel 5), plasma density (panel 6), proton temperature (panel 7), magnetic field intensity (panel 8), and solar wind speed (panel 9) in 1978 January 1 reservoir event. H1, H2, I8, and VY1 are short for Helios 1, Helios 2, IMP 8, and Voyager 1, respectively.

## The Energetic Electron Event on 2000 November 8

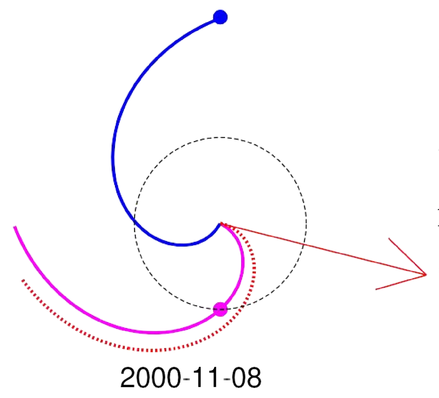


Figure 3. This figure shows a plot similar to Figure 1 except that the pink and blue dots represent the longitudes and radial distances of ACE and Ulysses, respectively. ACE was near 1 au, Ulysses was at 2.4 au, longitude 148°, and latitude 79°. .

In Figure 4, we plot the SEP event on 2000 November 8 observed by ACE and Ulysses. The local vertical geomagnetic cutoff rigidity of neutron monitor data from SOPO station is about 0.1. ACE observed more intense and faster-rising SEP intensities than Ulysses did during the rising phase of the event. According to every energy channel of energetic electrons, the intensities observed by ACE decreased gradually after the peak time before 2000 November 11. The SEP intensities observed by ACE suddenly dropped by a factor of 10 in several hours since 04 UT on 2000 November 11. Afterwards the reservoir phenomenon was observed by ACE and Ulysses. As shown in Figure 4, the sudden drops of SEP intensities happened in all energy channels at the shock passage at ACE. The sudden drops of SEP intensities observed by ACE were also accompanied by a Forbush decrease shown in the counting rates of neutron monitor. The sudden drops were observed by ACE but not observed by Ulysses. The onset time of drop was close to the shock time and the SEP intensities decreased by a factor of 10 in the following several hours, which indicates the sudden drop happened in the sheath region. As discussed in the previous sections and shown in Figures 2 and 4, due to the effects of magnetic boundary, the sudden drops of SEP intensities and the reservoir phenomenon were observed by multiple spacecraft simultaneously. The drops in the SEP intensities were observed in the region of sheath that was after the passages of the shocks but before the

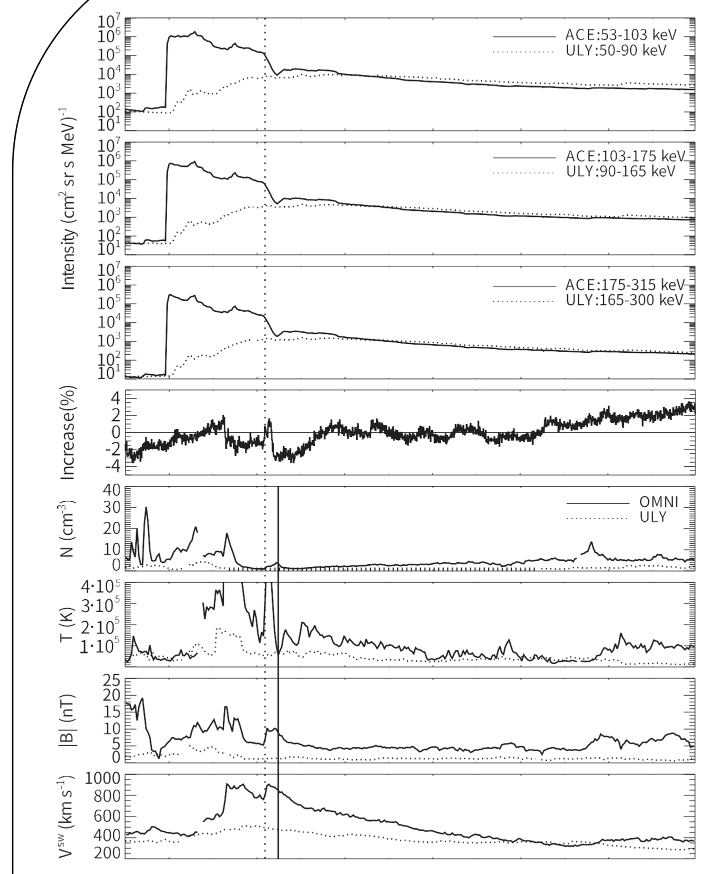


Figure 4. From top to bottom: energetic electron intensities (panel 1–3), neutron monitor count rates from SOPO station (panel 4), plasma density (panel 5), proton temperature (panel 6), magnetic field intensity (panel 7), and solar wind speed (panel 8) in 2000 November 8 reservoir event. Uly is short for Ulysses. The vertical dotted line indicates the onset time of the sudden drop in the SEP intensities observed by ACE. The vertical solid line indicates the front boundary time of ICME observed by ACE.

MC/ICME. In the 1978 January 1 event, a magnetic cloud was observed by all four spacecraft; but the sudden drops of SEP intensities were only observed by Helios 1, Helios 2, and IMP 8, whose solar distance was near 1 au but was not observed by Voyager 1 near 2 au. In the 2000 November 8 event, an ICME and the sudden drops of SEP intensities were observed by the ACE spacecraft but not by Ulysses. In the two events, magnetic boundary could be produced by the compression process between MC/ICME and ambient solar wind. Based on the observations, the effects of magnetic mirroring could be strong, and the diffusion process of SEPs might be weak, which led less particles to transport into the reservoir region. Because of such effects, the particle intensity gradients between different spacecraft suddenly decreased after the spacecraft passed the magnetic boundary. Furthermore, the effects of the magnetic boundary were also observed by the neutron monitor with an FD. The neutron monitor observed the decreased counting rates after the sudden drop of the SEP intensities. Therefore, one can assume there was a boundary for the energetic particles to propagate into the inner heliosphere.

## The magnetic boundary and perpendicular diffusion in the reservoir phenomenon

We plot a cartoon of the two SEP events in Figure 5 to illustrate the effects of perpendicular diffusion and magnetic boundary in the reservoir phenomenon. Because the effects of the magnetic boundary were not observed by Voyager 1 and Ulysses, the two spacecraft are not plotted in the Figure 5. In panel (a), the shock was first observed by Helios 1 and then was observed by Helios 2 and IMP 8. During the rising phase, the SEP intensities observed by Helios 1 were much higher than that observed by other spacecraft. The drops in the SEP intensities were observed in the region of sheath. After the drops of SEP intensities observed by Helios 2 and IMP 8, the intensities of energetic particles became uniform among the Helios 1, Helios 2, and IMP 8, and the reservoir phenomenon was observed by the three spacecraft in all four energy

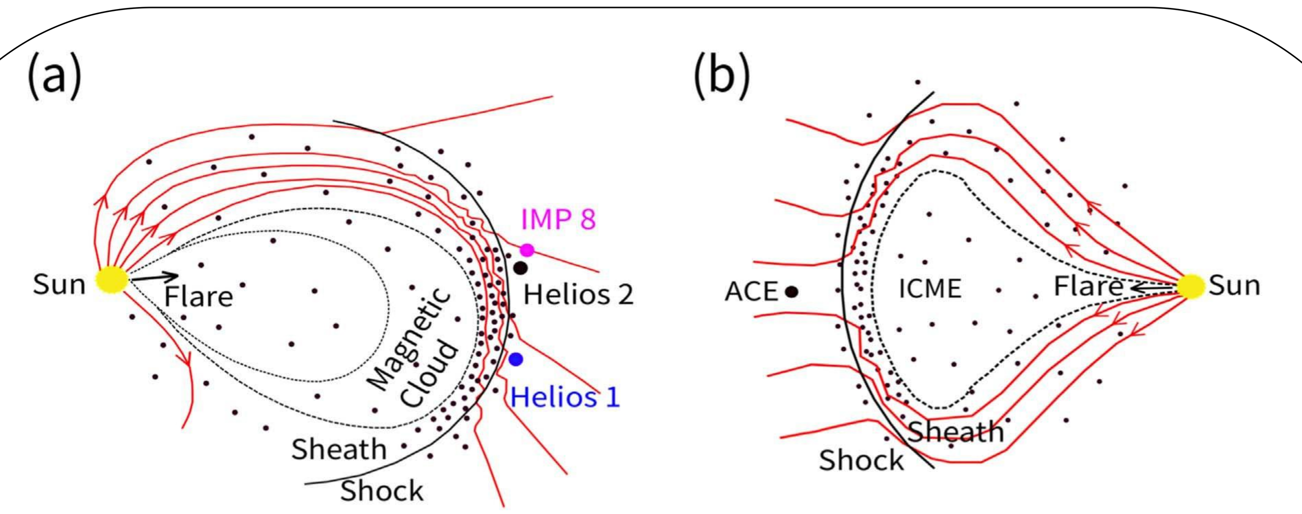


Figure 5. A cartoon to illustrate the effects of the magnetic boundary and perpendicular diffusion in the reservoir phenomenon. In panel (a), the 1978 January 1 SEP event is plotted in the ecliptic plane. In panel (b), the 2000 November 8 SEP event is plotted in the meridian plane. The black big dot represents the location of ACE. The dashed lines indicated the region of MC/ICME. The black line indicates the interplanetary shock driven by the MC/ICME. The region of sheath was between the shock and the MC/ICME.

channels. The end time of the MC observed by Helios 1, Helios 2, and IMP 8 were at 19 UT on January 5, 10 UT on January 5, and 14 UT on January 5, respectively. Therefore, the duration of the MC was about one day. After the drops of SEP intensities happened, energetic particles became uniform among different locations. The reservoir phenomenon lasted more than three days, which was longer than the duration of magnetic cloud. In panel (b), the shock and ICME were observed by ACE but were not observed by Ulysses. During the rising phase, the SEP intensities observed by ACE were much higher than that observed by Ulysses. The drops in the SEP intensities were observed in the region of sheath. After the drops of SEP intensities observed by ACE, the intensities of energetic particles became uniform between ACE and Ulysses, and the reservoir phenomenon was observed by the two spacecraft in all three energy channels. According to the ICME list provided by Richardson & Cane (2010), the start time of ICME was at 08 UT on November 11 and the end time was at 00 UT on November 12. Therefore, the duration of ICME was about sixteen hours. After the drops of SEP intensities happened, the energetic particles became uniform among different locations. The reservoir phenomenon lasted more than ten days, which was longer than the duration of ICME.

## Conclusions

In conclusion, with the effects of perpendicular diffusion, energetic particles could diffuse across the field lines, so the differences in SEP intensities observed by different spacecraft would gradually decline as time goes by during the decay phase. The effects of magnetic boundary could affect different spacecraft observed SEP intensities because energetic particles could transport to the heliosphere. Therefore, it could help to form the reservoir phenomenon observed by multiple spacecraft. As shown in the two SEP events, the effects of magnetic boundary could help to form the reservoir phenomenon in both the energetic proton and electron events in some large gradual SEP events.


**References**

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