



Modulation of Proton Fluxes at ~5 AU during the Largest SEP Events of 2005

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Abstract: The Ulysses spacecraft was close to the ecliptic at ~5 AU during periods of enhanced solar activity in January and September 2005. The Kiel Electron Telescope on board Ulysses registered a enhanced flux of cosmic ray protons in the energy range from 5 to 2000 MeV. The 5-25 MeV intensity has been above the quiet time level for more than two solar rotations during these periods. Two and three corotating interaction regions were observed during the energetic particle events in January 2005 and September 2005, respectively. In this contribution we investigate the modulation of galactic and solar cosmic rays during these conditions. In comparison with the October-November 2003 period we conclude that the largest solar energetic particle intensities were measured during the 2005 September 7 event, although the number of disturbances (shocks) was larger during the October-November period.

Introduction

Gradual Solar Energetic Particle (SEP) events are associated with large solar flares and Coronal Mass Ejections (CME's). Such events occur during periods of enhanced solar activity characterized by the appearance of major active regions. Such an active regions may transform to coronal holes which can last several solar rotations. The fast solar wind from these equatorial coronal holes interacts with the surrounding slow solar wind forming Stream Interaction Regions (SIR's) at distances of about 5 AU. A few SIRs last for more than one solar rotation leading to a Corotating Interaction Region (CIR). Individual CME's at these distances tend to form larger and more complex structures so called compound streams. Since the 1980's the effect of the solar wind structures on galactic and solar cosmic ray propagation has been analysed. Burlaga et al. [1] were the first who studied formation of a compound stream between 0.85 AU and 6.2 AU and its effects on solar energetic particles and galactic cosmic rays by using data from *Helios* and *Voyager*. The conse-

quences for energetic particle propagation to Ulysses in the intermediate heliosphere from solar energetic particle events, recurrent particle increases have been studied by Lim et al. [2], Richardson et al. [3] and Hofer et al. [4], respectively. In this paper we use the data from the KET [5], SWOOPS [6] and VHM/FGM [7] aboard Ulysses, which were obtained during two periods of enhanced solar activity in 2005 and compare the measurements with that during the large Halloween events in October to November 2003 [8].

Observations in 2005

Figures 1 and 2 display from top to bottom the intensities of 5-25 and 250-2000 MeV protons, the magnetic field strength, solar wind density and speed for a period of 100 days starting on January, 1, 2005 and August, 18, 2005, respectively. Overplayed to the 250-2000 MeV protons in the middle panel are the measurements of 165-500 MeV protons by GOES. The count rate of the 250-2000 MeV Ulysses channel was normalized to the 165-500 MeV GOES intensity in May-June

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2001, when both spacecraft were at heliocentric distances of ~1 AU in the ecliptic [9].

January 2005 period

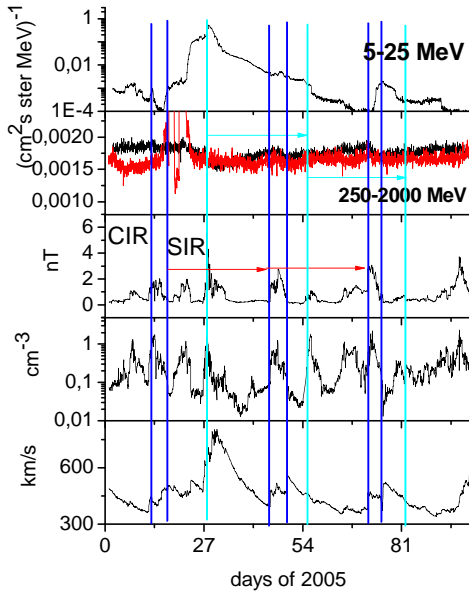


Figure 1: Ulysses observations during the first 100 days from January, 1, 2005. Displayed are from top to bottom the time profile of 5-25 MeV and 250-2000 MeV protons, measured by the KET, the magnetic field strength the solar wind density and velocity. The red curve in the second panel is the corresponding profile of 165-500 MeV protons measured by GOES near the Earth (maximums are out of scale). The pairs of vertical blue lines mark CIR boundaries and vertical cyan lines mark Forbush-like decreases.

In January 2005 Ulysses was at a heliocentric distance of about 5.3 AU and 16° South and 40° west. During the time three corotating interaction regions (red arrows) have been observed. Within that period two SIR from an active region (vertical cyan lines) have been obtained within a pair of CIR's (vertical blue lines).

The intensity increase of 5-25 MeV is correlated with the solar energetic particle event on January 20, 2005, which was located at N12W58. With this event a 2B, X7.1 flare was registered at 06:36, 07:01, and 07:26 UT. An intensity plateau followed and the maximum was observed 7 days

later, when the corresponding shock wave passed Ulysses. The observed time profile reflects the superposition caused by the adiabatic acceleration of the confined particles in the moving trap. In contrast to the 165-500 MeV protons at Earth no intensity increase has been observed in the Ulysses 250-2000 MeV proton channel. That channel is dominated by three recurrent decreases (~7%) and one Forbush-like decrease (~16%), which lasted for about one solar rotation and was associated with the compound stream. The 5-25 MeV proton increase on day 73 is caused by the reverse shock of the last CIR in that period. Such an enhancement is also observed on day 50 close to the reverse shock of the second CIR. It is, however, masked by the decay of the previous particle event.

September 2005 period

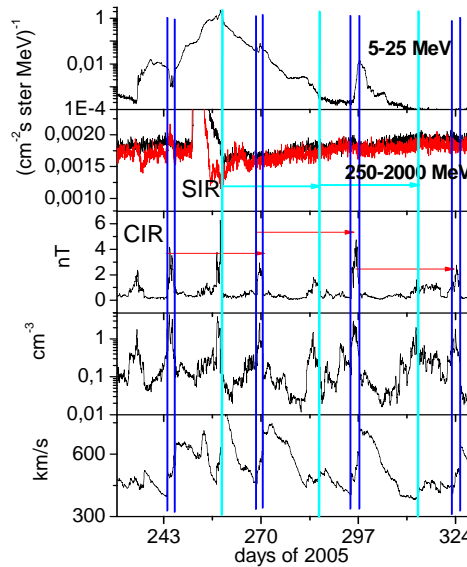


Figure 2: Same as in Figure 1 besides for August 18, 2005.

Figure 2 shows the Ulysses observations of another 100 day period starting on August 18, 2005. Ulysses was located at radial distance of ~4.8 AU and at a heliographic latitude and longitude of S29 and W178, respectively. Again three periods of ~26 days are observed, when disturbances from an active region have been bounded by a pair of recurrent flow. The amplitude of the recur-

rent cosmic ray decreases in the 250-2000 MeV protons is about 4%. A Forbush-like decrease has been observed on day 259 leading to an intensity decrease of $\sim 17\%$. The Ulysses measurements of 5-25 MeV protons indicate a particle enhancement for at least two solar rotations. On September 7, 2005 a large solar energetic particle event occurred. The corresponding 3B, X.17 flare occurred at 17:17, 17:40, 18:03 UT and was located at S06E89. This flare caused the largest increase within 250-2000 MeV (out of scale in Figure 2) ever observed during the Ulysses mission [7]. As for the January period the maximum intensity of 5-25 MeV protons is caused by the adiabatic acceleration particles confined in the trap. But in this case the disturbances are not correlated with disturbances from the major flare. The later enhancement on day 295 is again caused by the reverse shock of the CIR observed in this period. It is important to note, that no increase on day 324 was observed, when the level was back again to the quiet time period. This leads us to the conclusion that the SEP population is a seed population for the shock acceleration by the CIR.

Comparison with October 2003

Figure 3 displays in comparison to Figures 1 and 2 the magnetic field strength, the solar wind density, velocity and the 5-2000 MeV protons as measured by Ulysses. The blue vertical line pairs mark the occurrences of CIRs at Ulysses. The cyan lines indicate times, when Forbush like decreases have been observed in the 250-2000 MeV proton channel. The intensity level in the 5-25 MeV proton intensity after the major solar event of October 28, 2003 (S16E08, 4B, X17.2, 09:51, 11:10, 11:24 UT) is comparable to that in January 2005. It is however, much smaller than the intensities observed in September 2005. The absolute maximum in this low energy proton channel is in October 2003 event greater than in 2005. This might be explained by a probable contribution of the October 29 and November 2, 2003 solar events and a stronger influence of acceleration and/or adiabatic heating by the propagating CME shocks. Therefore we conclude that the largest flare produced proton intensities were produced on September 2005. As for the 2005 period the decaying phase of the particle

event is accompanied by enhancement associated with a CIR.

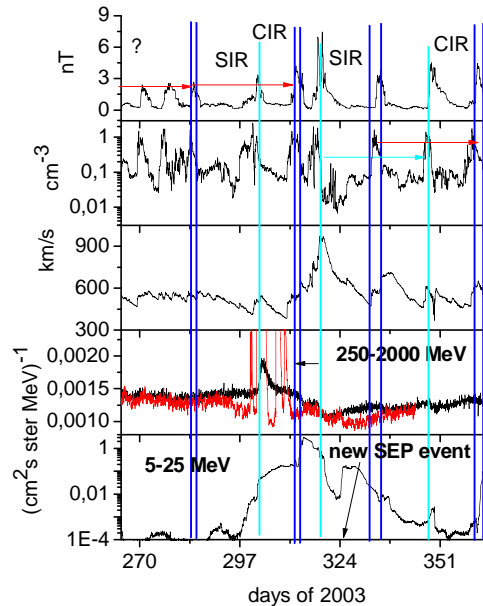


Figure 3: Ulysses observations during days of 265-365 in 2003. From top to bottom: Magnetif field strength, SW density and velocity, 5-25 MeV and 250-2000 MeV protons. The red curve in the second panel displays the intensity of 165-500 MeV protons measured by GOES near the Earth.

Conclusions

- The SEP properties observed from distant points of the heliosphere (at polar latitudes and ~ 5 AU) reflects better the integral characteristics of SEP events.
- The event of September 7, 2005 has shown the hardest proton spectrum and the largest number of 200-200 protons injected into the heliosphere.
- The majority of energetic particles observed by Ulysses at ~ 5 AU are of the solar origin. SIR/CIR's simply confine a background population of SEP remaining from earlier events
- The period of about 60 days after the SEE of 2003 is the most disturbed during the 23rd solar cycle.

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