Multi-point observations of CIR-associated energetic ions during Ulysses’ ecliptic crossing in 2007


*IEAP, University of Kiel, Germany

Abstract. The period between June and October 2007 (Carrington rotations 2058 to 2061) is characterised by low solar activity. Due to the Ulysses ecliptic plane crossing in August 2007 the opportunity of multi-spacecraft observations is offered combining Ulysses at 1.4 AU with ACE and the twin STEREO spacecraft at 1 AU. Several ion increases between 100 keV/n and 10 MeV/n which were unambiguously related to Corotating Interaction Regions (CIRs) have been measured by instruments of these four spacecraft. In order to correlate in-situ measurements and remote sensing observations of the parent coronal holes, the ballistic backmapping technique has been applied to the data. Due to less latitudinal separation between Ulysses and the other spacecraft in Carrington rotations 2059 and 2060, we concentrate on this period for a more detailed study. Therefore two significant CIR events and associated ion increases from day 5 to day 10 of August 2007 and from day 25 to 31 of August 2007, which are observed by all four spacecraft, lend themselves to an undisturbed comparison. Using the multi-spacecraft measurements for this two CIR-associated ion increases we could determine a radial gradient of about $(230 \pm 30) \%$/AU.

Keywords: Corotating Interaction Regions, energetic particles, radial gradient

I. INTRODUCTION

Corotating Interaction Regions (CIRs) are formed by the interaction of slow solar wind and following fast solar wind streams originating from coronal holes. At the edges of the structure, two compression waves evolve which typically steepen into a forward and reverse shock pair beyond 1 AU [9]. In absence of solar activity these shocks are the main source of energetic particles from several keV to several MeV in the inner heliosphere [4]. During its third fast latitude scan, Ulysses crossed the heliographic equator in August 2007. Solar minimum conditions and the presence of ACE and the twin STEREO spacecraft in the ecliptic offers an excellent opportunity of multi-spacecraft investigations of CIRs. Figure 1 shows the trajectories of the four spacecraft from 21 June to 8 October 2007 (Carrington rotations 2058 to 2061) in ecliptic coordinates. While ACE and the STEREOs are very close to the ecliptic plane with heliographic latitudes varying between 0.7 and 7.3 degrees, Ulysses moves from 35° S South to 40° N and with a radial distance to the Sun of 1.4 to 1.5 AU.

STEREO A and B follow Earth’s orbit, with STEREO A at ~0.96 AU and STEREO B at ~1.02 AU far from the Sun. In order to compare in-situ measurements with the global coronal structure, we use remote sensing observations of coronal structures based on a PFSS model ([1]) from the Global Oscillation Network Group (GONG)1.

Fig. 1. Trajectories of the four spacecraft Ulysses (black), ACE (gold), STEREO A (red), and STEREO B (blue) in ecliptic coordinates for the period under study. Squares and triangles mark the positions of the spacecraft for day 213 and 267, respectively. Parker spirals separated by 30 degrees in the ecliptic are denoted by the dotted curves.

A. Instrumentation

The STEREO mission consists of two nearly identical spacecraft which are placed in heliocentric orbits following the motion of the Earth. As consequence of slightly different heliocentric distances the spacecraft perform a longitudinal separation of ~ 22°/a with respect to the Earth. In-situ data used for our study includes plasma and energetic ion measurements provided by the PLAS-TIC experiment ([6]) and the IMPACT instrument suite ([10]). Onboard Ulysses plasma and magnetic fields are measured by the SWICS ([7]), SWOOPS ([2]) and VHM ([3]) instruments. The LET ([13]) instrument provides energetic ion intensities. Instruments used from ACE are SWEPAM ([11]), MAG ([14]) and EPAM ([18]) for plasma, magnetic field and ion measurements.
II. CIR OBSERVATIONS

A. Ballistic Backmapping of In-situ Data

Due to the co-rotating nature of CIRs and the longitudinal separation of the spacecraft, the same CIR structures are observed delayed. This leads to problems in the analysis of the events: time profiles measured by the four spacecraft are shifted and the same events are difficult to compare. Furthermore solar events can disturb CIR time profiles. To avoid this time delays and to distinguish co-rotating and non-corotating events in-situ solar wind measurements are mapped back to the source location of the Sun. Assuming the solar wind speed propagates radially with constant speed $v_{sw}$, the angle $\alpha$ rotated by the Sun during the transit time from the source surface to the observer location is given by

$$\alpha = \frac{\omega (R - r)}{v_{sw}}$$

where $\omega$ is the angular speed of the Sun, $R$ is the radial distance to the observer and $r = 2.5$ solar radii is the location of the source surface in the corona. Adding $\alpha$ to the heliographic longitude of the observer we obtain the source longitude. These source longitudes are subsequently transformed into decimal Carrington rotation numbers. For Ulysses travelling from -35° to 40° in latitude, differential rotation of the Sun is taken into account when evaluating $\alpha$. After backmapping, corotating high speed streams from the same coronal hole observed from different heliographic longitudes are expected to map to their source at the corona and should be coincident. Furthermore a direct comparison...
of backmapped *in-situ* data with synoptic coronal hole maps is possible and for every high speed stream the corresponding coronal hole can be identified.

**B. Multi-Spacecraft Observations of CIRs in Carrington Rotations 2058 to 2061**

Figure 2 shows backmapped solar wind speed in comparison with four synoptic coronal hole maps from GONG for the period under study (Carrington rotations (CR) 2058 to 2061). Green and red fields denote coronal holes with positive and negative polarity, respectively. The varying black line marks the neutral line and the blue lines connecting northern with southern coronal holes indicate the uppermost closed magnetic field lines in the corona. The green and red bands below the upper panel represent the backmapped *in-situ* magnetic field polarity measured by the four spacecraft with colors corresponding to the ones used in the GONG maps. Heliographic latitudes of the four spacecraft are plotted on top of the GONG maps (upper panel).

As shown by the synoptic coronal hole maps, four coronal holes (two from the North and two from the South of the Sun) are present in each rotation. The small southern coronal hole disappears in the transit from CR 2060 to CR 2061. The two large coronal holes at fractional Carrington rotations 0.4 (northern) and 0.7 (southern) dominate the *in-situ* measurements at ~1 AU in the ecliptic. Thus, the magnetic polarity structure, i.e., the sector structure, is nearly identical for ACE and the two STEREO spacecraft. Since Ulysses moves from high southern latitudes to the ecliptic and again to high northern latitudes, the *in-situ* magnetic field measurements are very different to the ones of the ecliptic for Carrington rotations 2058 and 2061. These differences are also reflected in the solar wind measurements (Figure 2 middle panel) and in the energetic ion measurements (Figure 2 lower panel): During the first half of CR 2058 Ulysses observes a significant CIR-associated ion increase correlated to the small southern coronal hole, which is not observed by the other spacecraft. In the second half of Carrington rotation 2061 Ulysses enters the northern polar fast solar wind and misses the CIR correlated with the broad southern coronal hole. Due to these differences, caused by latitudinal separation, a detailed comparison of Ulysses and 1 AU data is only meaningful when restricting the following analysis to Carrington rotations 2059 and 2060 only.

The differences between Ulysses and the other spacecraft in CR 2059 and CR 2060 can be explained as follows: At CR 2059, a particle increase was measured by Ulysses only. This increase is not correlated with a CIR but originates from a solar energetic particle event far behind the west limb. In CR 2060 Ulysses misses the high speed stream originating from the broad southern coronal hole (CR 2060.5-2060.8) due to a latitudinal separation of ~15°. The CIR caused by this stream and observed by the spacecraft in the ecliptic produces energetic particles at CR 2060.6 during the decay phase of the broad particle increase before. This second particle increase was also observed by Ulysses and is presumed to be due to latitudinal transport from the remote shock ([12]).

**III. Data Analysis**

**A. Radial gradients**

In Carrington rotations 2059 and 2060 Ulysses is located at 1.4 AU. As visible in Figure 2 only two significant particle increases corresponding to the high speed streams marked by A and B lend themselves for a radial gradient investigation. The solar wind speed profiles measured by the four spacecraft are in good agreement for these streams assuring that the CIR structure is the same at every spacecraft.

For the gradient calculation 1 MeV proton intensities measured by STEREO/SEPT and Ulysses/LET were used for 12 hour intervals around the reverse wave time. Also at higher energies (1.8-3.8 MeV) a gradient has been calculated using STEREO/LET and Ulysses/LET measurements (see Figure 3). In order to compare the resulting gradients to the ones found by [15] who used intensities normalized to measurements at 1 AU, we normalized the Ulysses intensities to an interpolated mean value between STEREO A and B representing the 1 AU value. Due to different energy channels of Ulysses/LET and STEREO/SEPT, a power law with an exponential cutoff \( I = I_0 E^{-\gamma} \exp\left(\frac{E}{E_c}\right) \) has been used to fit the CIR spectra. The result has been used to evaluate the intensity at 1 MeV. Ulysses/LET and STEREO/LET have comparable energy channels with the ranges 1.8 to 3.8 MeV and 1.8 to 3.6 MeV, respectively. Thus no interpolation was necessary in this case to calculate the corresponding intensities. Furthermore all values have been corrected by a factor resulting from an intercalibration of the different instruments (see [5]). Figure 4 shows the measurements of [15] who found a radial gradient of 350%/AU in the inner heliosphere and ~100%/AU for 1 to 6 AU. The Ulysses to STEREO ratios are included as squares (1 MeV values) and triangles (~2 MeV values) for both CR 2059 and CR 2060 events. The values result in an average radial gradient of (230±30)%/AU between 1 and 1.4 AU. Although [15] give a large variation of 20 to 200%/AU for their gradient of 100%/AU our value lies above. Since our measurement covers the inner range of the 1 to 6 AU interval we suggest a progressive steepening to the 350%/AU value, found by [15] for the inner heliosphere. Nevertheless our result of a large positive gradient is in agreements with the one from 1978.

**IV. Discussion and Conclusion**

In this work multi-spacecraft measurements from ACE, Ulysses and the two STEREO spacecraft have been used to investigate CIR-associated particle events for the period from June to October 2007 (Carrington rotations 2058 to 2061). *In-situ* plasma and particle data have been mapped back to their coronal source longitude in order to compare measurements of different
Fig. 3. CIR-associated ion increase at \( \sim 1 \) MeV (light traces) and \( \sim 2 \) MeV (dark traces) measured by Ulysses/LET, STEREO/LET and STEREO/SEPT during the CIR in Carrington rotation 2060. The solid lines mark the 12 hour intervals used for the gradient calculation, the dashed line marks the time of the reverse wave as deduced from plasma data.

Due to the smaller latitudinal separation of Ulysses to the other spacecraft in Carrington rotations 2059 and 2060, these rotations have been selected for a more detailed investigation. Although each of these two rotations contains two clear high speed streams originating from the broad northern and southern coronal holes, only one significant particle increase per rotation is observed. The backmapped solar wind profiles corresponding to this CIRs match very well for the four spacecraft, hence it can be assumed that all spacecraft observe the same CIR structure. For these two particle events a radial gradient has been calculated using 12 hour intensity measurements around the reverse wave times from Ulysses/LET and STEREO/SEPT at 1 MeV and from Ulysses/LET and STEREO/LET at \( \sim 2 \) MeV. The mean gradient we found is \( g_r = (230 \pm 30) \%/ \text{AU} \) between Ulysses at 1.4 AU and a 1 AU baseline calculated from an interpolated mean value between STEREO A and B. Although the radial gradient investigations by [15] and ours apply solar minima with contrary magnetic polarity, our findings confirm the previous in the sense of a large positive radial gradient which steepens in the inner heliosphere and appears to be independent of the solar cycle.

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REFERENCES