Stream interfaces and energetic ions II: Ulysses test of Pioneer results

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Abstract. Ulysses measurements of energetic and solar wind particles taken near 5 AU between 20 and 30 degrees south latitude during a well-developed recurring corotating interaction region (CIR) show that the CIR's corotating energetic ion population (CEIP) associated with the trailing reverse shock starts within the CIR at the stream interface. This is consistent with an earlier result obtained by Pioneers 10 and 11 in the ecliptic plane between 4 and 6 AU. The Ulysses/Pioneer finding is noteworthy since the stream interface is not magnetically connected to the reverse shock, but lies 12-17 corotation hours from it. Thus, the finding seems to be inconsistent with the basic model that generates CEIP particles at the reverse shock and propagates them along field lines. Eliminating the inconsistency probably entails an extension of the standard model such as cross-field diffusion or a non-shock energization process operating near the stream interface closer to the sun.

Background and Motivation

This paper follows up *Intriligator and Siscoe* [1994] (hereafter Paper 1) which used Pioneers 10 and 11 measurements taken between 4 and 6 AU during recurrences of the giant high-speed streams of 1974 to see how the corotating energetic ion populations (CEIPs) that accompany corotating interaction regions (CIRs) relate to the plasma and field structures that make up a CIR. Beyond about 2 AU, a CIR is usually bounded by forward and reverse shocks; and along its whole length it is usually partitioned near the middle by a stream interface, which separates denser, cooler slow solar wind plasma from thinner, hotter fast stream plasma [*Burlaga*, 1974]. The forward and reverse shocks are usually ensheathed in CEIPs. Their energy spectra, intensity variation with radial distance, and intensity contrast between forward and reverse shocks were successfully modeled by a Fermi acceleration model [*Fisk and Lee*, 1980]. We shall focus on two aspects: The trailing CEIP is usually much more intense and wider than the leading CEIP; and the leading and trailing CEIPs are separated by a particle intensity minimum, which lies near the middle of the CIR.

Paper 1 added the observation that the start of the trailing CEIP nearly always approximately coincides with the stream interface. This observation was surprising, for based on the following considerations, one would have expected the stream interface to be separated from the start of the trailing CEIP by about half a day, instead of effectively coinciding with it. 1) A CIR's forward and reverse shocks are thought to energize particles by Fermi acceleration [*Palmer and Gosling*, 1978] or by gradient drift acceleration [*Pesses et al.*, 1979]. These particles then propagate along field lines to create a CEIP. 2) The theory of supersonic flow along a curved wall applied to the flow of a fast solar wind stream along a curved stream interface - strictly speaking, along a stream interface with a different curvature in the corotating frame than the fast stream - predicts that the reverse shock should start not at the stream interface but some distance away from it [e.g., *Landau and Lifshitz*, 1959, Section 107]. Two numerical computations [*Pizzo*, 1989; *Hu*, 1993] modeling the solar wind situation quantified this prediction: both show that the starting point of the reverse shock stands off from the stream interface by a corotation time of at least 12 hours. 3) Since the role of the shock is to deflect the flow to be parallel to the stream interface in the corotating reference frame, the field line from the sun that goes through the

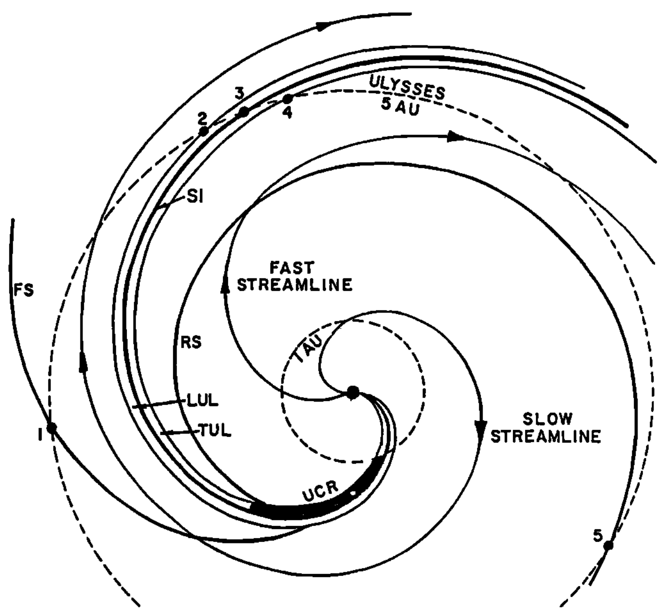

Figure 1. A sketch of the corotation interaction region (CIR) features (see text): forward shock (FS), reverse shock (RS), stream interface (SI), leading and trailing unshocked layers (LUL and TUL), unshocked compression region (UCR), and fast and slow streamlines in the corotating reference frame. The locations of Earth and Ulysses projected onto the heliospheric equatorial plane are also shown. Numbers mark Ulysses encounters with CIR features.

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shock's origin thereafter maintains about the same corotation distance from the stream interface.

Splicing the shock production model for CEIPs onto the stand-off model for the shock's starting point and the consequent stand-off of shock-connected field lines gives a combined model that predicts for distances beyond about 2 AU a 12 hour or more separation between the stream interface and the start of the trailing CEIP. This prediction Paper 1 shows to be incorrect.

Figure 1 shows the geometry of the features: The inner circle marks Earth's orbit. Through it run some spirals depicting field lines and flow stream lines in the corotating reference frame. The central spiral represents the stream interface (SI) separating a leading slow stream from a trailing fast stream. It is flanked by narrow, 14 corotation-hour flow channels (drawn to scale) of unshocked solar wind (labeled the leading unshocked layer, LUL, and the trailing unshocked layer, TUL). The SI spiral and the spirals bordering the LUL and the TUL correspond to a 440 km/s solar wind speed. The shaded area in the TUL represents an unshocked compression region (UCR), which enters into a CEIP generation scenario discussed later. The shading is only suggestive of the location of the UCR, not a quantitative depiction of it. (For example, the leading UCR is not shaded, and the shading should cross field lines.) At 2 AU, spirals representing the forward shock (FS) and the reverse shock (RS) branch from the borders of the LUL and TUL. The pitches of these spirals are exaggerated to ease viewing, and their common 2 AU origin distance is chosen to be characteristic of shock origin distances generally, but with no implication that the origin distance is usually the same for both shocks.

The two outer spirals represent field lines (or streamlines in the corotating frame) for the slow and fast streams. To ease viewing, they depict an exaggerated case with a factor of 4 between the fast and slow flow speeds. They are positioned to intersect their respective shocks at 3 AU, then bend to acquire the same pitch as the stream interface. The outer circle shows the trajectory of Ulysses at 5 AU and at a heliographic latitude of -30°. The numbers on it mark Ulysses' successive encounters with CIR features as the CIR (assumed to be oriented perpendicular to the heliospheric equatorial plane) corotates past the spacecraft: the fast shock (1), the border of the leading unshocked layer (2), the stream interface (3), the border of the trailing unshocked layer (4), and the reverse shock (5). The exaggeration of the pitches of the shock spirals is evidenced by the fact that in reality, the distances between points 1 and 2 and between 4 and 5 are typically only two to four times the distance between points 2 and 3 or 3 and 4.

To apply this figure to the CEIP-generation scenario described above, Ulysses would encounter CEIPs centered on points 1 and 5, and extending into the CIR from 1 to 2 and from 5 to 4, leaving the space between 2 and 4 empty. As Paper 1 reports, however, Pioneers 10 and 11 found the region from 3 to 4 not to be empty, but to be a continuous extension of the trailing CEIP. Further, they found that the stream interface forms a border for the trailing CEIP, playing a role that the CEIP-generation scenario cast for the field line through point 4. Given the possibly significant implication of the disagreement between the CEIP-generation scenario and the Pioneer observations, we use Ulysses data here to test the robustness of the observation. The Ulysses data also allow us to test the observation at other latitudes.

The Ulysses Observations

Kunow et al., [1994] describe energetic protons related to a recurrent interaction region observed on Ulysses at southern latitudes significantly away from the equatorial plane. They divided the time period from early 1992 onwards into a low latitude interval before the recurrent stream appeared, a middle latitude interval when the stream and its CIR were well developed, and a high latitude interval when only vestiges of the stream remained - though the effects of the CIR on energetic particles are still clearly seen.

We concentrate here on the middle latitude region extending from 20 to 30° south heliographic latitude, when Ulysses was still near 5 AU. Across the CIRs of this region, the intensities measured in the 5.4 - 23 MeV ion channel varied most with increases up to four orders of magnitude [*Kunow et al.*, 1994] and with clear instances of leading and trailing CEIPs. To check the result of Paper 1, we superposed on these Ulysses energetic ion data the positions of the stream interface as determined with data taken by the Ulysses solar wind instrument [*Gosling et al.*, 1993].

Figure 2 shows, for one middle latitude CIR, where hourly averages of the energetic particle intensity, the solar wind speed and the exponential of the specific entropy, called here the argument of the specific entropy: ion temperature divided by the square root of the ion number density (see Paper 1). This CIR resembles most of cases observed by the Pioneers: forward and reverse shocks flanking a stream interface (which as in Paper 1, is defined by a relatively abrupt increase in specific entropy); a CEIP pair: a pronounced, broad trailing CEIP and a possible, barely visible leading CEIP. The CEIPs (to the extent that the leading one can be identified) are separated by an intensity minimum. The peaks in the CEIPs approximately line up with the shocks, which is a well-established association. The relevant association for us, however, is the lineup between the stream interface and the leading edge of the trailing CEIP. Thus, this example, corroborates the findings of Paper 1.

Figure 3 shows a Ulysses CIR where the behavior of the energetic particles is more unusual. There is the usual pat-

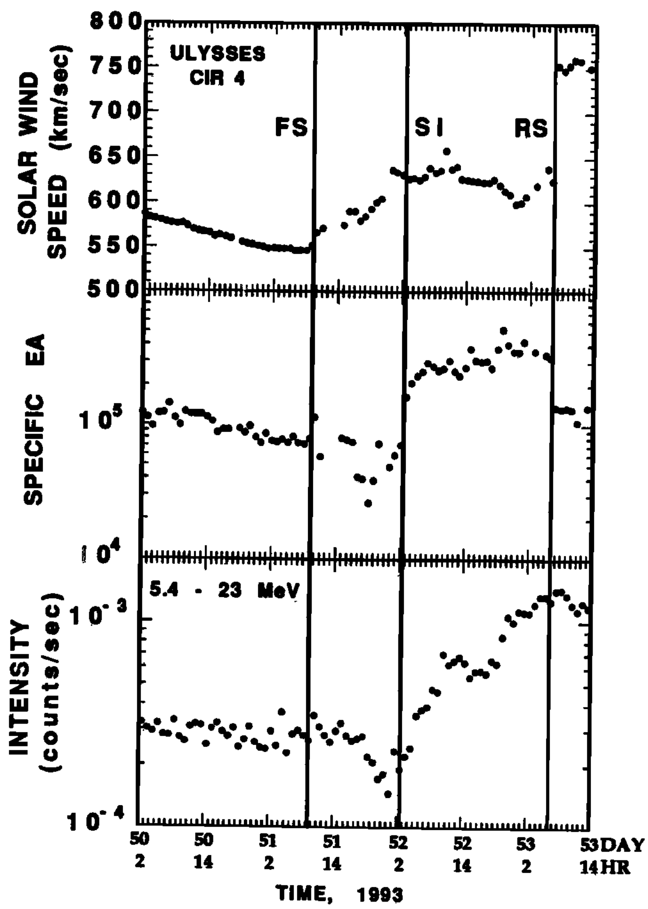

Figure 2. CIR parameters for a typical CIR of a recurrent stream of Ulysses at about -30° latitude near 5 AU. The stream interface (SI) is marked by the abrupt increase in specific entropy. The "specific entropy argument" (Specific EA) in panel 2 is $T/n^{1/2}$ with T in K and n in cm^{-3}.

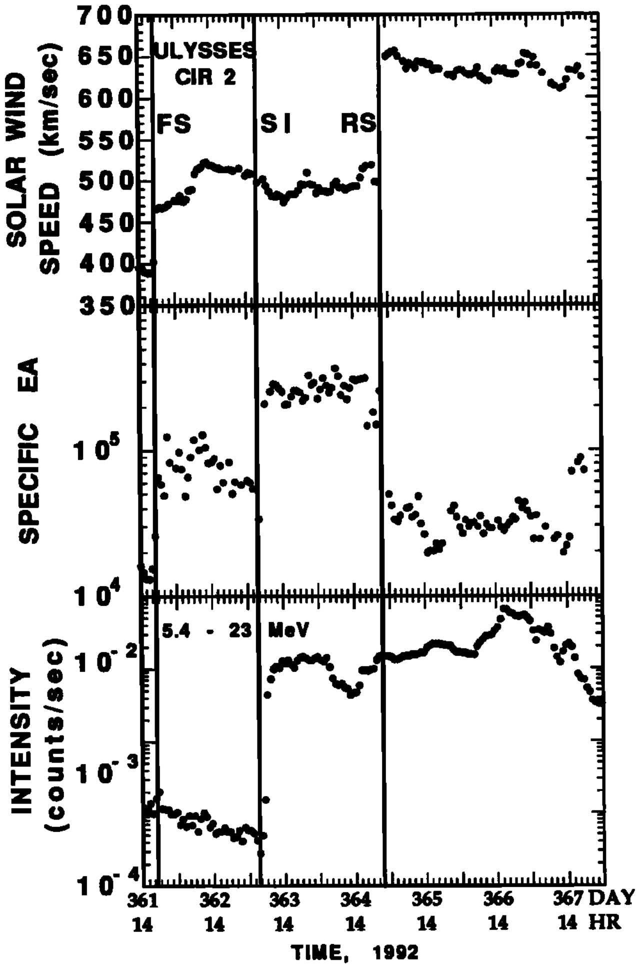

Figure 3. Same as Figure 2 for a CIR seen at Ulysses at about -20° latitude near 5 AU. In this atypical case, the CEIP intensity increases sharply at the SI.

tern of a weak leading CEIP followed by a valley of low intensities followed by a pronounced trailing CEIP, but the transition to the trailing CEIP at the stream interface is unusually sharp. Between the reverse shock and this discontinuity, the intensity of the trailing CEIP is relatively constant. One other example of this type was seen in the Pioneer 10 data [Paper 1]. As discussed below, these two cases are challenging for CEIP production models.

Figure 4 combines the Ulysses energetic particle intensity profiles of Figures 2 and 3 with three others selected strictly on the basis of CEIPs identified in the energetic particle data, that is, plasma data were not involved in the selection process. Each case is normalized to a common intensity at the stream interface. This format allows direct comparison with Figure 3 in Paper 1. Vertical lines to either side of the stream interface show the approximate size of the predicted unshocked layers [*Pizzo*, 1989; *Hu*, 1993]. The width of the trailing unshocked layer can be shown to depend only on the relative speed difference between the stream interface and the fast stream, the Mach number of the fast stream, and the heliographic latitude. For a sharp velocity gradient from the slow stream to the fast stream, the width of the layer turns out to be inversely proportional to the product of the relative speed difference, the square of the Mach number, and the cosine of the latitude. The values of the relative speed difference and the Mach number that Pizzo and Hu used in their models were typical of the streams that Ulysses and the Pioneers encountered. Their models independently give about 12 hours for the width of the two unshocked layers. To account for the dependence on heliographic latitude - which for the Ulysses observations was about -30° - we increased the width in Figure 4 from 12 hours to 14 hours.

The normalized intensity profiles in Figure 4 reveal the following: 1) On the trailing side of the stream interface, there is no interval within which the particle intensity remains at a minimum as if the interval were unconnected to a particle source. Instead, the intensity rises immediately and continuously to peaks which are generally associated with direct connection to a particle source - the reverse shock. 2) The intensity profile is asymmetric with respect to the stream interface. Compared to the trailing CEIP, the leading CEIP is barely visible or even absent. 3) The inter-CEIP intensity minimum tends to be deepest at the stream interface. 4) The slope of the intensity of the trailing CEIP tends to be steepest adjacent to the stream interface. 5) The slope of the intensity of the leading CEIP at the stream interface tends to be much less than the slope on the trailing side. This effect contributes to the sharp asymmetry of the intensity profile with respect to the stream interface. 6) The intensity is generally continuous across the stream interface (Figure 3 is an exception). These properties also characterize the CEIP intensities observed by the Pioneers as discussed in Paper 1.

Discussion

The Ulysses findings reported here showing an approximate coincidence within CIRs of the stream interface and the onset of the trailing CEIP agree with the Pioneer findings reported in Paper 1. The results seem to require an extension of the basic three-part scenario that has been proposed to account for CEIPs: 1) Corotating shocks generate CEIP particles; 2) these particles propagate along magnetic field lines, which maintain an approximately constant corotation time relative to the stream interface; and 3) at their closest point, shock waves, and hence, their CEIPs, stand off from

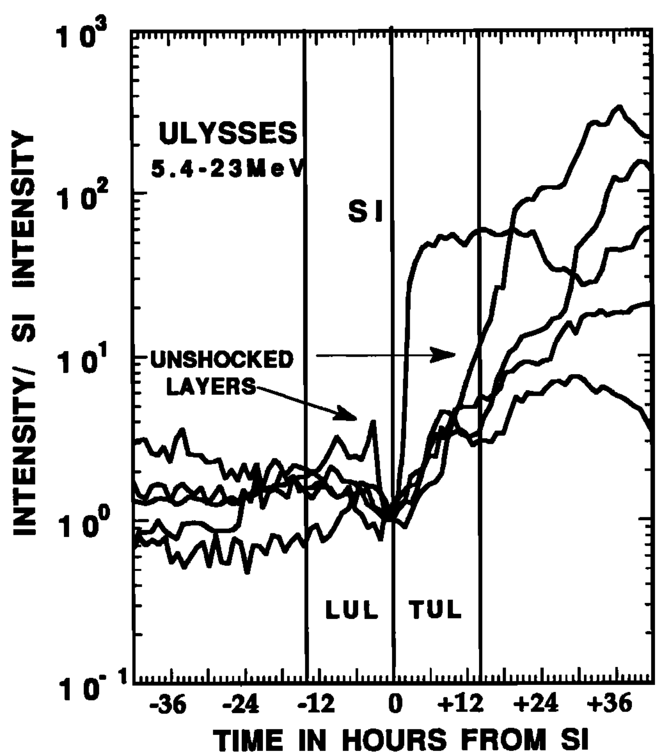

Figure 4. A superposition of five Ulysses CEIP intensity profiles each normalized to its value at the stream interface. The space between the two vertical lines centered on the stream interface approximates the width of the leading and trailing unshocked layers.

the stream interface by 12 or more hours of corotation time. This scenario does not account for the CEIP ions in the unshocked layers as Ulysses and the Pisoneers observed. Paper 1 mentions two possible modifications of this scenario that might allow CEIPs to extend into the unshocked layers: cross-field diffusion and non-shock energization in the unshocked layer.

Cross-field diffusion is a familiar concept. The non-shock energization process is a new idea which needs a few words of explanation. CEIP particles in the unshocked layer might be produced closer to the sun on the field lines in the unshocked compression region (shaded region in Figure 1) and propagate outward to fill the gap. This possibility amounts to a direct extension of the standard CEIP production model to let it operate also in the unshocked layer. Such an extension works, for example, in the *Palmer and Gosling* [1978] and *Fisk and Lee* [1980] versions of the model, in which the particles are energized by Fermi acceleration acting through the convergence at the shock of the pre- and post-shock flows. Figure 1 indicates that convergence also occurs in the unshocked compression region, just not enough to cause a shock. The same condition of fast stream overtaking slow stream operates there, only weaker because the spiral is more radial. Thus, we might expect energetic particle production to occur within a considerable radial portion of the unshocked compression region, only with weaker intensities.

The non-shock energization scenario is consistent with observations reported by *Richardson and Zwickl* [1984] and discussed further by *Richardson* [1985]. They find in data taken at 1 AU that ions are accelerated up to several tens of keV in CIRs. The region of accelerated ions extends from the stream interface rearward for typically more than a half day. In these cases there is no shock wave, yet the energized ions stream away from the sun.

Both the cross-field diffusion and non-shock energization scenarios will be quantitatively treated in subsequent papers. Neither modification accounts for the two atypical cases which have relatively discontinuous intensities at the stream interface. As noted in Paper 1, to account for these atypical cases we might need to invoke a second process. For example, in the diffusion hypothesis the diffusion coefficient would have to suffer a big change at the stream interface first to uniformly fill in a 12 hour unshocked layer then to hold back a factor-of-ten gradient across a 1 hour stream interface. The same problem faces the compression hypothesis. That the atypical cases might imply that two processes to operate is supported by the fact that Pioneer 10's atypical case occurred after Pioneer 11, closer to the sun but on a nearly direct radial line to Pioneer 10, had measured the same feature and found it to have a normal slope. In this instance, therefore, the assumption of time independence in the corotating frame appears to have been violated. This suggests that atypical cases might be time-dependent distortions of the typical case.

Conclusions

Ulysses data taken between 20 and 30 degrees south latitude near 5 AU corroborate the finding from Pioneer data taken in the ecliptic plane near 5 AU that the trailing CEIPs is closer to the stream interface than expected from a model in which particles are accelerated at the reverse shock and thence propagate away from the shock along magnetic field lines. In fact the onset of the trailing CEIP coincides with the onset of the stream interface to within the uncertainty in determining these times, which is about 1 hour. Thus, CEIP particles are found throughout the approximately 12 hour unshocked layer on the trailing side of the stream interface. CEIP production by cross-field diffusion or by Fermi acceleration in the unshocked compression region (see Figure 1) might account for the observations. Both possibilities are being investigated by means of quantitative modeling.

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