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Stream interfaces and energetic ions closer than expected: Analyses of Pioneers 10 and 11 observations

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Abstract. An empirical study of corotating interaction regions (CIRs) observed between 3.9 AU and 5.9 AU on Pioneers 10 and 11 shows that the main corotation energetic ion population (CEIP), which is associated with the trailing reverse shock, terminates within the CIR at a definite, structural boundary, which we show here is the stream interface. This new result has significant implications for solar wind and energetic particle modeling. In particular it implies either that the reverse shock forms closer to the stream interface than models suggest or that the theories that treat the generation and transport of these energetic ions, such as preshock Fermi acceleration and cross-field diffusion must be combined or extended. We test these scenarios by comparing the CEIP intensity profiles on the two sides of the stream interface. We find that while each automatically accounts for one or two aspects of the results none of them alone can account for all of our empirical results.

Background, Context, And Relevance

This work is part of a project to use the near-radial alignment of Pioneers 10 and 11 during 1974 and the recurrence of the giant streams of 1974 to comprehensively map the quasi-steady structures associated with corotating streams and to quantitatively specify their physical parameters. Such maps and specifications constitute an ecliptic solar wind baseline between 4 AU and 6 AU. The present contribution concerns the spatial relation between the energetic ion component of CIRs and the structural solar wind elements of CIRs.

The energetic ion component of CIRs is organized into pairs of corotating energetic ion populations (CEIPs) associated with a CIR's leading and trailing edges. *Barnes and Simpson* [1976], *McDonald et al.* [1976], *Pesses et al.* [1978], and *Van Hollebeke et al.* [1978] have documented their basic properties. *Barnes and Simpson* [1976] noted that the particle intensity is observed to decrease substantially near the center of a CIR, thus distinguishing the leading and trailing CEIPs. These authors and *Van Hollebeke et al.* [1978] found the trailing CEIP is usually more pronounced than the leading CEIP. (This holds also for the cases studied here.) *Tsurutani et al.* [1982] noted that the minimum between the leading and trailing CEIPs occurs near the maximum in field magnitude at the approximate center of the CIR.

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It is generally observed that the CIR's forward shock lies in the leading CEIP, and its reverse shock lies in the trailing CEIP. Each shock appears to reside within an energetic ion sheath of its own making. Indeed this is the consensus model for the origin of CEIPs. *Palmer and Gosling* [1978], who first proposed the model, invoked Fermi acceleration between converging irregularities upstream and downstream from the shock to accelerate the ions. The motion during and after the acceleration is primarily parallel to the magnetic field. They noted that parallel motion away from the shocks naturally accounts for the fact that the leading CEIP is separated from the trailing CEIP by an energetic-ion-intensity minimum in the center of the CIR, between the two shocks. Since the center of the CIR is magnetically connected to neither shock, it receives no accelerated ions. *Fisk and Lee* [1980] added adiabatic cooling in the expanding solar wind to the theory and successfully accounted for the shape of the energy spectrum within CEIPs.

While the properties of CEIPs were being discovered and explained in terms of corotating shocks and parallel propagation, the properties of corotating shocks were independently being elucidated. Of direct relevance here is the spatial relation between the shocks and the stream interface. *Siscoe* [1976] noted that in the frames of reference of both the preceding slow stream and the succeeding fast stream, the stream interface appears to be a wall bending into the stream. Standard supersonic flow theory applied to this geometry predicts that the forward and reverse shocks should form away from the wall, not at it. In the CIR context, this means that the stream interface should reside in a gap between the forward and reverse shocks. This result is in apparent qualitative agreement with the CEIP observations and interpretations: the minimum between the leading and trailing CEIPs marks the gap.

MHD models of the stream interaction have quantified the size of the gap. Both *Pizzo* [1989] and *Hu* [1993] find that the shocks form 7° to 10° of heliocentric azimuth on either side of the stream interface, which corresponds to 12 to 17 hours in corotation time. Field lines in CIR models tend to preserve their corotation-time spacing with heliocentric distance because the convergence of the slow and fast streams has been largely nullified in the CIR. Thus, at all distances the closest field line to the stream interface that went through a shock at some point lies between 12 and 17 corotation hours away. The final step in this logic notes that on the basis of the shock-generation-and-parallel-propagation (SGPP) model of CEIPs, one would expect CEIPs to be absent within the 12 to 17 hour shock-free gap on either side of the stream interface.

We present here a test of this expectation based on data from Pioneers 10 and 11 taken during the giant streams of 1974. We find many instances in which, instead of being separated from the stream interface by 12 to 17 hours, the leading edge of the (reverse shock) trailing CEIP coincides with the stream interface. The stream interface seems to form a structural boundary to the trailing CEIP, which is a concept that is not presently part of the SGPP model of CEIPs.

Analysis Of Observations

Figure 1 shows Pioneer 11 data from Bartels Rotation 1923. The solar wind speed in the top panel shows that the fast stream has developed a CIR with distinct forward and reverse shocks. The stream interface also shows as a speed increase, which, however, is not its defining trait. We identify the stream interface with a sudden rise in specific entropy caused by a coincident density drop and temperature rise [*Burlaga,* 1974; *Gosling et al.*, 1978]. The second panel shows the entropy jump defining the stream interface and the entropy jump marking the two shocks.

The third panel shows the interplanetary magnetic field orientation in the heliospheric azimuthal plane. It locates the time of passage of the heliospheric current sheet at about 6 hours before the passage of the stream interface. This observation is significant. On similar plots for many recurrences of the streams of 1974 the heliospheric current sheet and the stream interface essentially coincide so that one cannot determine which of them forms the boundary to the trailing (reverse shock) CEIP. Here they are separated enough to resolve the ambiguity.

The fourth panel shows that energetic ion data from three instruments agree on two essential, independent facts: (1) there is a structural boundary to the trailing CEIP, and, (2) the stream interface, not the heliospheric current sheet, is that boundary. (The McDonald data are 6 hour averages. Thus, the fact that the point at the heliospheric current sheet is at the background level implies that the flux had dropped to background before that point, as the other data show explicitly.) The first fact can be verified on many stream recurrences, but the ambiguity we have discussed exists for these. The second fact can also be inferred from Figure 5 of *Tsurutani et al.* [1982] in the sharp change in the energetic particle proton/helium ratio and in the energetic particle spectral index at the leading edge of the trailing CEIP. Resolving the ambiguity lets the other cases be interpreted as applying to the stream interface.

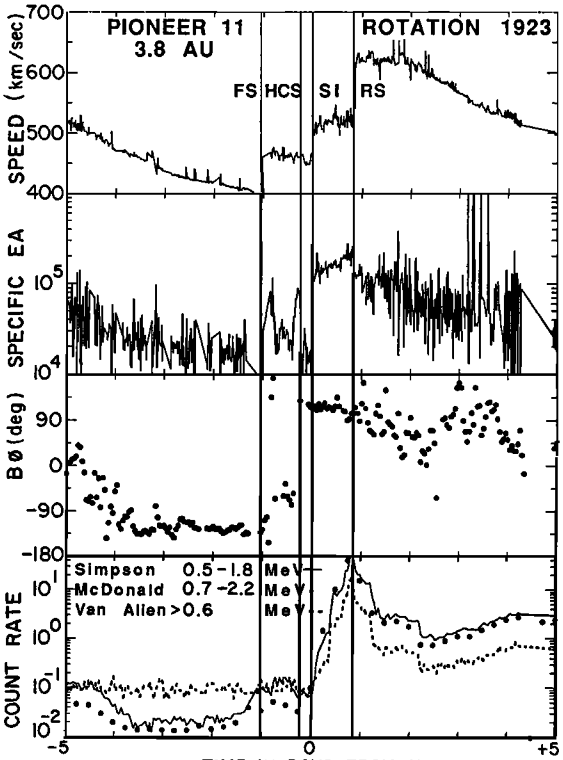

Figure 1. Corotating Interaction Region parameters for stream 1 of Solar Rotation 1923 as seen at Pioneer 11. Abbreviations refer to the following: FS, forward shock; HCS, heliospheric current sheet; SI, stream interface; RS, reverse shock. The "Specific Entropy Argument" plotted in panel 2 is $T/n^{3/2}$ with T in K and n in cm^{-3}. Specific entropy is proportional to the log of this quantity. The polytropic index is taken to be 3/2 because this gives a good fit to the requirement that the specific entropy remain constant with distance (see *Siscoe and Intriligator,* 1993).

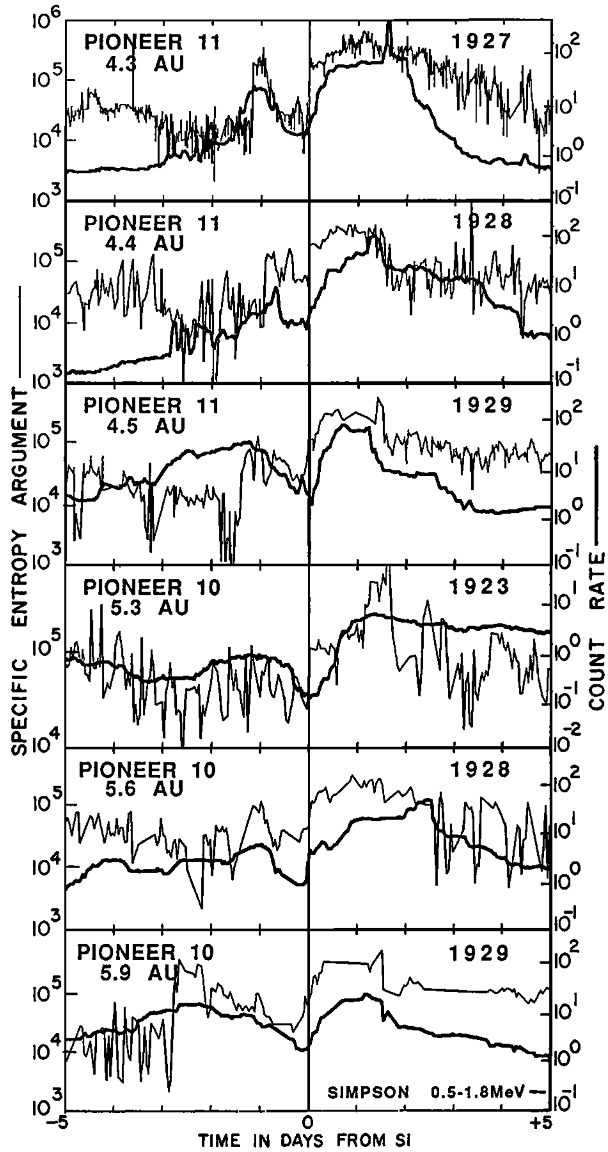

Figure 2. Profiles of the specific entropy argument and the Simpson 0.5-1.8 MeV energetic particle intensity (dark line) for six recurrences of the stream of Figure 1 showing more instances of the near coincidence of the stream interface with the forward boundary of the trailing (reverse shock) CEIP.

Figure 2 shows 6 other instances from Pioneers 10 and 11 of the near coincidence of the boundary of the trailing CEIP and the stream interface. This collection of examples clearly shows that the trailing CEIP does not end 12 or more hours away from the stream interface. Here as in Figure 1, the predicted gap is populated with energetic ions above the background level. On the other hand, in nearly every case the trailing CEIP shows a change in slope of the particle flux from flat to steep toward the stream interface about 12 hours ahead of the stream interface. Also the predicted circa 12 hour gap is present for most of the leading (forward shock) CEIPs.

Figure 3 combines the seven intensity profiles of Figures 1 and 2. Each profile is normalized to the intensity at the stream interface. Vertical lines 12 hours to either side of the stream interface indicate the approximate size of the supposed shock-free gap. The line on the leading side roughly bounds the region of flat profiles; the line on the trailing side roughly marks the change in slope from flat to steep.

Although not directly related to the point of this communication, we note that the examples shown in Figures 1 and 2 illustrate the general tendency reported by *Barnes and Simpson* [1976] and *Van Hollebeke et al.* [1978] that the reverse shock is generally the stronger generator of energetic ions. This agrees also with the models of *Pizzo* [1989] and *Hu* [1993] showing that the reverse shock forms closer to the sun - and is therefore, presumably, stronger - than the forward shock.

That the forward shock is generally a weaker source of energetic ions than the reverse shock does not obviously account for the asymmetry in the energetic ions distributions in the leading and trailing shock-free gaps on either side of the stream interface. In nearly all cases the slope of the leading-side energetic ion population is shallowest adjacent to the stream interface. This is opposite to the behavior of the ion population in the trailing gap. As noted above, on the trailing side, the slope is steepest adjacent to the stream interface. An explanation of the origin of energetic ions in the shock-free gaps must account for the difference in the leading and trailing populations.

As a general rule, the intensity is continuous across stream interfaces, although Solar Rotation 1928 at Pioneer 10 presents an exception to this rule. Also as a general rule, the slope is discontinuous at stream interfaces with the leading-side (forward shock) slope being shallower than the trailing-side (reverse shock) slope. In fact it is this property that gives the stream interface the appearance of being a barrier to the CEIPs.

Discussion

The continuity of intensity and the discontinuity in slope at stream interfaces are probably diagnostics of the origin and

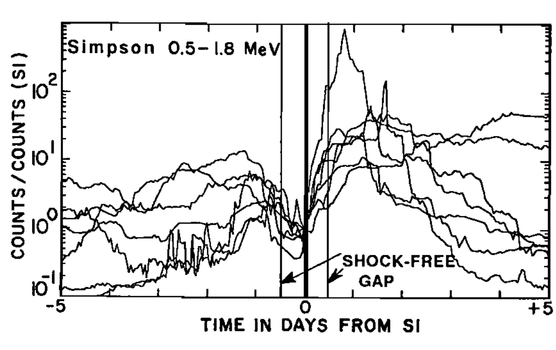

Figure 3. A superposition of the seven intensity profiles of Figures 1 and 2 each normalized to its value at the stream interface. The space between the two lines centered on the stream interface approximates the shock-free gap.

transport of the energetic ions in the shock-free gaps. We consider three scenarios that might account for the presence of energetic ions in the supposedly shock-free gap between the stream interface and the trailing CEIP, and test the ability of each to account for the two diagnostic properties. The three scenarios are pre-shock Fermi acceleration, an attached shock, and cross-field diffusion. Qualitatively each automatically accounts for one or two aspects of the data, but as we will see, without invoking special properties, none automatically accounts for all pertinent aspects of the data. It is possible, for example, that at times both preshock Fermi acceleration and cross field diffusion are operating and that their relative strengths are dependent on the local conditions.

The observation of a particle gap between the leading CEIP and the stream interface as predicted by the SGPP model and the observation of a change in slope of the particle intensity near the edge of the predicted gap between the stream interface and the trailing CEIP suggest that the SGPP model is correct as far as it goes, but that it needs to be supplemented with a mechanism that adds energetic ions to the gap between the stream interface and the reverse shock. Pre-shock generation could supply the particles. Since in the aerodynamic model of stream interactions compression occurs between the stream interface and the point where the shock forms, the Fermi acceleration mechanism of Palmer and Gosling can operate in the gap. The compression is weakest at the stream interface, and it grows continuously to the full shock value at the shock. Thus, this mechanism naturally accounts for the observed signature of the gap around 12 hours away from the stream interface - the change in slope - and it accounts qualitatively for the observed profile of the particle intensity in the trailing gaps. There is an apparent counter-example to the pre-shock compression scenario. The profile measured by Pioneer 10 for Solar Rotation 1928 shows the trailing CEIP butting firmly up against the stream interface. If compression is responsible for this case, it must operate at nearly full strength right up to the interface. This may be consistent with a kink in the heliospheric current sheet which occurs at this time. Alternatively, this example suggests that occasionally the reverse shock might be attached to the stream interface.

A challenge to the pre-shock compression scenario and the attached-shock scenario is the fact that if they operate in the trailing gap they should also operate in the leading gap, since the factors determining their existence appear to be similar in both cases. That is, these mechanisms should produce qualitatively similar intensity profiles in both gaps, but with independently determined intensities on the two sides (presumably weaker on the leading side). As noted above, however, in general the particle profiles are qualitatively different in the two gaps, and the absolute values of the intensities are in general equal at the stream interface. These observational constraints pose serious problems for the preshock compression and attached shock models.

An explanation in terms of cross-field diffusion accommodates the observational constraint of continuity of intensity at the stream interface. Indeed, diffusion models require continuity of intensity, since a discontinuity implies an infinite diffusive flux. With an additional assumption a diffusion explanation can also accommodate the observational constraint of a discontinuity of slope of the intensity profile at the stream interface. A nonhomogeneous diffusion coefficient changes the slope of the intensity profile. Thus many intensity profiles can be accounted for in terms of the spatial distribution of the sources and the inhomogeneity of the diffusion coefficient. For example, the flat minima for all but SR 1929 might imply that the diffusion coefficient tends to maximize in the high density region just prior to the stream interface. In principle, this possibility can be checked.

The discontinuity in intensity for SR 1928 at Pioneer 10 is inconsistent with a simple diffusion interpretation. Since the discontinuity is not evident at Pioneer 11, this case seems to violate the requirement of time stationarity in the corotating frame. We also note for SR 1928 a wider kink in the heliospheric current sheet at Pioneer 10 than at Pioneer 11. Perhaps time-dependent advection is working with diffusion in this case. More examples must be documented and analyzed to say more about exceptions like this.

This discussion does not settle the question of the origin of the particles in the supposed shock-free gap nor the meaning of the contiguity between two structures that have spatially independent origins - the stream interface and the trailing CEIP. Its purpose is to raise the issue for studies by investigators with other data sets and with quantitative models of these structures.

Conclusions

Our conclusion are: 1) that the stream interface forms a structural boundary to corotating energetic ion populations (CEIPs) associated with the prolific reverse shocks in CIRs in the vicinity of the ecliptic plane at distances of 4 AU to 6 AU. The abrupt increase in specific entropy at the stream interface is an effective marker of this boundary. Since at all distances the closest magnetic field line to the stream interface that went through a shock lies between 12 and 17 corotation hours away from the stream interface, one would expect CEIPs to be absent within this shock-free gap on either side of the stream interface. 2) The gap is often filled with energetic particles (CEIPs) which are presumably of shock origin. 3) There is an asymmetry in CEIP profiles with respect to the stream interface. 4) There is a continuity of CEIP intensity at the stream interface. 5) There is a discontinuity in CEIP profile slope at stream interfaces. 6) The CEIP properties in 4) and 5) are diagnostics of the origin and transport of the energetic ions in the shock-free gaps. To account for these two diagnostic properties we consider and test three scenarios: (a) pre-shock Fermi acceleration, (b) cross-field diffusion, and (c) an attached shock. 7) No single scenario can account for the diversity of CEIP profiles observed in the shock-free gap nor the contiguity between the two structures - the stream interface and the trailing (reverse shock) CEIP - that have spatially independent origins. These new results must be taken into account in future empirical studies with other data sets and in quantitative modeling of these structures.

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