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REPLY TO HEIKKILA

Mike Lockwood

Rutherford Appleton Laboratory, Chilton, UK

Mark F. Smith

Southwest Research Institute, San Antonio, TX, U.S.A.

Walter Heikkila's comment on our paper [Lockwood and Smith, 1989] agrees that the DE-2 observations we presented show a transient injection, rather than an intersection with a stable cusp (see Newell [1990] and Lockwood and Smith [1990]), but proposes that the event was a "plasma transfer event" (PTE), not a flux transfer event (FTE). In this reply, we do not intend to discuss the physics of the magnetopause and weigh up the relative merits of time-dependent reconnection theory [Southwood et al., 1988; Scholer, 1988] with that of impulsive plasma penetration [Heikkila, 1982, 1984] (which give the FTEs and PTEs, respectively), other than to note that other authors have cast doubt on the PTE concept [Cowley, 1984; 1986]. Neither will we add to Heikkila's discussion on how the part of the low-latitude boundary layer on closed field lines is populated with magnetosheath plasma, other than to note that reconnection can be invoked if some field lines are opened and then closed again [Nishida, 1989]. Rather, we will limit our discussion to whether a cloud of magnetosheath plasma, were it able to impulsively penetrate onto closed field lines, would give the signatures observed by DE-2 during the pass we presented.

There are very few predictions concerning the ionospheric signature of a PTE. However, because momentum would be imparted to the high altitude portion of a flux tube, the work of Southwood and Hughes [1982] can be applied to predict the flows and currents in the ionosphere (and the pattern of field-aligned currents) as was done for an FTE by Southwood [1987]. In fact, if there are no differences between the induced ionospheric conductivity changes for an FTE and a PTE, their signatures will have the same twin-vortical form. However, as pointed out by Cowley [1986], the major difference between FTE and PTE flow signatures is one of direction of motion. We would expect an FTE to initially move zonally around the polar cap boundary (under the influence of magnetic tension) before slowing and moving into the polar cap (under the influence of anti-solar magnetosheath flow) [Lockwood and Freeman, 1989; Saunders, 1989]. Conversely, a PTE signature should move equatorward and tailward (as the magnetosheath plasma penetrates and moves antisunward). For both a PTE and an FTE the mean plasma flow inside the event must always be the same as the event motion [Lockwood et al., 1990]. Inside the event we have presented we find the plasma flow to be well aligned with the polar cap boundary, as seen simultaneously by the DE-1 imager. This alignment is to within about 2° and hence if there is an equatorward (penetration) component it is very small. If DE-2 intersected an FTE early in its lifetime or possibly a PTE later in its lifetime, there could be purely zonal motion around the polar cap boundary (as observed) in both cases, hence the direction of flow does not distinguish between the two in this case. We note Heikkila states we "assume" the event later moved "towards open field lines": motion into the polar cap is a consequence of an FTE interpretation, but our analysis of the DE-2 data was in no way dependent on making this assumption.

It is instructive at this point to consider the ground-based observations which lead us to consider the data in terms of an FTE. The combined observations by optical instruments on Svalbard and the EISCAT radar have shown auroral and plasma flow transients (with 8 minute repetition period when the IMF is continuously southward) which move zonally and then poleward into the polar cap [Lockwood et al., 1989a;b; Sandholt et al., 1990]. This pattern of motion is as described above for FTEs but the drift into the polar cap discounts PTEs. Furthermore, the sense of the zonal motion of each transient appears to be controlled by the sense of the IMF B_y component (although note that available statistics on this are still poor – Sandholt, [1988]), in the same way that average currents and flows in the cusp are known to be. It is important to verify this relationship because it is easily explained in terms of FTEs but we know of no reason why PTEs should behave this way. Furthermore, the ground-based observations reveal transients moving west round the northern hemisphere, afternoon sector polar cap boundary (under positive IMF B_y) and east around the morning sector (under negative IMF B_y). Again, this is easily explained by magnetic tension but it is very difficult to see how penetration of antisunward-moving sheath plasma would cause this sunward flow around the polar cap boundary: as shown from Heikkila's Figure 1, antisunward flow around this boundary (with a smaller equatorward component as the patch penetrates) would be predicted for a PTE. If a pulse of enhanced solar wind dynamic pressure impinged upon the magnetopause away from noon, it can generate a traveling vortical flow pattern which moves away from the point of impact, sunward around the polar cap boundary [Southwood and Kivelson, 1990]: however, this does not give nett sunward motion of the ionospheric plasma, as is observed, and does not involve any plasma penetration across the magnetopause (i.e. such events are not PTEs) [see also Lockwood et al., 1990].

Another crucial difference between an FTE and PTE is that the injected ions are on (newly) open field lines in an FTE, whereas they are on closed field lines in a PTE. It is very difficult to make this distinction experimentally. In our original paper, we used both the flux and pitch angle distribution of > 35 keV electrons (not just the latter, as

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stated by Heikkila) to infer that the injection was on open lines. Heikkila states that this is explained by pitch angle scattering on closed field lines, but this is not adequate as observed fluxes decrease at all pitch angles (by over two orders of magnitude). However, we do agree that these electron data are not conclusive, but for a different reason – namely that low intensity, isotropic distributions will be present on the outermost closed field lines due to electron loss processes at the magnetopause. Could, then, the ion injection be on closed field lines which have been depleted of > 35 keV electrons by such a mechanism? For the PTE theory, the satellite must have remained on closed field lines until after 09:55:47 UT which means that electrons were lost from a shell which was at least one degree of invariant latitude thick. Part A of Figure 1 of our original paper shows that the flux and anisotropy of these electrons decreased gradually, reaching their polar cap values (or at least noise levels) at 09:55:29. Many other features appear in the data at exactly this time (to within about 1 second): the onset of the main burst of injected ions (panel b); the onset of precipitating 100 eV electrons (panel c); the onset of westward, rapid flows (panels d and e); and the change in sense of the eastward magnetic field perturbation, ΔB_ϕ (panel g). As described in our original paper, these signatures are all expected at the boundary of closed and newly-opened flux tubes in the FTE model. For the PTE model, it seems a major, and highly unlikely, coincidence that the observed electron fluxes reach their "polar cap" values at exactly the point to where the injected ions have penetrated. It is a coincidence because the electron loss mechanism invoked to explain panel a (the > 35 keV electrons) is entirely independent from the penetration mechanism invoked to explain panel b (the injected ions) in the PTE interpretation. We believe that pitch angle scattering is observed as the filling of the loss cone after 09:55:00 and that an electron loss mechanism is also apparent in the data as the gradual decline in fluxes (at both pitch angles shown) prior to 09:55:29. Without these effects, the FTE model would predict constant anisotropy and flux before 09:55:29, when there would have been a step function decrease in fluxes at both pitch angles shown.

In conclusion, we believe the data are much better explained by an FTE transient than a PTE transient. However, it is notoriously difficult to determine whether a satellite is on open or closed field lines. The direction of motion, being almost exactly along the polar cap boundary, does not conclusively differentiate between a PTE and FTE in this case. However, we note that the ground-based observations which prompted our original paper show a pattern of motion consistent with FTEs and entirely inconsistent with PTEs.

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M. Lockwood, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, U.K.

M. F. Smith, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228, U.S.A.

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