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How the magnetopause transition parameter works

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Abstract. The transition parameter is based on the electron characteristics close to the Earth's dayside magnetopause, but reveals systematic ordering of other, independent, data such as the ion flow, density and temperature and the orientation and strength of the magnetic field. Potentially, therefore, it is a very useful tool for resolving ambiguities in a sequence of satellite data caused by the effects of structure and motion of the boundary; however, its application has been limited because there has been no clear understanding of how it works. We present an analysis of data from the AMPTE-UKS satellite which shows that the transition parameter orders magnetopause data because magnetic reconnection generates newly-opened field lines which coat the boundary: a direct relationship is found with the time elapsed since the boundary-layer field line was opened. A simple model is used to reproduce this behaviour.

Introduction

Studies of electron observations by the AMPTE-UKS satellite at the dayside magnetopause showed a systematic relationship between the (number) density and temperature. From this, *Hapgood and Bryant* [1990; 1992] devised the transition parameter τ which was found to order independent data on the ion gas and magnetic field, thereby revealing an underlying structure which is usually complicated in the time sequence of data by multiple and partial boundary crossings caused by magnetopause motions. Figure 1 illustrates how τ is generated. The electron density is plotted against the electron temperature on a log-log scale. Because there are bi-directional streams of electrons along the magnetic field in some parts of the low-latitude boundary layer (LLBL), the scatter is reduced if the field-perpendicular temperature is used. The data are fitted with a characteristic curve which varies in detail from case to case but, in the main, has the same general form. The high density, low temperature end of this curve (data from the magnetosheath) is ascribed the value $\tau = 0$ whereas the low density, high temperature (magnetosphere) end of this curve is $\tau = 100$. Between these two points, τ is the percentage of the distance along the fitted curve. In figure 1, the triangles are at intervals of τ which are 5 apart.

The crosses in figure 1 are all data from the interval 11:45 - 12:42 UT on 28 October 1984, an outbound magnetopause crossing of AMPTE-UKS. Earlier in the pass (10:43 - 10:49 UT), UKS was in the magnetosphere (at 9 hrs MLT, 26° magnetic latitude and a radial distance of $10R_E$) and observed a characteristic set of signatures called a flux transfer event (FTE) during which the electron data varied as shown by the open squares in figure 1. This is a much-discussed event, presented by *Farrugia et al.* [1988] and most recently re-analysed by Lockwood et al. (Lockwood, M. et al., The cause of the 24 October 1984 AMPTE flux transfer event, submitted to J. Geophys. Res., 1997: hereafter referred to as LEA). It can be seen that the electron behaviour has the same general form in the FTE as in the magnetopause crossing. This is a feature of FTE signatures which strongly suggests that they are manifestations of the same structures and mechanisms as seen during magnetopause current sheet crossings [*Hapgood and Lockwood,* 1995]. In the case shown here, the magnetopause end of the curve for the FTE is very similar to that for the magnetopause crossing (almost 2 hours later) but, whereas the magnetospheric electron gas had the same perpendicular temperature for these two intervals, its density was higher by a factor of about 1.4 at the time of the FTE. The values of τ during the FTE used here were computed using the shown fit to the magnetopause crossing data; however, almost identical values were derived if a fit to the FTE data was employed (with the same $\tau = 0$ point). In this paper, we make use of this FTE to investigate how the transition parameter orders the magnetopause observations. We use the concept of particle populations in the LLBL evolving with time-elapsed since reconnection, as illustrated schematically in figure 2.

FTE Observations on 28 October 1984

The histograms in the top 5 panels of figure 3 show measurements of the ion gas during the FTE: the ion density in the full (10eV-20 keV) energy range of the instrument, N; the ion density in the range 10-20 keV, $N_{[E>10keV]}$; the ion temperature, T; the field-parallel ion velocity, V_{para} ; and the pressure of the ion gas, P. In each case, the data have been fitted with a curve produced by the model of *Lockwood et al.* [1996], using the procedure outlined below. The ion distribution functions outside and at the centre of this event [*Smith and Owen*, 1992] are used here to define the ion populations in the LLBL from the magnetosphere and magnetosheath, respectively. The mixing of these ions, with allowance for reflection and transmission of both species of ions by both Alfvén

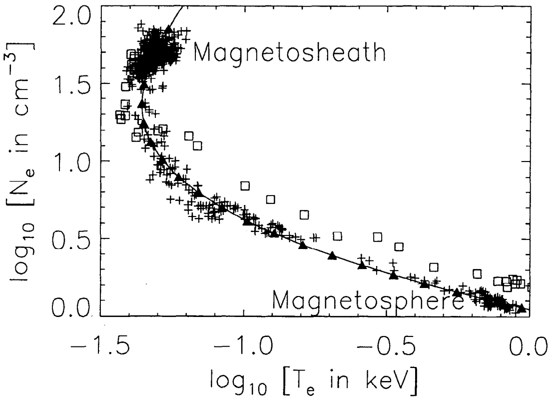

Figure 1. The variation of electron density with perpendicular electron temperature (on a log-log scale) for the magnetopause crossing of AMPTE-UKS during the interval 11:45-12:42 UT on 28 October 1984 (crosses). The triangles divide the fitted curve into 20 equal lengths and are ascribed transition parameter values 5 apart between τ=0 (magnetosheath) and τ=100 (magnetosphere). The data for the FTE event at 10:43-10:49 UT, earlier on the same pass, are shown as open squares.

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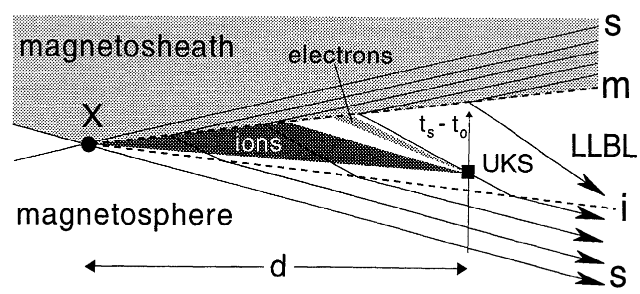

Figure 2. Schematic of AMPTE-UKS in the open LLBL, between the magnetopause (m) and interior (i) Alfvén waves emanating from the reconnection site (X-line), X. Field lines evolving away from X are shown at five elapsed times since they were opened (t_s-t_o), including zero for the magnetic separatrices (s). The spectrum of sheath ions reaching UKS has a spread of trajectories shown by the dark shaded wedge, the trajectories of the sheath electrons are much closer to field-aligned (lighter shaded wedge). The populations seen depend on UKS's depth into the LLBL, i.e. on the (t_s-t_o) at a given distance d from X.

waves emanating from the reconnection site [see *Lockwood et al.,* 1996], is then computed from the ion flight times at each selected time elapsed since reconnection, (t_s-t_o). (The time of observation of a given field line is t_s and the time that it was reconnected is t_o).

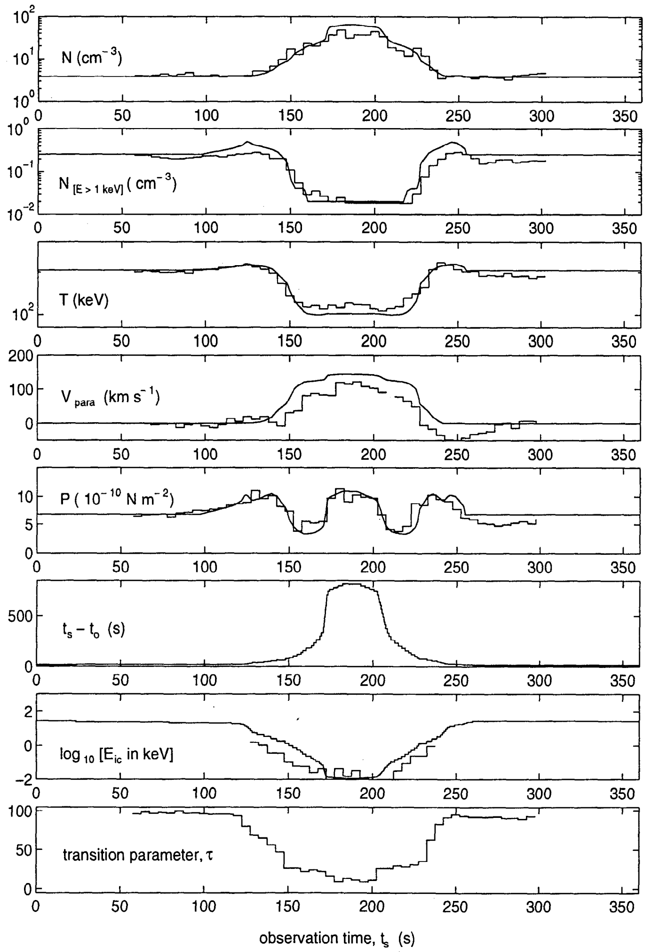

Figure 3. AMPTE UKS observations of an FTE on 28 October 1984, plotted as a function of observation time, t_s, which is zero at 10:43 UT. All moments, modelled and observed, assume isotropy (see text for details).

The distance d between the satellite and the reconnection site (X-line) is assumed to be constant and here put equal to 6R_E (1R_E = 6370 km). The value of d adopted is not significant, other than all (t_s-t_o) axes on plots scale linearly with d. The moments of the total ion distribution function were computed as a function of (t_s-t_o) and the fits to the data produced by adjusting the variation of (t_s-t_o) with observation time t_s until good agreement was obtained with the observed variations of N and $N_{[E>10keV]}$. It can be seen that this also produces good fits to the observed variations in T, V_{para} and P. The layered variation of P (with high P on the edges and at the centre, separated by a layer of lower P) provides a particularly stringent test of the model and has not previously been explained. The sixth panel of figure 3 gives the best-fit variation of (t_s-t_o) and the seventh the variation of the corresponding lower cut-off energy of magnetosheath ions in the LLBL, $E_{ic} = (m/2)[d/(t_s-t_o)]^2$, where m is the ion mass. As a further check of the fit, E_{ic} is here compared with the histogram of values derived from the ion data by the time-series method introduced by *Lockwood et al.* [1994] and tested by *Lockwood and Davis* [1996]. The bottom panel shows the variation of the transition parameter τ. The model predictions shown have great implications for our understanding of the cause of this FTE, as discussed by LEA: however, this is not the subject of the present paper. Rather, we here concentrate on the implications for understanding the transition parameter.

Figure 4 shows the variation of τ as a function of the fitted (t_s-t_o) in the form of a hodogram (solid line). The path followed on entering the event is similar to that seen in reverse when leaving the event. As (t_s-t_o) increases from 0 to 850 s, τ drops from 100 to near 10 by following two straight lines: in the first 100 seconds following reconnection, τ drops steeply from 100 to near 25, but thereafter it follows a line of much lower gradient.

Studying Plate 1 of *Farrugia et al.* [1988] offers an explanation of this behaviour in terms of particle flight times along the newly-opened field lines. During the intervals when the fitted (t_s-t_o) in figure 3 varies between 0 and 100 s, the electron energy-time spectrogram shows a clear and progressive decay in the fluxes of the highest-energy (magnetospheric) electrons. This is also seen in figure 5 of the present paper (adapted from *Farrugia et al.* [1988]). Figure 5b shows that the density of electrons at energies 2-16 keV, $N_{e[E>2keV]}$, decayed as τ fell from 100 to about 40 (outside the vertical dashed lines), along with the electron temperature, T_e (figure 5c). This interval therefore appears to be on

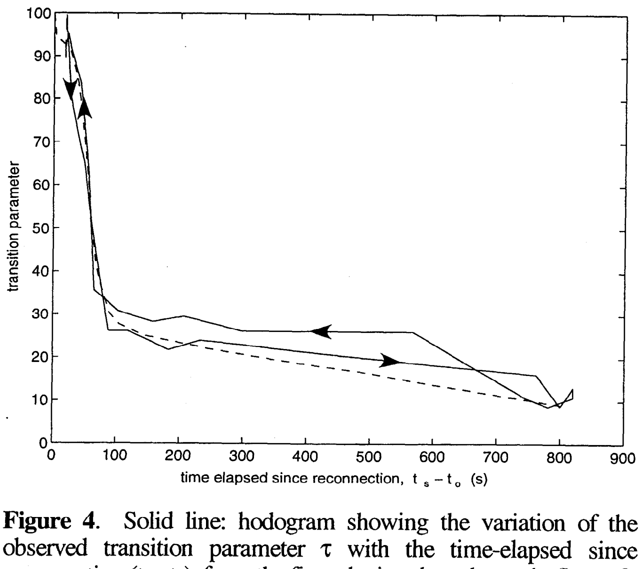

Figure 4. Solid line: hodogram showing the variation of the observed transition parameter τ with the time-elapsed since reconnection (t_s - t_o), from the fit to the ion data shown in figure 3. Dashed line: model prediction made by applying the transition parameter to the modelled electron data shown in figure 6.

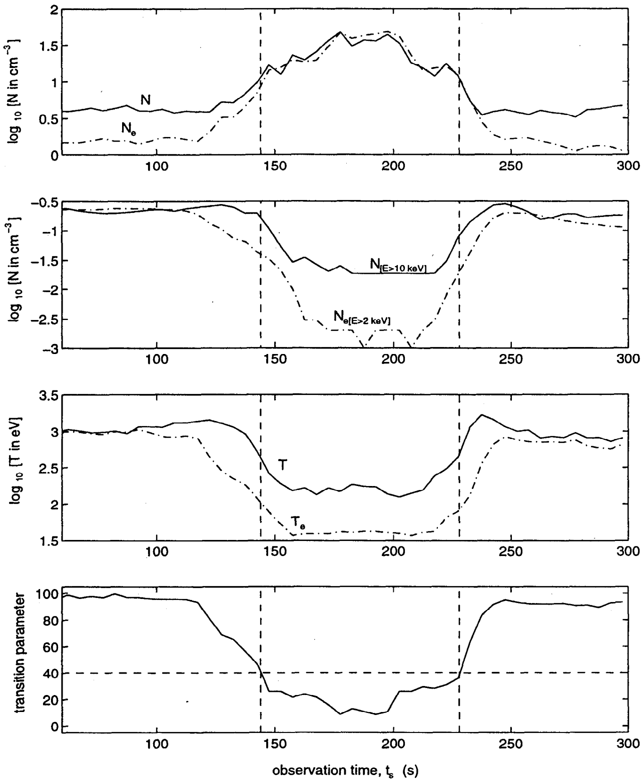

Figure 5. (a). Total electron and ion densities, N_e and N, seen by the instruments on AMPTE-UKS during the FTE event (b). electron density in the range 2-16 keV and ion density in the range 10-20 keV, $N_{e[E>2keV]}$ and $N_{[E>10\ keV]}$ (c) electron and ion temperature, T_e and T and (d) the transition parameter, τ. All data are shown as a function of observation time t_s (which is zero at 10:43 UT). The dot-dashed lines show the electron data.

in which magnetospheric electrons escaped through the magnetopause. This loss occurred before/after much of the corresponding changes in the ions on entering/leaving the event, i.e. at a lower $(t_s\text{-}t_o)$. However, the total electron density, N_e (figure 5a) only rose by a relatively small amount above magnetospheric values in these periods and, as at all other times within the event, was the same as the density of the detected ions, N. The rise in N was small at $(t_s\text{-}t_o) < 100$s because only the most energetic of the entering sheath ions had sufficient time to reach the satellite. In the core of the event (between the dashed lines), when $(t_s\text{-}t_o)$ rose from 100 to 850, this quasi-neutrality was also maintained but N and N_e reached larger values as more sheath ions (with accompanying sheath electrons) arrived; the electron temperature drop continued with the decrease in ion temperature, but ceased at the event centre, as all magnetospheric electrons had escaped.

A Simple Model of the Transition Parameter

It is possible to test this interpretation of the variation of τ with $(t_s\text{-}t_o)$ using a simple model of the electron behaviour, along with the ion model of *Lockwood et al.* [1996]. Magnetospheric electrons moving towards the magnetopause are assumed to be free to escape into the sheath after their flight time from the satellite to the boundary. Such electrons will initially be replaced by others which have mirrored in the converging geomagnetic field at low altitudes and are moving towards the magnetopause; however, this supply of replacement electrons is cut off when the field line is opened. This is first noted at high energies and at low pitch angles (i.e. for low flight times), as was observed by *Gosling et al.* [1990]. Electrons moving towards the Earth are also assumed to be free to escape, but only after their flight time to a mirror point closer to the Earth and back to the boundary. Thus the timescale for their escape is set by the field-aligned distance from the satellite to the Earth, which is here taken to be $20R_E$. At a given $(t_s\text{-}t_o)$, only magnetospheric electrons whose flight time to escape to the sheath is greater than $(t_s\text{-}t_o)$ remain. Figure 5a shows that quasi-neutrality was maintained within the event (outside the event this does not appear to be true, presumably because of an excess of magnetospheric electrons above the energy range of the instruments). The model achieves electrical neutrality within the event by considering there to be a small potential barrier caused by an accumulation of electrons somewhere between the magnetopause and the satellite. The height of this potential barrier, V_b, is set such that the total electron density at the satellite N_e equals that of the ions N. This is possible because the potential barrier prevents the lowest-energy sheath electrons from reaching the satellite. Such a barrier was considered by *Wing et al.* [1996] as a way to model the flux of sheath electrons into the cusp/cleft ionosphere. The ion density N is computed as a function of $(t_s\text{-}t_o)$ by the model of *Lockwood et al.* [1996], as used in the fits to the ion data in figure 3. The moments of the initial magnetosheath and magnetospheric electron populations are taken from the $\tau = 0$ and $\tau = 100$ ends of the transition parameter plot shown in figure 1. The electron temperature, T_e, is then computed for the derived total electron distribution function at each $(t_s\text{-}t_o)$.

The results are shown in figure 6: part (a) gives the variation of the T_e with $(t_s\text{-}t_o)$ and 6b shows the associated rise in electron density, $N_e = N$. The initial drop in T_e (at 0-5 s) reflects the loss of the electrons moving towards the magnetopause, but those moving toward the Earth take longer to escape: however, even those at

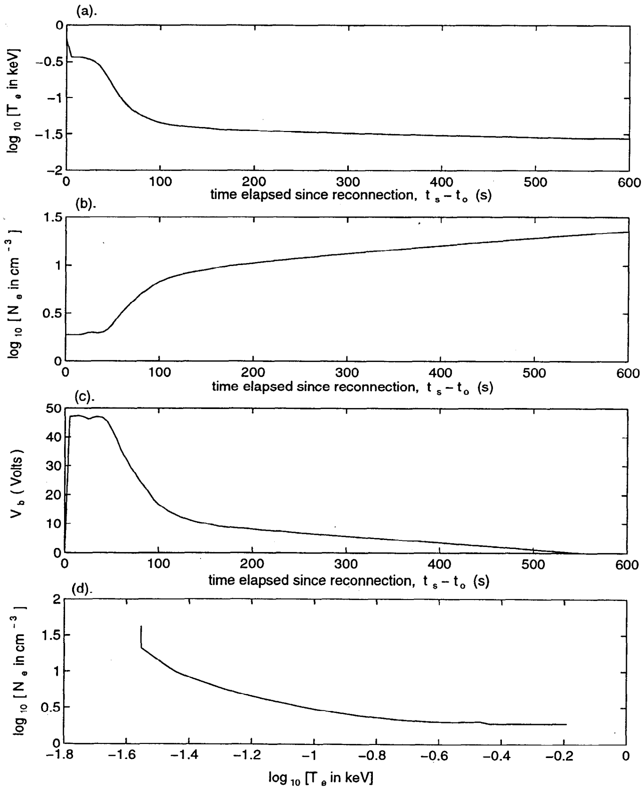

Figure 6. Simulated transition parameter: (a). the logarithm of electron temperature, T_e, as a function of time elapsed since reconnection, $(t_s - t_o)$; (b). the log of electron density N_e; (c). the voltage V_b of the potential barrier needed to maintain quasi-neutrality and (d). the log of T_e as a function of the log of N_e.

large pitch angles are largely lost by $(t_s\text{-}t_o)$ = 100s, when T_e approaches its magnetosheath value. A subsequent small and slow drop in T_e is seen as lower energy sheath electrons are allowed across the boundary by the drop in V_b. Figure 6c shows the V_b required to ensure $N_e = N$: initially V_b is near 45 V (a value which depends sensitively on T_e in the magnetosheath) but decays as N_e increases so that after $(t_s\text{-}t_o)$ = 100s, V_b decreases slowly.
Figure 6d is a plot of N_e against T_e on a log-log scale. Comparison with figure 1 shows that the model has reproduced most of the features of the observed variation. Indeed, the only feature missing is a small rise in T_e as N_e reaches its largest values (when τ descends below 10). This is a feature of the magnetosheath immediately outside the magnetopause (and any remnant plasma depletion layer there) and cannot therefore be reproduced by the model which applies only to the newly-opened field lines on the inside of the magnetopause current sheet. The current sheet was observed (as a change in field orientation) at around $\tau = 10$ during the magnetopause crossing. That the observed τ does not fall below 10 within the FTE confirms that the satellite remains within the magnetosphere within the event, as was concluded by *Smith and Owen* [1992] from the form of the ion distribution function at its centre. The curve shown in figure 6d can be used to derive a synthesised transition parameter, using the same procedure as for the observations. The $\tau = 0$ point used is that of the input sheath population which is not reached by the model as it does not allow for the satellite passing through the magnetopause and into the magnetosheath. The modelled transition parameter is shown as a function of time elapsed since reconnection by the dashed line in figure 4. The similarity to the observed variation is clear and from this, and from the similarity of the magnetospheric half of the $\log(N_e)$-$\log(T_e)$ curve, we conclude that the open magnetosphere model can describe the basic behaviour of the electron gas on which the transition parameter depends.

Discussion

Loss of magnetospheric electrons through the magnetopause along newly-opened field lines causes a steep drop of the electron temperature at elapsed times since reconnection between $(t_s\text{-}t_o)$ of 0 and 100 s (for the assumed distances to the magnetopause and the Earth of 6 and 20 R_E). This drop is clearly revealed in the observations, as shown in figure 5. On this timescale, few sheath ions have reached the satellite: so, to maintain quasi-neutrality, few sheath electrons will have reached the satellite. As a result, there is a small rise in N_e in this interval but a large drop in T_e. This gives a large drop in the transition parameter from 100 at $(t_s\text{-}t_o) = 0$ to near 25 at $(t_s\text{-}t_o) \approx 100$ s. At $(t_s\text{-}t_o) > 100$ s, the density N_e rises as more magnetosheath ions arrive, but the electron temperature T_e is roughly constant, there being no more magnetospheric electrons in the mixture. This constitutes a further (smaller) drop in τ to values near 10 at $(t_s\text{-}t_o) \approx 850$s.

The model therefore provides an adequate description of the transition parameter, however, it is not a complete description of the electron gas. For example, no account is taken of possible changes in upgoing ionospheric electron fluxes. In addition, *Farrugia et al.* [1988] show that bi-directional streams of middle-energy (100-500 eV) electrons are present at those times when V_b is large ($\tau \approx$ 100-25, $(t_s\text{-}t_o) \approx$ 0-100 s). These streams are not generated by the model. Plate 1 of *Farrugia et al.* [1988] reveals that the development of the streams is closely related to the loss of higher-energy magnetospheric electrons, but that they are absent after $(t_s\text{-}t_o) \approx 100$ s ($\tau < 25$). These streams are probably initially Earthward but are mirrored in the converging field and return to the spacecraft. They are also ordered by τ and are probably related to the need to maintain quasi-neutrality at all points along the field line, which is achieved here for the location of the satellite with the simple potential barrier restricting the entry of sheath electrons. As the energy of the streaming electrons exceeds that of the sheath electron gas in the model, their presence means that T_e will be slightly underestimated by the model in the interval $(t_s\text{-}t_o) \approx$ 0-100 s. However, the streams do not raise the perpendicular electron temperature on which the modelled transition parameter is based.

The two-gradient nature of the variation of τ with $(t_s\text{-}t_o)$, as in figure 4, should be present in all cases when the satellite passes through a part of the magnetopause where newly-opened field lines, produced by magnetopause reconnection, are present: those flux tubes evolve from the reconnection site to the point in question under the joint action of magnetosheath flow and magnetic tension. The precise form of the variation of τ with $(t_s\text{-}t_o)$ will not always be exactly as modelled in figure 4 and may depend on various parameters including the magnetosheath and magnetospheric electron and ion temperatures and densities and on the field-aligned distances of the satellite from the X-line and the Earth.

Lastly, we note that the transition parameter usually orders magnetopause data. Exceptions to this in the AMPTE-UKS data set are rare: of 31 dayside magnetopause crossings, 27 (85%) were well-ordered by the transition parameter [*Hapgood and Bryant*, 1990]. Given the success of the open magnetosphere model in explaining the behaviour of the transition parameter, as is argued here, we conclude that at least some newly-opened field lines coat most of the dayside magnetopause most of the time, irrespective of how patchy or bursty the reconnection is.

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