Magnetic flux transport in the Dungey cycle: the role of substorms in flux closure

S. E. Milan, G. Provan, and B. Hubert

Abstract: We investigate the dayside and nightside magnetic reconnection rates that drive the Dungey convection cycle in the magnetosphere, focusing on the contribution of substorms to the flux closure process. We find a good correspondence between substorms and episodes of nightside reconnection; the average amount of open flux closed is 0.3 GWb, which represents almost 50% of the 0.65 GWb that is typically present at substorm onset. Although conventional wisdom suggests that magnetospheric convection is in the main driven by tail reconnection occuring at a distant X-line independently of substorms, we find no clear signatures of reconnection during non-substorm intervals. This suggests that (almost) all of flux closure in the Dungey cycle occurs at a near-Earth X-line during substorms.

Key words: Substorms, Magnetic reconnection, Dungey cycle, Flux transport.

1. Introduction

The last few years have seen an increasing use of the technique of measuring changes in the size of the polar cap to estimate dayside and nightside reconnection rates (e.g. [15, 9, 10, 13, 11, 12, 7]). These reconnection rates control the rate of flux transport within the Dungey cycle ([2] and [3]), the driver for the majority of magnetospheric dynamic phenomena. When the day- and nightside reconnection rates are unbalanced the open flux content of the magnetosphere waxes and wanes as described by the expanding/contracting polar cap paradigm (ECPC), as proposed by e.g. [16] and [1]. This paper examines the role of substorms in the closure of open flux within the Dungey cycle.

A summary of nightside reconnection rates observed during substorms was recently presented by [14]. These results indicated that while the duration and rate of reconnection was highly variable between substorms, often 0.3 GWb of open flux was closed, representing approximately a half of the open flux in the magnetosphere at onset. Substorms, then, play an extremely important role in flux closure in the Dungey cycle, as predicted by [8]. This brief report presents an extended set of results, and comments on changes in the open flux content of the magnetosphere during substorms.

2. Observations and discussion

Changes in the open flux contained within the polar cap are found from auroral images taken from space, SuperDARN radar [5] observations, and measurements of precipitating particles by low-Earth polar orbiting spacecraft, as described in detail by [13]. Results of a 12-hour observing period on 26 August 1998 are shown in Figure 1 (also investigated in detail by [11]). Panel (a) shows the variation in open flux, F_{PC}, determined using these techniques (thick grey curve) between 00 and 12 UT, the period that auroral images were available. F_{PC} varies between 0.2 and 0.9 GWb in this interval, increases being due to the opening of flux at the magnetopause by low latitude reconnection when the interplanetary magnetic field (IMF) is directed southwards, and decreases due to reconnection in the tail mainly during substorm activity. Thus, the change in F_{PC} can be described as a competition between the dayside and nightside rates of reconnection, Φ_D and Φ_N:

$$\frac{dF_{PC}}{dt} = \Phi_D - \Phi_N. \quad (1)$$

Changes in F_{PC} do not allow unambiguous measurements of Φ_D and Φ_N, but only the difference between them. To remove this ambiguity, measurements of the ionospheric convection flow are necessary, as described by [13] and [7]. However, an approximate disentanglement of the contributions of Φ_D and Φ_N to dF_{PC}/dt can be found if Φ_D is assumed to be proportional to the Y-component of the solar wind motional electric field $V_{SW}B_S$, where V_{SW} is the solar wind speed and B_S is the southward component of the IMF, as described by e.g. [9]. For reference, IMF B_z measured by ACE and lagged to the magnetopause is presented in panel (d). Assuming an effective dayside X-line length $L_{eff} \approx 5R_E$ allows the dayside reconnection rate to be written

$$\Phi_D = L_{eff} V_{SW} B_S \quad (2)$$

which is indicated by the solid curve in panel (e). This time series of Φ_D has been used in conjunction with Eq. 1 to find the expected variation in F_{PC} with time, assuming in the first instance that no nightside reconnection takes place, that is $\Phi_N = 0$, and this is shown by the dotted line in panel (a). Although the observed and predicted curves do not match, the rate of increase of F_{PC} is well-captured by the predictions during periods of southward IMF. Discrepancies between the predicted and observed curves is then due to the occurrence of nightside reconnection. We consider this nightside reconnection to occur in specific episodes (4 in the present interval) which are each associated with uniform Φ_N for the duration of the event. We have chosen the start and end of each reconnection burst, and the rate of reconnection during the burst, to achieve as good a fit as possible between predicted F_{PC} (Eq. 1), shown by the

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black curve in panel (a), and the observations. The occurrence of these bursts and their associated Φ_N is shown by grey rectangles in panel (e).

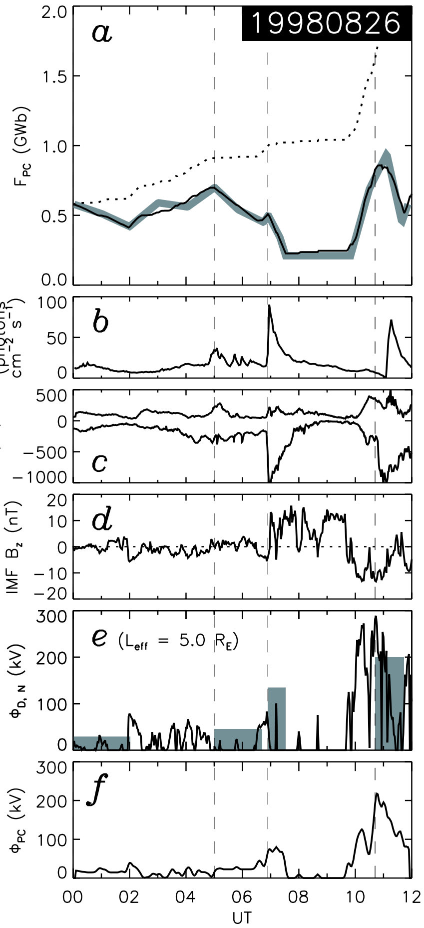

Fig. 1. (a) The observed open flux in the northern polar cap (grey curve) for a 12-hour period on 26 August 1998, along with modelled variations (dotted and solid curves, see text for details). (b) Maximum auroral brightness in the nightside sector. (c) AL and AU auroral indices. (d) IMF B_z measured by the ACE spacecraft and lagged to the magnetopause. (e) Estimated dayside (solid curve) and nightside (grey rectangles) reconnection rates. (f) Estimated transpolar voltage, Φ_{PC}.

We can assess the association between the reconnection bursts so-determined and substorm activity by comparing with panels (b) and (c) which show the maximum auroral brightness observed in the night sector by the auroral imager and the AU and AL indices, respectively. The auroral brightness shows a sharp increase at substorm onset due to the formation of the substorm auroral bulge, e.g. 04:55, 06:55, and 11:00 UT, which then fades over a period of an hour or so. The AL index exhibits sharp bays at substorm onset due to the formation of the substorm current wedge (SCW), most clear at 06:55, and 10:45 UT. (The delay between the AL bay and auroral luminosity enhancement at 10:45 is found to be due to incomplete coverage of the nightside auroral oval by the imager of this time.) In some cases the AU and AL evidence for substorm activity is not overwhelming, for instance 04:55 UT, though a clear dipolarization of the tail field is seen at GOES-10 at this time [11], indicative of substorm onset. On the other hand, smaller and more symmetrical increases in AU and decreases in AL are associated with enhancements in convection, driven mainly after southward turnings of the IMF, e.g. 02:10 and (most clearly) 10:00 UT. These convection-driven perturbations in AU and AL are, as expected from the ECPC model, associated with periods of growth of F_{PC}.

We find an excellent agreement between the onset of tail reconnection signatures (periods of $\Phi_N > 0$ and contractions of the polar cap) with auroral and magnetometer signatures of substorms, cementing the relationship between substorms and the Dungey cycle (e.g. [8]). The close association between reconnection onset and AL bays indicates that the formation of the SCW and the activation of the tail X-line are closely related (at least at our time-resolution of ~ 10 minutes). Due to the link between substorms and reconnection, we assume that the onset of flux closure is associated with the formation of a near-Earth X-line (NEXL). Interestingly, we see no evidence for nightside reconnection during obvious non-substorm intervals, which would be expected to occur at a distant tail X-line (DXL). If reconnection does take place at a DXL, then we conclude that the flux through-put associated with this process is small in comparison to the reconnection at the NEXL during substorms. Magnetospheric convection is often thought of as being driven by reconnection at the dayside and at a DXL, with the formation of a NEXL being necessary only following a large accumulation of open flux during substorm growth phase, which must be rapidly disconnected. Our present observations suggest that a DXL is unnecessary in the convection cycle, and most (or all) accumulated open flux is disconnected during substorms by a NEXL.

Assuming that convection is driven solely by the dayside and nightside reconnection identified in panel (e) we can estimate the transpolar voltage Φ_{PC}, the rate of antisunward flux transport in the Dungey cycle, from

$$\Phi_{PC} = \frac{1}{2}(\Phi_D + \Phi_N) \tag{3}$$

([8] and [14]). Estimates of Φ_{PC} from Eq. 3 are shown in panel (f), and it would be interesting to compare these with measurements of the transpolar voltage from, for instance, SuperDARN. This will be the subject of a forth-coming study.

The data presented for the 26 August 1998 interval are typical of 9 intervals, totalling 73 hours of observations, that we have analyzed (see forth-coming article in *J. Geophys. Res.*). During the 73 hours of observations we identified 25 nightside reconnection events. The characteristics of these events are indicated in Figure 2 which show, in the form of histograms, (a) the open flux at the onset of each event, (b) the flux remaining at the end of each event, (c) the reconnection rate, (d) the duration, and (e) the total flux closed during each event. The main finding we take from these is that the reconnection events begin in the main once $F_{PC} >$ 0.5 GWb and stop once $F_{PC} <$ 0.5 GWb. The most common value of flux closed is 0.25 GWb. The average flux closed is 0.3 GWb, which compared with the average open flux at onset, 0.65 GWb, indicates that on average almost 50% of the flux present in the polar cap prior to onset is subsequently closed during the event.

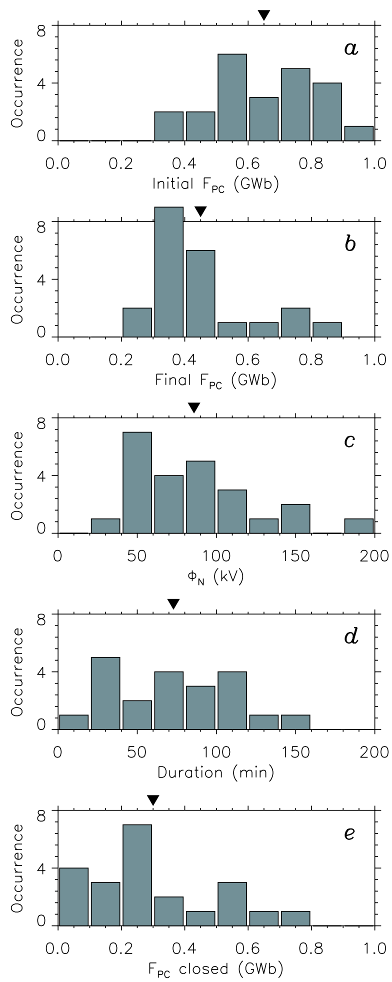

Fig. 2. The characteristics of 25 nightside reconnection bursts identified during 73 hours of observations. (a) The open flux F_{PC} at onset of each event; (b) F_{PC} at the end of each event; (c) the reconnection rate and (d) duration of each event; (e) the amount of flux closed during each event. Arrows indicate the average of each distribution.

In Figure 3 we investigate the relationship between F_{PC} and IMF B_z for the 73 hours of observations. Statistical models suggest that the auroral oval is located at lower latitudes during periods of strong dayside coupling or enhanced geomagnetic activity. An example is the model of [6], based on the observations of [4], which provides a functional representation of the poleward and equatorward boundaries of the auroral oval, parameterized by disturbance level (represented by the Q index in the model of [6]). However, at any one moment the latitude of the auroral oval is dictated by the open flux content of the magnetosphere, so that when F_{PC} is large the oval is located at low latitudes and vice versa, and we do not expect a direct relationship between geomagnetic activity and F_{PC}. Despite this, Fig. 3 indicates that on average F_{PC} is indeed elevated during periods of southward IMF, though the spread in the data is very large. In actuality, the data show that during periods of southward IMF the polar cap enters a cycle of polar cap expansions and contractions, giving rise to the large spread in F_{PC} values; when the IMF is directed northward F_{PC} remains more uniform and has on average a smaller value. Hence, it is not possible to determine the latitude at which the auroral oval will be located for a given disturbance level, except in a statistical sense. Our results show rather that during disturbed periods the auroral oval will change constantly in latitude.

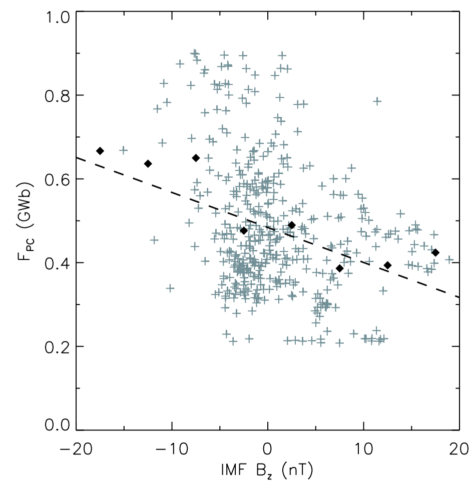

Fig. 3. The relationship between F_{PC} and IMF B_z for the 73 hours of observations. The diamonds indicate the average F_{PC} in 5 nT-wide bins of IMF B_z. The dashed curve indicates a least-squares fit to the distribution.

Finally, we compare the histogram of the open flux at the onset of each reconnection burst (Fig. 2a) with the occurrence distribution of F_{PC} itself. Figure 4 shows the F_{PC} occurrence distribution for the 73 hours of observation; F_{PC} varied between about 0.2 and 0.9 GWb during our observing intervals. The mean value of F_{PC} is 0.46 GWb, so we notice immediately that substorm onset occurs most frequently when the magnetosphere has accumulated a greater than average open flux content. We take the histogram in Fig. 2a and normalize it with respect to the F_{PC} occurrence distribution, shown as the black curve in Fig. 4. This represents the number of substorms that occur per hour at different values of F_{PC}. This shows a dramatic increase in the probability of substorm onset as F_{PC} rises above 0.6 GWb. This suggests that the tail flaring associated with large amounts of accumulated open flux are partly responsible for triggering substorm onset.

3. Conclusions

Determining the open flux content of the magnetosphere from auroral, radar, and LEO particle observations of the size of the polar cap is a powerful technique for the investigation of large-scale solar wind-magnetosphere coupling. This brief investigation of changes in the size of the polar cap allows us to conclude that substorms play a fundamental role in the closure of flux within the Dungey cycle. Substorms on average close 0.3 GWb of open flux, the average flux contained in the magnetosphere at onset being 0.65 GWb. The probability of onset of tail reconnection (or, equivalently, substorm onset) increases dramatically once the open flux accumulated through dayside reconnection grows above 0.6 GWb. Flux closure during substorms appears to be able to account for the full magnetic flux

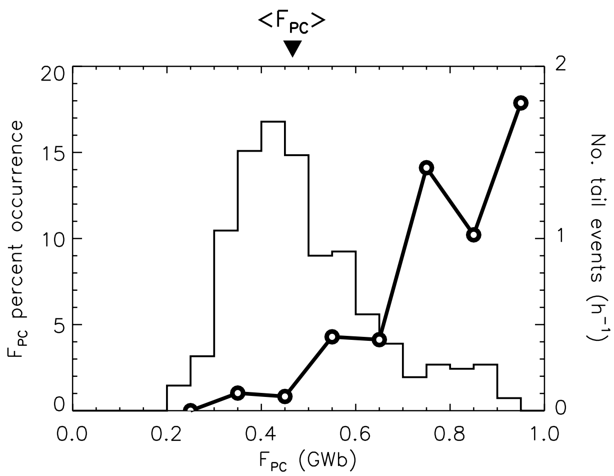

Fig. 4. The overall occurrence distribution of F_{PC} during the 73 hours of observations. Superimposed is the distribution of F_{PC} at the onset of the 25 reconnection events (Fig. 2a) normalized with respect to occurrence distrubution of F_{PC} (curve).

throughput of the Dungey cycle. This reconnection presumably takes place at a near-Earth X-line, formed at substorm onset. We find no evidence for closure of flux during non-substorm periods, which would take place at a distant X-line. If a DXL does exist, we conclude that it plays only a minor role in flux closure and the Dungey cycle.

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