Substorm onset latitude and the steadiness of magnetospheric convection*

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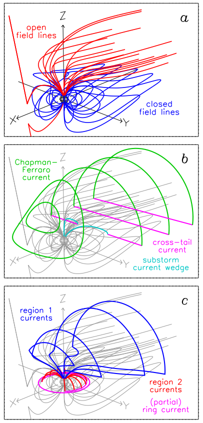
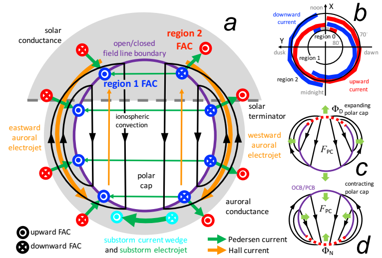


Magnetospheric current systems

Currents flow wherever there is a gradient in the Earth's magnetic field, such as at the magnetopause and in the magnetotail. Solar wind-magnetosphere-ionosphere coupling also deforms the magnetic field, leading to a current circuit associated with the Dungey cycle and magnetospheric convection.



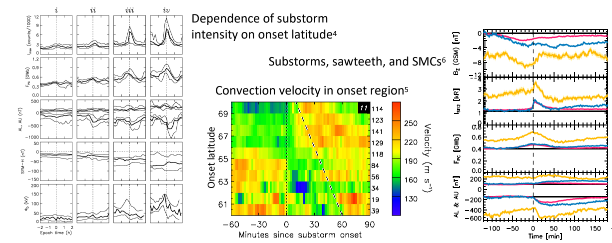
Birkeland currents from AMPERE

The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) exploits magnetometer observations from the 66 satellites of the Iridium telecommunications constellation to reconstruct the field-aligned or Birkeland currents that couple the magnetosphere and ionosphere[1].

Magnetic perturbation measurements from each satellite are used to constrain a spherical harmonic fit of the pattern of perturbations over both northern and southern polar regions. From this, current density maps are derived in both northern and southern hemispheres with a cadence of 2 mins.

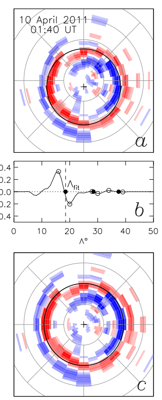
Background and Motivation

The more open flux that is accumulated prior to substorm onset (the lower the substorm onset latitude), the greater the intensity of the resulting substorm[4]. Low latitude onset substorms experience convection braking in the auroral bulge region[5]. Some substorms can segue into periods of steady magnetospheric convection if the IMF remains directed southwards after onset[6]. We investigate these inter-related scenarios.

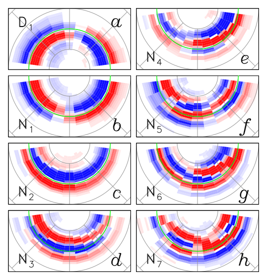


This study

Principal Component Analysis is performed on Birkeland or field-aligned current (FAC) measurements from AMPERE[2]. These FACs couple the Dungey convection in the magnetosphere and the ionosphere[3]. The resulting eigenFACs are employed to perform superposed epoch analyses of substorms that have continued solar wind driving after onset. We investigate the conditions under which substorms can give rise to periods of steady magnetospheric convection (SMC).



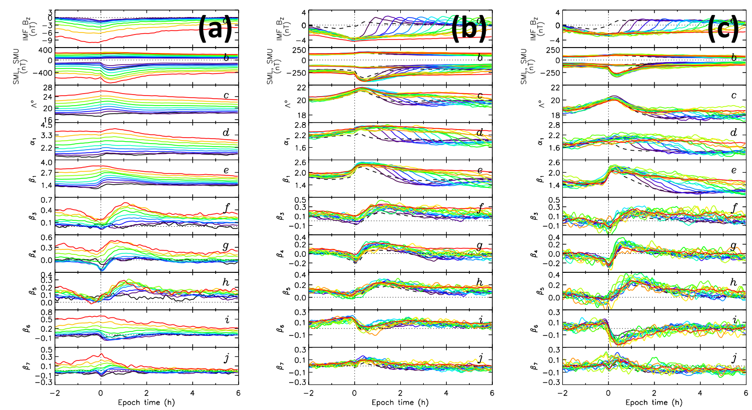
Prior to analysis, the AMPERE current maps are scaled to a uniform size. A circle is fitted to the boundary between the region 1 and 2 current ovals, and the data resampled to a uniform radius.



The PCA *eigenFACs* show the FAC patterns that vary coherently within the dataset. We employ one dayside and seven nightside eigenFACs to quantify the response of the FACs to substorms and SMC.

Superposed epoch analyses

SEAs are conducted using substorm onsets identified by SuperMAG as the zero epoch. **(a)** Lower latitude onsets are more intense (e.g. AL bay); we identify two classes of substorms, higher latitude and lower latitude, with different nightside FAC responses. **(b)** If the IMF remains southwards after onset, open flux, current magnitude, and AL bay remain elevated until the IMF turns northwards again. **(c)** Ensuring that no substorms occur in the 6 hours after the initial onset improves the distinction between the substorm and the following period of steady magnetospheric convection. This occurs for high latitude onsets only.

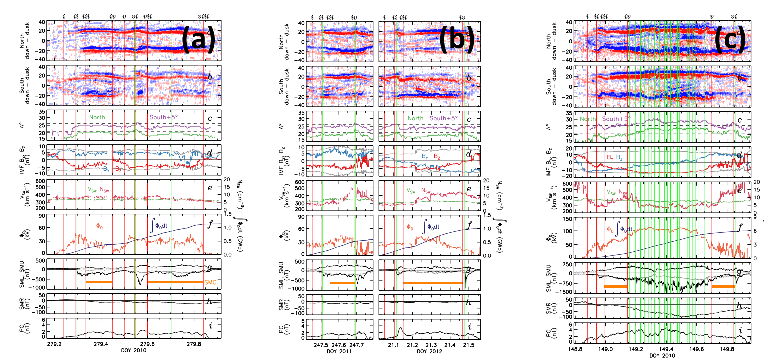


Conclusions

Following substorm onset, the subsequent behaviour of the magnetosphere depends on whether the IMF remains southwards and the onset latitude of the substorm. If the IMF promptly turns northwards, a "classic" substorm occurs. If the IMF remains southwards and the onset latitude is high, then the substorm subsides but the magnetosphere enters an interval of steady convection until the IMF subsequently turns northwards. If the IMF remains southwards and the substorm onset latitude is low, or the polar cap grows during the subsequent SMC, then steady magnetospheric convection is no longer possible, and multiple injections follow. We speculate that this behaviour is controlled by frictional coupling between the ionosphere and atmosphere in the auroral bulge region (convection braking), which is enhanced for low latitude onsets.

Case studies

(a) and **(b)** We present several examples of substorms that segue into SMC because the IMF remains southwards after onset. **(c)** During prolonged southward IMF, convection is steady until the oval expands beyond a certain size, at which point multiple onsets occur, indicating non-steady convection.



[1] B. J. Anderson et al., Sensing global Birkeland currents with Iridium engineering magnetometer data, *Geophys. Res. Lett., 27*, 4045-4048, 2000.
[2] S. E. Milan et al., Principal Component Analysis of Birkeland currents determined by the Active Magnetosphere and Planetary Electrodynamics Response Experiment, *J. Geophys. Res. Space Physics, 120*, 2015.
[3] S. E. Milan et al., Overview of solar wind-magnetosphere-ionosphere-atmosphere coupling and the generation of magnetospheric currents, *Space Sci. Rev., 206*, 2016.
[4] S. E. Milan et al., A superposed epoch analysis of auroral evolution during substorm growth, onset and recovery: open magnetic flux control of substorm intensity, *Ann. Geophys., 27*, 659-668, 2009.
[5] A. Grocott et al., Superposed epoch analysis of the ionospheric convection evolution during substorms: onset latitude dependence, *Ann. Geophys., 27*, 591-600, 2009.
[6] M.-T. Walach and S. E. Milan, Are steady magnetospheric convection events prolonged substorms? *J. Geophys. Res. Space Physics, 120*, 2015.

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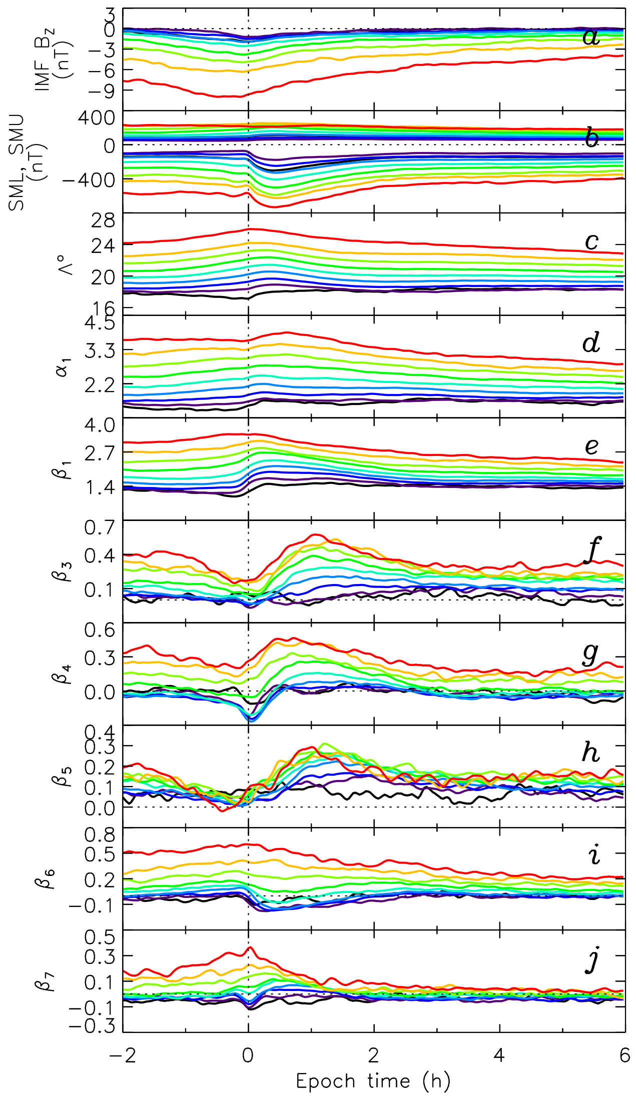
A superposed epoch analysis of substorms from 2010-2016 identified in the SuperMAG substorm onset list. We use AMPERE to determine the radius of the R1/R2 FAC rings (a proxy for polar cap flux), the magnitude of the R1/R2 currents, and the magnitude of different FAC patterns near midnight.



The radius of the R1/R2 FACs. Substorms are subdivided into categories based on the radius at substorm onset, and colour-coded from **blue** (contracted polar cap, high latitude onset) to **red** (expanded polar cap, low latitude onset).

The polar cap expands during the growth phase and contracts after onset. Expansion / contraction is greatest for red substorms.

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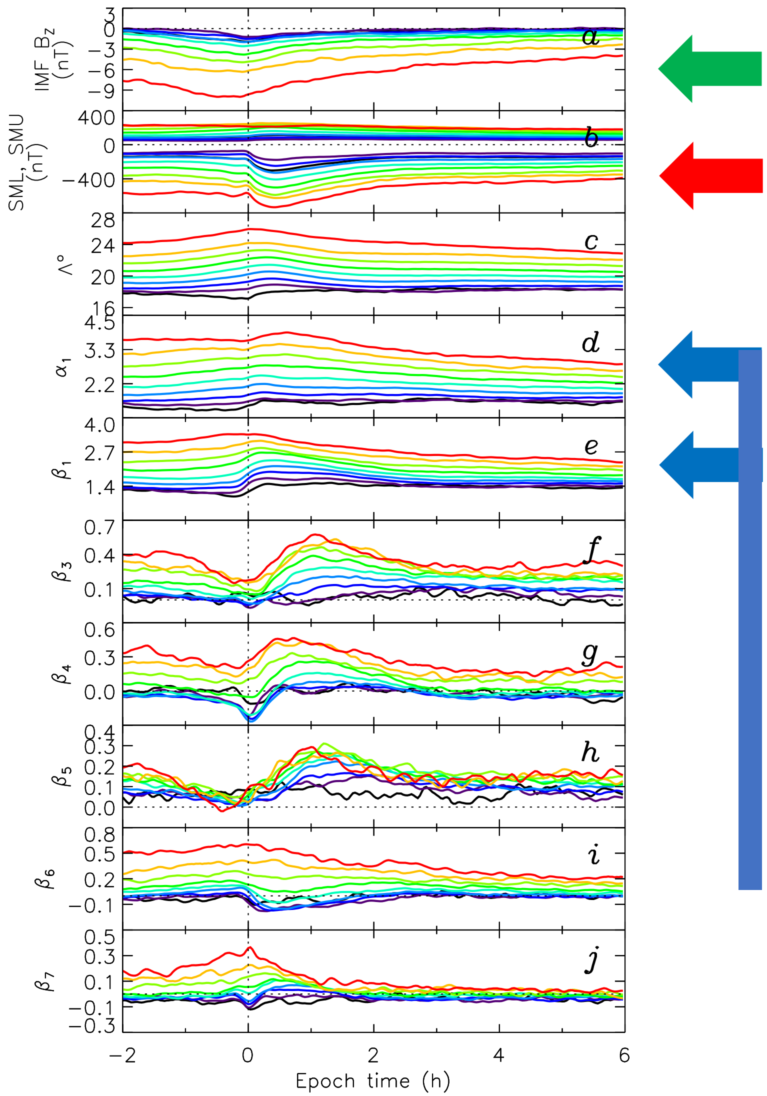

IMF B_Z is most southwards for red substorms.

SuperMAG AU and AL. The magnetic perturbations are greatest for red substorms; polar cap size controls substorm intensity (also substorm brightness [Milan et al., 2009]).

Magnitude of R1/R2 FACs on the dayside and the nightside. Convection is strongest during red substorms.

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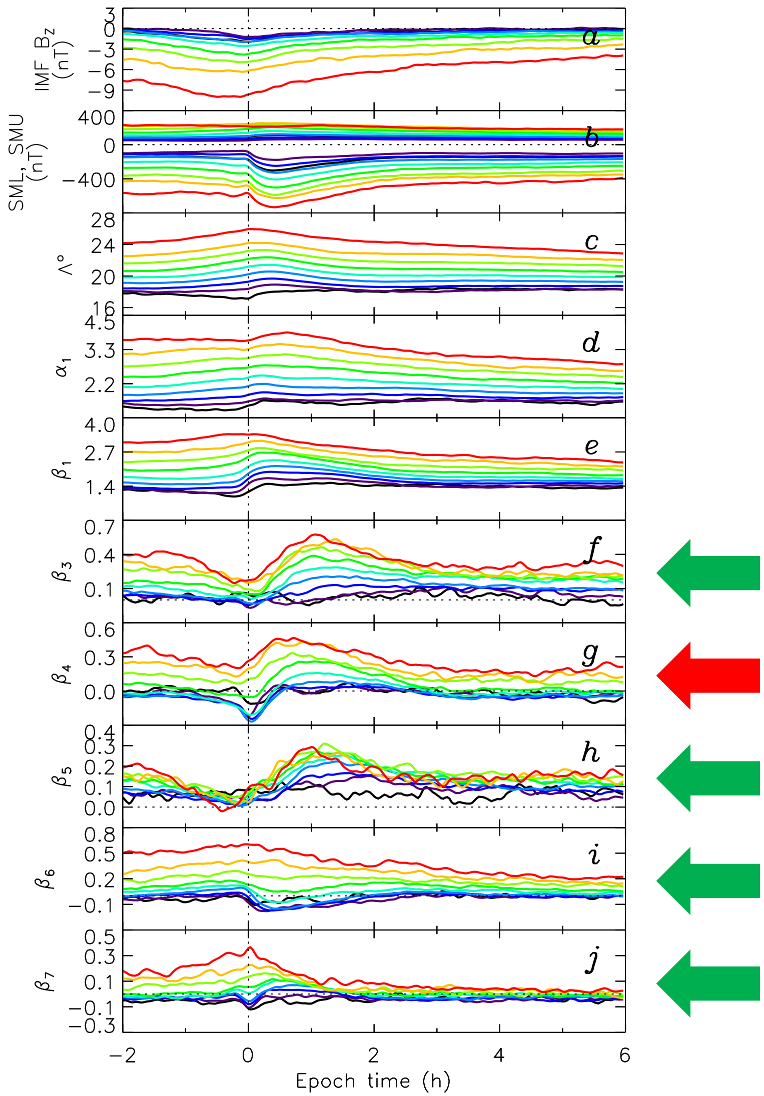

Magnitude of different FAC patterns at midnight (see paper for description of each pattern).

Most important point is that red and blue substorms have different behaviours, indicating two classes of substorms, differentiated by substorm onset latitude (size of polar cap at onset).

e.g. here, red substorms show increase in magnitude after onset, blue substorms decrease around onset.

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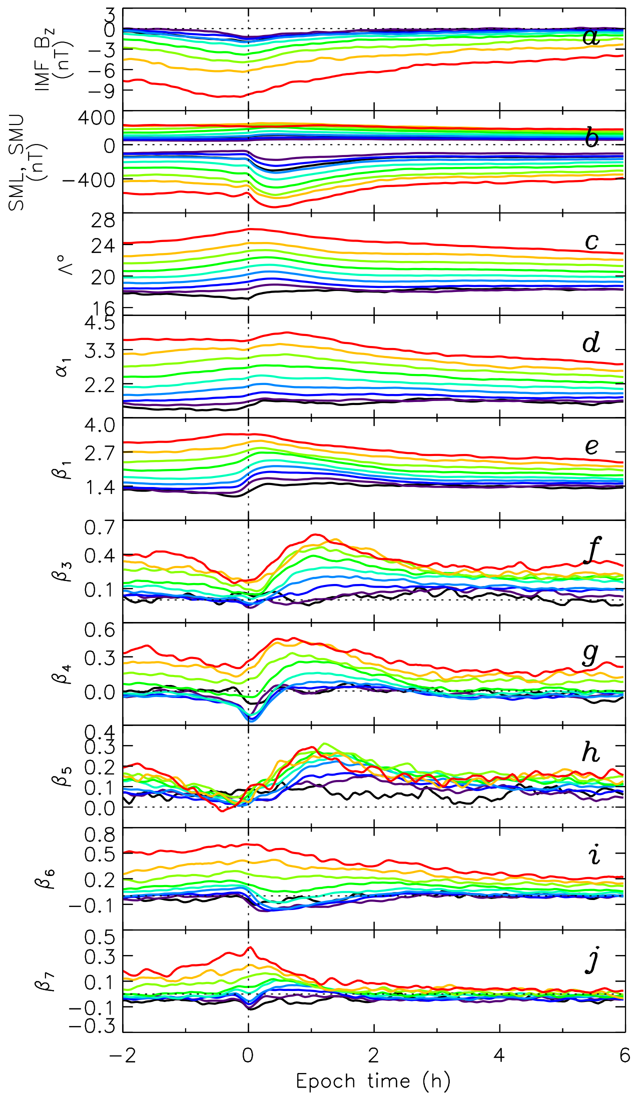

Conclusion #1

Substorm intensity is determined by the polar cap flux at onset: lower latitude (red) substorms are more intense and are brighter (higher auroral bulge conductance) than higher latitude (blue) substorms. Supports conclusions of Milan et al. [2009].

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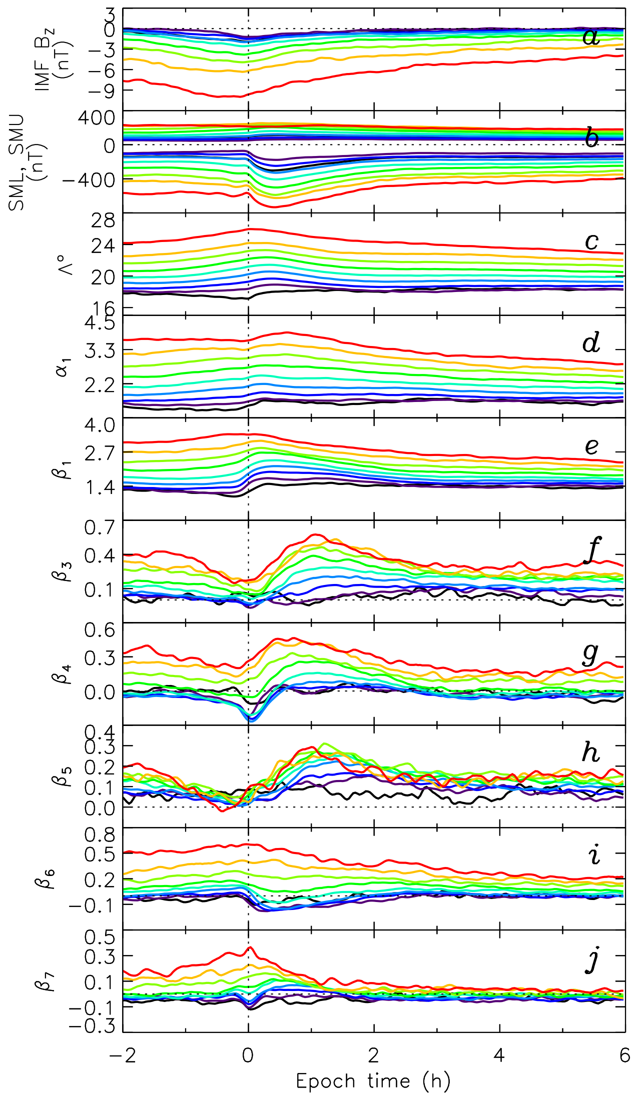


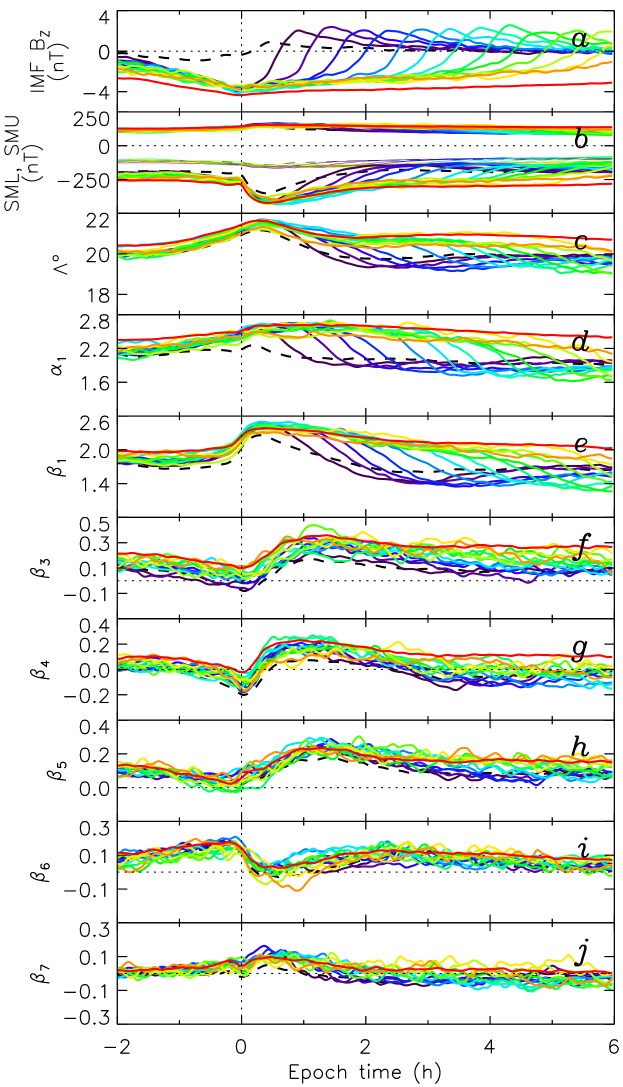
Conclusion #2

We identify two classes of substorm; nightside behaviour depends on onset latitude.

Grocott et al. [2009] also identified two classes of substorms when considering the nightside ionospheric convection response to onset: high-latitude substorms have prompt convection response; low-latitude substorms display convection-braking due to high auroral bulge conductance, producing frictional coupling between the ionosphere and atmosphere.

We identify blue and red substorms with prompt convection and convection-braking.

Substorms tend to occur during IMF $B_Z < 0$. Some time after onset there will be a turning to $B_Z > 0$. This is a superposed epoch analysis of substorms in which the northward-turning occurs soon or later after onset.



Substorms are categorized by whether the northward turning occurs rapidly, within 30 min (blue), or delayed, after 6 h (red), and in between.

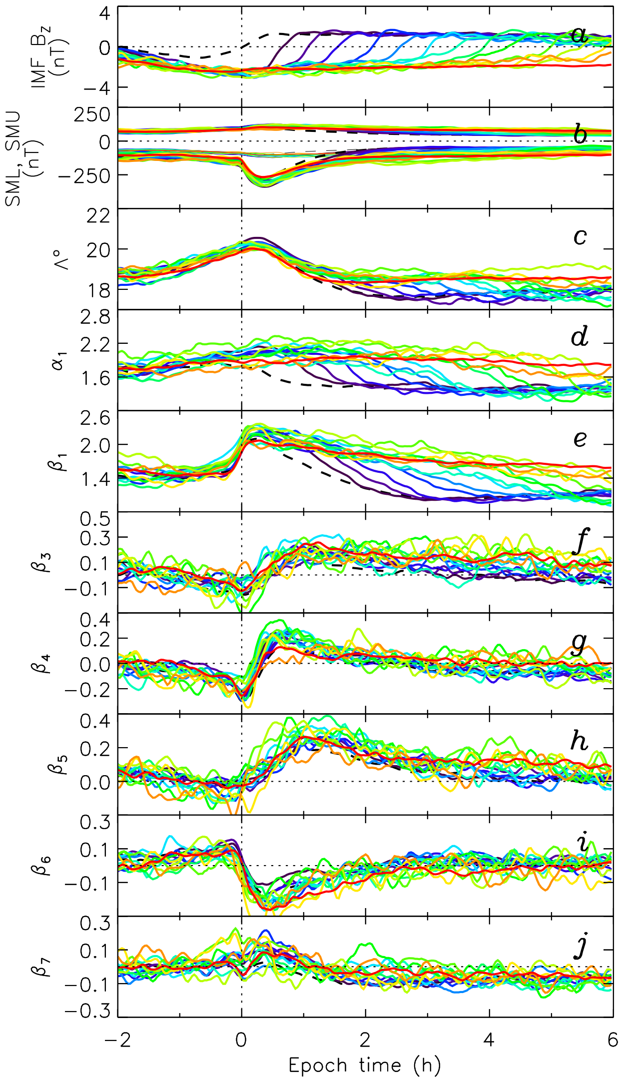
The polar cap expands during the growth phase, contracts after onset, and then stabilizes at an intermediate size for the duration of IMF $B_Z < 0$. After the northward turning the polar cap contracts.

The R1/R2 currents also remain enhanced for the duration of IMF $B_Z < 0$, and then weaken after the northward turning.

Conclusion #3

The magnetosphere enters a period of "steady magnetospheric convection" (SMC) after substorm onset, with an enhanced polar cap size, for the duration of dayside driving.

The same analysis is repeated for the high- and low-onset substorms (high latitude onsets shown below).



The AU/AL response to these substorms is most clear, with a ~1 h substorm bay irrespective of the duration of the dayside driving

Conclusion #4

The magnetosphere can only enter a state of SMC following high latitude onsets in which convection-braking does not occur.

Low latitude onsets suffer from convection-braking; SMC cannot occur if convection-braking takes place!