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Open flux in Saturn's magnetosphere

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ABSTRACT

We characterise the interaction between the solar wind and Saturn's magnetosphere by evaluating the amount of 'open' magnetic flux connected to the solar wind. This is deduced from a large set of Hubble Space Telescope images of the ultraviolet aurora, using the poleward boundary of the main aurora as a proxy for the open-closed field line boundary in the ionosphere. The amount of open flux is found to be 10–50 GWb, with a mean of 35 GWb. The typical change in open flux between consecutive observations separated by 10–60 h is −5 or +7 GWb. These changes are a result of imbalance between open flux creation at the dayside magnetopause and its closure in the magnetotail. The 5 GWb typical decrease in open flux is consistent with in situ measurements of the flux transported following a reconnection event. Estimates of average, net reconnection rates are found to be typically a few tens of kV, with some extreme examples of unbalanced magnetopause or tail reconnection occurring at ∼300 kV. The range of values determined suggest that Saturn's magnetosphere does not generally achieve a steady state between flux opening at the magnetopause and flux closure in the magnetotail. The percentage of magnetic flux which is open in Saturn's magnetosphere is similar to that measured at the Earth (2–11%), but the typical percentage that is closed between observations is significantly lower (13% compared to 40–70%). Therefore, open flux is usually closed in smaller (few GWb) events in Saturn's magnetosphere. The exception to this behaviour is large, rapid flux closure events which are associated with solar wind compressions. While the rates of flux opening and closure should be equal over long timescales, they are evidently different on shorter (up to tens of hours) timescales. The relative independence of the magnetopause and tail reconnection rates can be attributed to the long loading timescales required to transport open field lines into the tail.

1. Introduction

The interaction of the solar wind and interplanetary magnetic field (IMF) with a planetary magnetosphere is important for the transfer of plasma and momentum between the different environments. In the Dungey (1963) description of an 'open' magnetosphere, this interaction is driven by magnetic reconnection between the planetary and interplanetary fields when they have an anti-parallel component at the dayside magnetopause. The open field lines are then dragged anti-sunward by the solar wind flow to form long magnetotail lobes. A simple schematic of the open magnetosphere is shown in Fig. 1a. To complete the circulation of flux, reconnection occurs again in the tail and results in closed planetary field lines planetward of the reconnection site, which return to the dayside, and tailward, disconnected field lines. The disconnected field lines can take the form of a closed loop, a plasmoid, followed by the post-plasmoid plasma sheet (PPPS), which is produced by rapid reconnection of open field lines planetward of the plasmoid (Richardson et al., 1987). This scenario is illustrated in Fig. 1d.

The ionospheric footprint of the open field lines forms the approximately circular polar cap, the size of which is modulated by the balance between opening of flux at the dayside magnetopause and closure in the magnetotail. The side and polar views of the polar cap (bounded by the open-closed field line boundary, OCB) are illustrated in Fig. 1b and c. When unbalanced magnetopause (flux-opening) reconnection occurs, the open-closed boundary expands to lower latitudes to accommodate the

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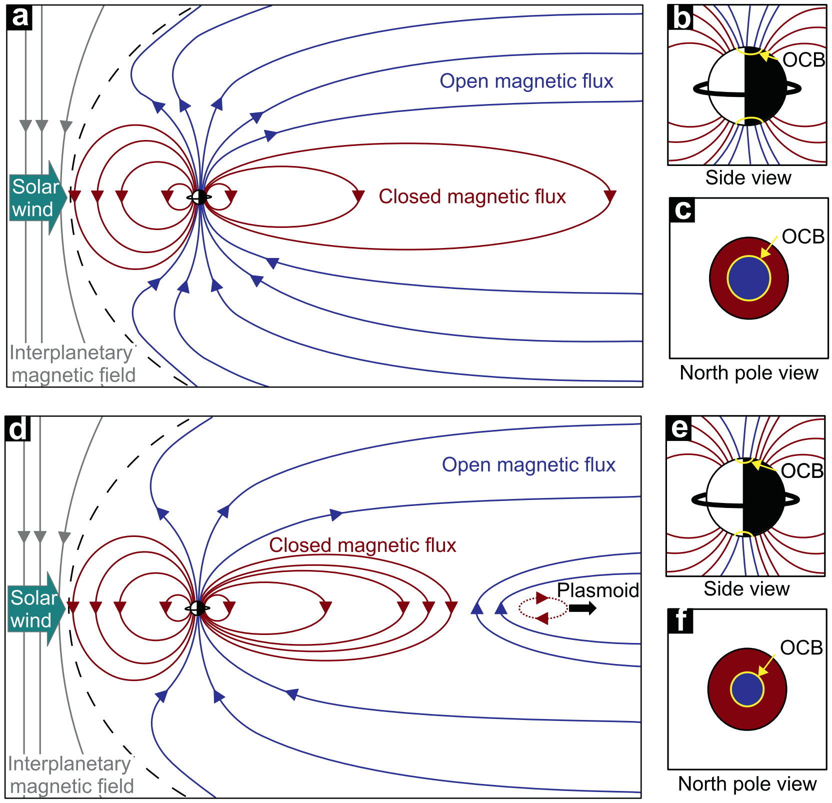

Fig. 1. Schematic of Saturn's open magnetosphere (a) before, and (d) after a tail reconnection event which closes some of the open flux in the tail lobes. (b and e) The corresponding locations of the open-closed field line boundary (OCB) in the ionosphere. (c and f) The polar view of the OCB.

new open flux. Conversely, when open flux is removed via unbalanced tail reconnection, the open-closed boundary contracts to higher latitudes. This is shown in Fig. 1e and f.

Observations of Saturn's aurorae show that they generally form a 'main oval' ring of emission circling the poles although with considerable substructure imposed (Broadfoot et al., 1981; Clarke et al., 2005). These aurorae are associated with an upward-directed (from the ionosphere) field-aligned current which lies close to the boundary between open and closed magnetic field lines, driven by the flow shear between sub-corotating open and outer magnetosphere flux tubes, and the near-rigid corotating middle and inner magnetospheric flux tubes (Cowley et al., 2004; Badman et al., 2006; Bunce et al., 2008). The darker area poleward of the main auroral oval maps to open field lines, and its size is determined by the balance between opening of flux at the dayside magnetopause and closure in the magnetotail, as described above. In this case, observations of Saturn's aurora can be used to estimate the amount of open flux in Saturn's magnetosphere, and deduce the balance between magnetopause and tail reconnection (Badman et al., 2005; Belenkaya et al., 2007).

While the conditions which control the rate and location of reconnection at Saturn's magnetopause have been debated (Scurry and Russell, 1991; Grocott et al., 2009; Lai et al., 2012; Masters et al., 2012), observations at the magnetopause have provided evidence of an open magnetopause required to sustain the open polar caps (Huddleston et al., 1997; McAndrews et al., 2008; Lai et al., 2012; Badman et al., 2013). Likewise, reconnection events have been identified in Saturn's magnetotail (Bunce et al., 2005; Jackman et al., 2007, 2008a; Hill et al., 2008). Jackman et al., 2011 performed a superposed epoch analysis of 34 plasmoids identified so far, and found evidence for a significant PPPS at Saturn, representing the closure of a significant amount (3 GWb) of open flux in a typical reconnection event in Saturn's tail.

In this study the open flux content of Saturn's magnetosphere is estimated using a large collection of images of the UV aurora, using the poleward edge of the auroral emission as a proxy for the open-closed field line boundary. Its variation and rate of change are also estimated and compared to values obtained from in situ measurements by Cassini, and global MHD simulations, in order to characterise the balance of magnetopause and tail reconnection over different timescales at Saturn.

2. Auroral images

This study employs 108 images of Saturn's UV aurora obtained by the Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS) instruments onboard the Hubble Space Telescope (HST) during 2000–2013. The data were reduced and projected onto a latitude-local time grid following the methods described by Grodent et al. (2003, 2005) for STIS images during 2000–2005, and Clarke et al. (2009) for ACS images from 2007 onward. The auroral morphology during each campaign has been detailed by Gérard et al. (2004) (1997–2001 campaigns), Clarke et al. (2005) and Grodent et al. (2005) (2004 campaign), Gérard et al. (2006) (2005 campaign), Clarke et al. (2009) (2007–2008 campaigns) and Nichols et al. (in preparation) (2011–2013 campaigns).

For each campaign, when successive images were obtained on the same HST orbit, i.e. within an observing interval of <45 min, these have been combined to increase the signal to noise. Although the instrument sensitivities and data reduction methods varied between campaigns on different years, in this study we are concerned only with relative intensity between the bright auroral and dark polar cap regions for each image, rather than their absolute values, so such differences do not affect our results.