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Observations of loading-unloading process at Saturn's distant magnetotail

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Abstract: Using in-situ measurements from the Cassini spacecraft in 2013, we report an Earth substorm-like loading-unloading process at Saturn's distant magnetotail. We found that the loading process is featured with two distinct processes: a rapid loading process that was likely driven by an internal source and a slow loading process that was likely driven by solar wind. Each of the two loading processes could also individually lead to an unloading process. The rapid internal loading process lasts for ~ 1-2 hours; the solar wind driven loading process lasts for ~ 3-18 hours and the following unloading process lasts for ~1-3 hours. In this letter, we suggest three possible loading-unloading circulations, which are fundamental in understanding the role of solar wind in driving giant planetary magnetospheric dynamics.

Keywords: Saturn magnetosphere; loading-unloading process; magnetic reconnection; dipolarization

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1. Introduction

The energy loading-unloading process in a magnetosphere has been reported at Earth (Akasofu, 1964; McPherron et al., 1973), Mercury (Slavin et al., 2010; Sun WJ et al., 2015), Jupiter (Kronberg et al., 2005) and Saturn (Mitchell et al., 2005). The loading-unloading concept was originally introduced to describe Earth substorm. The loading process is associated with a growth phase of a substorm, when the magnetospheric current is enhanced, current sheet thins and the lobe magnetic field increases. The unloading process is responsible for the substorm expansion phase, when the magnetospheric currents divert into the ionosphere; current sheet expands in north-south direction and the lobe magnetic field decreases. An unloading process is usually much more rapid than a loading process (see a recent review paper by Akasofu (2017)).

There are various timescales of loading-unloading processes at different planets. At Mercury, a loading-unloading process usually lasts for a few minutes (Slavin et al., 2010). At Earth, this process lasts for tens of minutes to a few hours (e.g., Akasofu (1964), Lui (1996), Pu ZY et al., (2010) and Yao ZH et al., (2012)). At Jupiter and Saturn, the unloading process has been found to last for a few hours to tens of hours (Kronberg et al., 2005; Mitchell et al., 2005). A loading process is usually much longer than the unloading process. For example, Ge YS et al. (2007) showed that the growth phase for a Jovian substorm lasts for about 3 days, which is also consistent with the occurrence rate of energetic particles (Kronberg et al., 2007; Krupp et al., 1998). We need to be aware that most of the previous loading-unloading processes are based on measurements from co-rotating magnetosphere, suggesting that the internally driven process would significantly contribute to these processes, or even dominate them. In addition, the planetary periodicities exist in almost the whole magnetosphere (inner, middle and outer), although their mechanisms are still under debate (Arridge et al., 2011; Carbary et al., 2007; Espinosa et al., 2003; Southwood and Kivelson, 2007).

The internally driven unloading processes and their auroral consequences are widely identified at Saturn (Jackman et al., 2009; Mitchell et al., 2005, 2016; Radioti et al., 2013; Russell et al., 2008), which shows different features from that at the Earth. For example, Hill et al. (2005) found that the energetic particle injections at Saturn's inner magnetosphere are almost randomly distributed, which is significantly different from the local time dependent substorm injection at the Earth (Birn et al., 1997). It is poorly understood how a solar wind driven loading-unloading process would differ from the internally driven process at Saturn.

In this letter, we investigate the loading-unloading process in the magnetotail, using Cassini measurements from mid-November in 2013, when the spacecraft was at ~ 60 R_S (1 R_S = 60268 km), with local time at ~1.7 LT and close to the plasma sheet on the northern hemisphere. Specifically, we aim to understand the contributors from the solar wind and internal sources in loading Saturn's nightside distant magnetotail.

2. Observations

Figure 1 shows 1-min resolution magnetic field data from the Cassini magnetometer (Dougherty et al., 2004) in Kronographic Radi-

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al-Theta-Phi (KRTP) coordinates during 13 November and 16 November 2013. From the top to bottom, plotted are the magnetic components and the magnetic strength. During this period, Cassini was located near midnight, at ~ 60 R_S. Previous studies have shown that signatures of the tailward reconnection site (e.g., B_θ<0) are often observed within 60 R_S (Jackman et al., 2014), suggesting that the open-closed field line boundary is usually around this distance. We thus call this region distant magnetotail, where the most distant closed field lines are located. The magnetic field at the distant magnetotail is less affected by planetary rotation, as no clear planetary spin modulation was observed for this event. A spin modulation signature shows periodic oscillation of current sheet, which is very different from the measurements presented in this letter. Please see the signals of spin modulation from previous literature (Arridge et al., 2009; Carbary and Mitchell, 2013; Yao ZH et al., 2017a).

Yao ZH et al. (2017b) identify two types of dipolarization using measurements from multiple Cassini instruments. The localized reconnection generated transient dipolarizing flux bundle (TDFB) would show simultaneous discontinuity-like enhancements on both B_θ and $|B_r|$. However, an Earth substorm-like current redistribution dipolarization (CRDD) is featured with B_θ increase that is accompanied by $|B_r|$. This is because the TDFB front boundary is a discontinuity, while the CRDD that is caused by the current sheet expansion corresponds to the reconfiguration of magnetic topology. Five current sheet expansions (green shadow) during this period are identified from variations of the magnetic field components B_θ increase and $|B_r|$ decrease (mostly from $|B_r|$ and B_T decrease), which we call unloading process (labeled at the top of Figure 1). Prior to each current sheet expansion, there was a longer period with an opposite trend (blue and pink shadow) that increase $|B_r|$ and B_T, which we call loading process.

During each unloading period, B_Φ perturbation is also detected, which usually suggests a formation of field-aligned current (Liu J et al., 2013; Sergeev et al., 1996; Yao ZH et al., 2013). The field-aligned current formation is also a key phenomenon in a substorm (Boström, 1964; Lui, 1991).

It is clear that the loading process could be divided into two periods, i.e., the rapid one marked by the blue shadow, and the slow one marked by the pink shadow. As we have previously introduced that the loading process at Earth is usually much slower

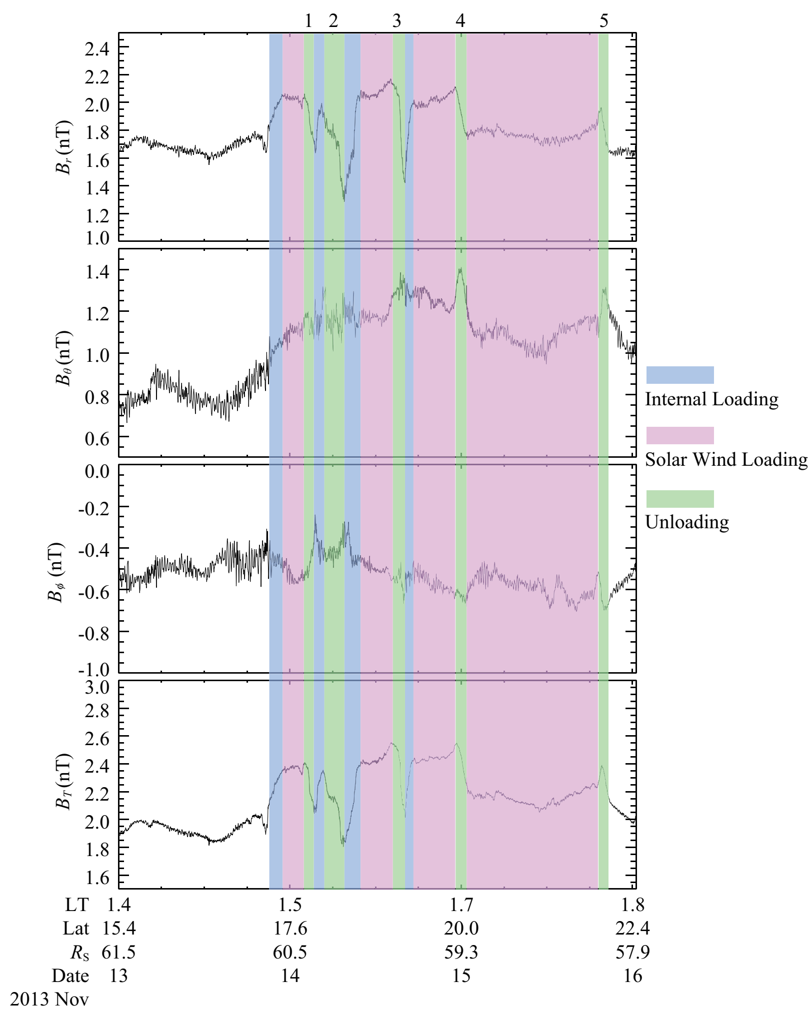

Figure 1. The 1-min resolution magnetic field during 13 November and 16 November 2013. The blue shadows indicate the rapid loading processes (i.e., internally driven); the pink shadows indicate the slow loading processes (i.e., solar wind driven) and the green shadows show the unloading processes. The five events are labeled on the top of this figure.

than the unloading process, the “rapid” or “slow” are thus introduced based on the comparison with the time scale of the unloading process. For the five loading-unloading events in Figure 1, the rapid loading processes last for ~1-2 hours, the slow loading processes last for ~3-18 hours and the unloading processes last for ~ 1-3 hours.

The pink shadow marked loading processes are much slower than the unloading processes; we thus suggest that these loading processes were mainly driven by solar wind, as at Earth. The rapid loading process is significantly different from the loading process at Earth, which we suggest to be driven by internal source. We will discuss the detailed relation between the two loading processes and the unloading process in next section.

3. Discussion and Summary

A loading process at Earth that is only driven by solar wind usually lasts for a few hours, while the unloading process usually lasts for tens of minutes. Regarding the much larger magnetosphere, and much further from the Sun, we would expect the solar wind driven energy loading at Saturn to be slower than at Earth. At Earth and Mercury, the loading-unloading process is only driven by solar wind, while at the fast rotating Saturn and Jupiter, the internal sources are suggested to dominate these loading-unloading processes. In this letter, we examine the energy loading-unloading process at Saturn’s distant magnetotail where solar wind has a maximum impact in driving the magnetotail dynamics, and we have found that solar wind could play very crucial role in driving the loading-unloading process at this distance. We also notice that there was one other period that Cassini travelled into a similar region in 2006, and observed multiple enhancement of negative B_θ, which is usually considered as a signature of magnetic reconnection (Jackman et al., 2007). The enhancement of positive B_θ in this paper suggests a more tailward extended magnetotail plasma sheet, and thus we observe the Earth substorm-like magnetic dipolarization. The continual positive B_θ and its multiple positive enhancements all suggest that the spacecraft was in the closed field line, so we suggest the open field line during a quasi-steady state is beyond 60 R_S.

We present three possible loading-unloading circulations in Saturn’s distant magnetotail (near midnight, beyond 60 R_S) in Figure 2. Figure 2a shows the initial magnetic topology (the red curve). Figure 2b and 2c show the stretching process (from red to black curves) that was driven by an internal source and solar wind source, respectively. The green arrows show the motion of magnetic field for the two processes. Figure 2d shows the unloading process that is associated with Saturn’s distant magnetic reconnection, which drives a dipolarization towards the planet and a plasmoid towards the tail. We here point out that the global magnetic topology change is caused by the magnetospheric current redistribution associated with reconnection, but not a direct consequence of the reconnection process. This is understandable from the Ampere’s law that electrical current directly changes the magnetic field. The three possible loading-unloading circulations are described as below.

(1) As indicated by the red arrows (a→b→c→d), an internal loading process (blue periods in Figure 1) rapidly stretches the field lines in the distant magnetosphere, followed by a solar wind driven slow loading process (pink periods in Figure 1). This type of loading process preceded the 1st, 3rd and 4th energy unloading in our event.

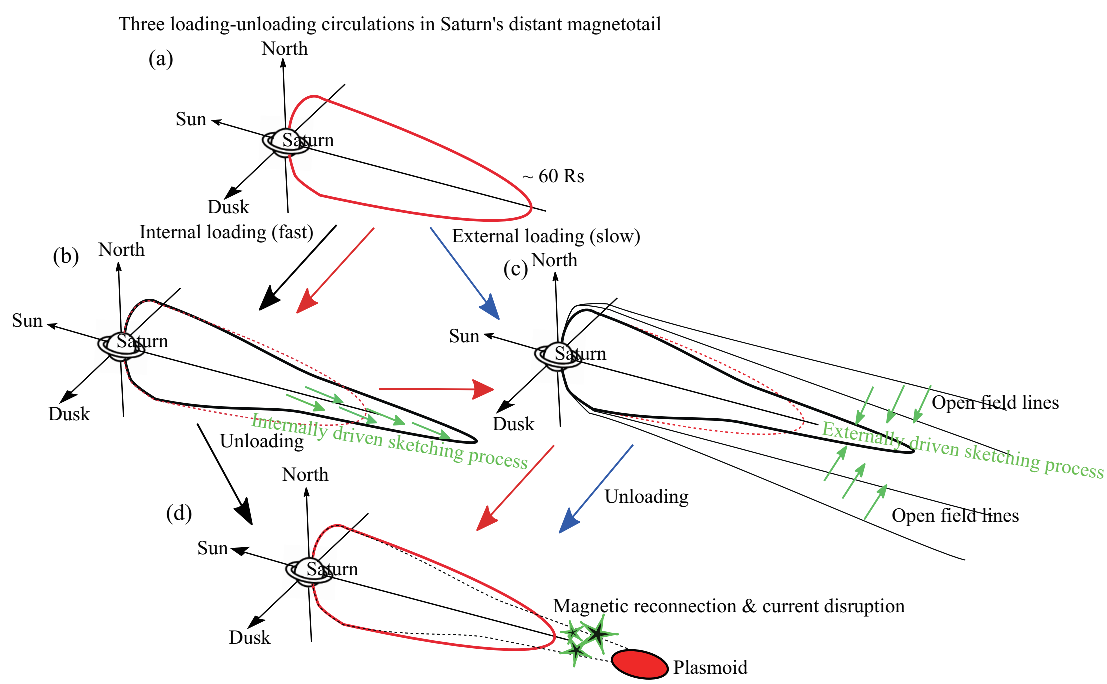

Figure 2. An illustration of three types of loading-unloading circulations. The black arrows represent the only internal loading process; the blue arrows show the only solar wind loading process and the red arrows illustrate a joint loading process. (a) The initial unloaded state. (b) The internal loading process that stretches the magnetic field line. (c) The solar wind driven loading process that stretches the magnetic field line. (d) The unloading process in the distant stretched field line.

(2) The black arrows (a→b→d) show the unloading process following a single loading process from the internal source. The 2nd unloading process belongs to this category.

(3) The blue arrows (a→c→d) show the only solar wind driven loading process that is followed by an unloading process. In our event, the 5th unloading is this type.

Since the solar wind loading process is much slower than the internally driven loading process, we thus expect a much longer time scale for a loading process that is only driven by solar wind. This is consistent with the fact that the loading process prior to the 5th unloading event lasts for a much longer period (~ 18 hours) than the other four loading processes.

It is interesting to notice that a rapid internal loading process immediately follows an unloading process (except the 4th unloading process). We here suggest a potential physical explanation for this phenomenon. For the stretched distant magnetosphere (Figure 2b or 2c), a dynamic balance exists between the tailward transport driven by the centrifugal force and the planetward transport associated with the Dungey cycle. The current disruption (Figure 2d) initiated by reconnection would thicken the current sheet, and thus depress the Dungey cycle reconnection, consequently, the inner side centrifugal force driven tailward transport would dominate, and rapidly load magnetic energy in the distant magnetotail. The 4th unloading process was much less dramatic than the 1st, 2nd and 3rd unloading processes, thus we suggest that the 4th unloading process did not produce a highly imbalanced condition in the radial direction, so that no significant internal loading process was initiated afterwards.

In conclusion, we report the Earth-like magnetic energy loading-unloading process at Saturn's distant magnetotail, where the plasma does not co-rotate with the planet. The rapid loading processes last for ~1-2 hours, the slow loading processes last for ~3-18 hours and the unloading processes last for ~ 1-3 hours. The loading-unloading duration is ~5-10 times longer than such a process at Earth. Unlike the Earth, the loading process is not fully controlled by solar wind, in contrast, the inner source could provide a much more rapid loading process. Considering the two distinct contributors in the loading process, we propose three types of loading-unloading circulations for Saturn's distant magnetotail. Coincidentally, each of the proposed circulations has been supported by at least one event during the time period presented in Figure 1.

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