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Reconnection sites in Jupiter's magnetotail and relation to Jovian auroras

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ABSTRACT

The Galileo spacecraft explored Jupiter's magnetotail in a low-inclination orbit, where it detected the signatures of tail reconnection. In this paper, we examine and classify the tail reconnection signatures into four types: dipolarizations, strong northward B_θ excursions, tailward-moving plasmoids and planetward-moving plasmoids. The distribution of these four types of events is used to infer the most probable location of the Jovian tail reconnection site to be near 0200 LT at a planetocentric distance of 80 Jovian radii. Dipolarizations are mainly observed planetward of this point, and strong northward B_θ excursions and plasmoids are found mostly tailward. The observations also suggest that the Jovian tail reconnection starts at a point (neutral point), a localized region in the tail, instead of along an extended azimuthal line (X-line). Using the updated Khurana's Jupiter's magnetospheric model, which includes the external field and the effects of the swept-back configuration of tail field lines, we map the signatures of Jovian tail reconnection into the Jupiter's ionosphere. We confirm that the dawn auroral storms or the polar dawn spots observed by the Hubble Space Telescope (HST) are located close to the extrapolated footpoints of tail dipolarizations and could be the auroral signatures of tail reconnection.

1. Introduction

Magnetic reconnection plays an important role in magnetospheric physics. In the Earth's magnetosphere, dayside reconnection between the solar wind and Earth's magnetic field opens previously closed field lines. The reconnected magnetic flux is transported to the tail and is accumulated in the open field of tail lobes (Dungey, 1961). Nightside reconnection returns magnetic flux to the dayside. In the terrestrial substorm process, magnetic reconnection occurring in the near-Earth tail maintains the conservation of magnetic flux in the magnetosphere by explosively closing open tail magnetic flux (Baker and McPherron, 1990; Baker et al., 1993; Baker et al., 1996; McPherron et al., 1973; Russell and McPherron, 1973; Russell, 1974). In planetary magnetospheres, magnetic reconnection has been discovered in Jupiter's magnetotail (Nishida, 1983; Russell et al., 1998; Russell et al., 2000) and in Saturn's magnetotail (Jackman et al., 2007; Russell et al., 2008).

The reconnection site in the near-Earth tail has been extensively investigated. It has been found that reconnection usually occurs near the center of the tail between $20R_E$ and $30R_E$ downtail (Nagai et al., 1998; Nagai and Machida, 1998), and very rarely inside $9R_E$ (Ge and Russell, 2006; Miyashita et al., 2005a, 2005b). In the Jovian magnetotail, reconnection is expected to arise in a different location (Vasyliunas, 1983) due to the different plasma environment and plasma circulation in Jupiter's magnetosphere. The strong mass-loading from Io and the rapid rotation of Jupiter produce a plasma disk inside the Jovian magnetosphere and generate a swept-back configuration of the tail magnetic field. Appropriate to the configuration of the magnetodisk, Vasyliunas (1983) proposed a qualitative picture of the reconnection site in the Jovian magnetotail which extended from the pre-midnight sector to the dawn flank. This picture has been partially confirmed by the observations of energetic particle bursts from Galileo (Kronberg et al., 2005; Kronberg et al., 2007; Krupp et al., 1998), in which almost all events are in the post-midnight or dawn sector. Using the particle flow bursts, Woch et al. (2002) also inferred that the near-Jupiter neutral line extended tailward to $120R_J$ at midnight and becomes closer in the dawn sector, while Vasyliunas' neutral line was expected closer to the Jupiter in the midnight sector and further tailward on the dawnside of Jovian magnetotail. Moreover, the neutral line inferred from the particle bursts still carries a significant uncertainty (see Fig. 3(a) in Woch et al., 2002), where significant tailward flows appear planetward of the separatrix and some planetward flows tailward. However, using particle bursts to infer the Jovian tail reconnection has its limitations. First, due to the limited telemetry rate of the Galileo spacecraft, the availability of particle data is limited, which makes it difficult to investigate the complete picture of Jovian tail reconnection. Studies of terrestrial reconnection, especially those of the relationship of tail reconnection with substorm activity, show that fast flows from tail reconnection usually have limited widths and slow down as they approach the inner magnetosphere. However, the signatures in the magnetic field caused by tail reconnection, such as

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dipolarizations of the magnetic field, can propagate into much broader regions and closer into the inner magnetosphere than the fast plasma flows themselves (Ohtani et al., 2006). The magnetic signature of a moving plasmoid can be detected even when the satellite is located in the tail lobes, i.e., the Traveling Compressional Regions (TCRs), while the fast plasma flows are hardly observed in the lobes. Furthermore, the availability of magnetometer data from Galileo is much more complete than that of the particle data. Thus, it is necessary to re-investigate Jovian tail reconnection and its relation to the probable Jovian substorm activity by examining the behavior of the magnetic field during Jovian tail reconnection.

Polar auroras have been extensively observed by the Hubble Space Telescope (HST) and have been reported by many authors (e.g., Bhardwaj and Gladstone, 2000; Clarke, 2003; Waite et al., 2000; Waite et al., 2001). Jupiter's polar auroral emissions, caused by energetic particle precipitations, can provide more insights about the dynamic processes in the Jovian magnetosphere, especially for reconnection. Jupiter's polar auroral emissions can be divided into three regions: the dawnside dark region, the poleward swirl region, and the duskside active region, which is thought to be connected with dayside reconnection and is similar to flux transfer events (FTEs) at the Earth (Grodent et al., 2003b). Some transient auroral activities on the dawnside, called dawn storms (e.g., Ballester et al., 1996; Clarke et al., 1998; Gerard et al., 1994), have been proposed to be associated with tail reconnection (Cowley et al., 2003; Woch et al., 2002).

Recently several detailed studies based on images taken by HST with better spatial resolutions such as from the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS) revealed polar auroral spots that occur in the dawn and midnight region (Grodent et al., 2003b; Grodent et al., 2004; Radioti et al., 2008). These polar auroral emissions including the "multiple dawn arcs" (Grodent et al., 2003b), the "midnight spots" (Grodent et al., 2004), and the "polar dawn spots" (Radioti et al., 2008) are suggested to be associated with tail reconnection. For example, the "multiple dawn arcs" and the "midnight spots" are found to corotate with the planet, and their sizes, durations and locations are consistent with the auroral emissions triggered by tail reconnection (Grodent et al., 2003b; Grodent et al., 2004). Moreover, Radioti et al.'s statistical study (2008) has shown that the "polar dawn spots" have a 2–3 day periodic re-occurrence rate, which is consistent with the periodicity of Jovian substorms suggested by Woch et al. (1998), Kronberg et al. (2008b) and other authors (Krupp et al., 1998; Louarn et al., 1998). Thus the "polar dawn spots" are suggested to be signatures of tail reconnection. However, the mapping of the "polar dawn spots" by Radioti et al. (2008) using the VIP4 magnetic field model (Connerney et al., 1998) shows that these events are located more dawnward of substorm-like events observed by Galileo in the Jovian tail. Thus it is important to examine where the Jovian tail reconnection mostly occurs and where these events map into Jupiter's ionosphere with a more accurate Jupiter magnetospheric field model.

In an earlier paper, we examined the evidence for a growth phase in Jovian substorms (Ge et al., 2007a) and we also performed preliminary investigations of the Jovian tail reconnection site using their magnetic signatures (Ge et al., 2007b, c, d, 2008). In this paper, we investigate the strong excursions of the north–southward (theta) component of the tail magnetic field, which have been identified as the magnetic field signatures of tail reconnection (Russell et al., 1998). By examining the magnitude and polarity of those strong excursions, we determine the configuration of the tail neutral points. In the second part of the paper, we use an updated magnetosphere model of Khurana (1997, 2006) to map the tail dipolarization region into the Jovian ionosphere and compare it with the location of the Jovian auroras. Those wishing greater detail on the Galileo measurements and the events upon which the statistical results in this paper are based are referred to the Ph.D. dissertation part of which this paper summarizes (Ge, 2009).

2. Observations of localized tail reconnection and plasmoids

2.1. Dipolarizations in the near-Jupiter magnetotail

The Galileo spacecraft probed Jupiter's magnetotail as its line of apsides rotated from the position behind the dawn terminator to close to the dusk terminator in a series of orbits labeled G2–G28. The magnetic field was regularly measured during this period, and the 24-s resolution magnetic field data are used in this study. We investigate the magnetic field measurements in the RTP coordinates system, where the radial direction is positive outward, the theta component is positive southward and the phi component in the azimuthal direction. Galileo's observations of Jupiter's tail magnetic field are characterized by a quasi-square wave pattern in the radial and azimuthal components. This pattern is caused by the motion of the current sheet over the spacecraft with the 10-h rotation of the Jupiter (Khurana and Schwarzl, 2005; Russell et al., 1998). These two components are also anti-correlated, showing that the magnetic field is swept back out of the meridian plane. Despite the large changes of the radial and azimuthal components during the crossing, the theta component usually remains steady around 1–2 nT (see the second panels in Figs. 2 and 3 in Ge et al., 2007a, 2007b) in the tail.

However, the field configuration is dramatically changed during dynamic tail reconnection events. As shown in Fig. 1, the theta component of the magnetic field suddenly increases to 11.13 nT from its background value of 2 nT. During the excursion of the theta component, there is a strong enhancement of total field strength. These signatures have been identified as the signature of tail reconnection Russell et al., (1998). In this event, the positive excursion of the theta component suggests that the reconnection occurs tailward of the Galileo spacecraft, causing the field vector to become vertical. The reconfiguration of the Jovian magnetotail field from tail-like, when the magnetic field is mainly in the radial and azimuthal direction, to a more vertical orientation, is very similar to the dipolarization signature in the terrestrial magnetotail, except for the substantial enhancement of the field strength. In the Jovian magnetotail, the reconnected magnetic field lines are thought to be compressed against the plasma sheet by the high reconnection rate, while in the terrestrial magnetosphere the magnetic flux also builds up during dipolarizations in substorms, but with a much smaller extent (e.g., Runov et al., 2009).

The reconfiguration of Jovian tail magnetic field is considered to be a signature of tail reconnection not only because of its dipolarization nature but also because of the correlation of the field reconfiguration and particle bursts (see Table 1 in Kronberg et al., 2005). Table 1 in Kronberg et al. (2005) lists the event shown in Fig. 1 and it corresponds to the inward particle bursts, consistent with this excursion occurring planetward of the reconnection site.

The shaded areas in Fig. 1 indicate time intervals when the radial and azimuthal components become correlated in-phase rather than the usual out of phase. This phase change signals that the swept-back configuration has changed into a swept-forward configuration. This change results from the conservation of angular momentum when the plasma moves rapidly inward. On the planetward side of the reconnection region, the inward-moving plasma has higher azimuthal velocity than the corotation