Growth phase of Jovian substorms

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Received 10 September 2007; accepted 2 November 2007; published 6 December 2007.

1. Introduction

[1] Strong northward and southward field turnings in the near Jovian magnetotail have been observed by Galileo. These sudden dipolarizations and plasmoid formations have been interpreted as signatures of tail reconnection, similar to those seen in terrestrial substorms. In this paper, we examine the temporal behavior of the magnetic field strength in the lobes of the Jovian tail and find that it increases smoothly prior to reconnection events and decreases after them. The tail field variations are similar to those during the growth phase and expansion phase of terrestrial substorms but last a much longer time, about three days. These lobe field changes appear not to be caused by the solar wind dynamic pressure \( P_{\text{dyn}} \). Thus substorms in the Jovian tail resemble terrestrial substorms in that they have growth phases with increases of the magnetic field strength in the near-planetary tail field followed by sudden decreases of the field strength when reconnection occurs and plasmoids are released. Citation: Ge, Y. S., L. K. Jian, and C. T. Russell (2007), Growth phase of Jovian substorms, Geophys. Res. Lett., 34, L23106, doi:10.1029/2007GL031987.

2. Observations

[2] The first stage of terrestrial magnetospheric substorms is the growth phase, which is followed by the expansion and recovery phases [McPherron, 1970]. During the growth phase the dayside magnetospheric magnetic flux reconnects with the southward interplanetary magnetic field and is transferred to Earth’s tail lobes by the solar wind. The magnetotail flares at a greater angle to the flow and the solar wind dynamic pressure \( P_{\text{dyn}} \) has a larger component normal to the tail magnetopause. Thus, the tail lobe field is enhanced during the growth phase of terrestrial substorms [Fairfield and Ness, 1970; McPherron, 1972; Russell and McPherron, 1973]. The growth phase is a crucial stage during which the Earth’s magnetosphere accumulates adequate energy to power the sudden energy release of the subsequent substorm expansion phase.

[3] The occurrence of Jovian substorms has been inferred from observations of northward and southward turnings of the near-tail magnetic field [Nishida, 1983; Russell et al., 1998, 2000] and energetic particle bursts [Kronberg et al., 2005; Woch et al., 1999]. However, the physical processes of Jovian substorms are far from fully understood due to the limitation of the Galileo measurements. We expect some differences because the high Mach number of the Jovian bow shock is expected to weaken the reconnection rate on the dayside magnetopause as happens for high Mach number at Earth [Scurry and Russell, 1991; Scurry et al., 1994]. This difference could affect the occurrence of the growth phase in the Jovian tail.

[4] The circulation of the Jovian plasma is driven by the rotational energy of its plasma disk [Vasyliunas, 1983]. This rotational energy arises from the acceleration to corotational velocities of the mass added to the magnetospheric plasma by Io. The energy comes from the rotational energy of the planet coupled to the magnetosphere via field-aligned currents from the ionosphere. When the rotational energy becomes too high for the magnetosphere to contain it, tail reconnection occurs to release the extra mass down to the tail and the emptied flux tubes back to the inner magnetosphere [Kronberg et al., 2005; Russell et al., 1998, 2000]. It is possible that the storage of the mass-loaded flux in the tail plasma sheet increases the tail flaring angle just as transfer of flux from the dayside to the terrestrial tail lobe by reconnection does at Earth. Thus despite the differences in the drivers of plasma convection we still might observe a growth phase in Jovian substorms.

[5] We examine measurements from seven Galileo orbits within the Jovian magnetotail to investigate variations of the lobe field strength at the time of reconnection events. During this period the Ulysses spacecraft was near aphelion during 1997, covering from about 4.9 to 5.3 AU, and approaching the ecliptic plane. We use 1-second resolution magnetic field measurements and 4-minute resolution plasma measurements to monitor corotating interaction regions that could intersect Jupiter. To check for CMEs, which propagate almost radially from their point of origin, we examine the SOHO LASCO observations [Brueckner et al., 1995] close to the Sun, accounting for expected propagation time, to determine if CMEs erupted near Jupiter’s central meridian. Both Ulysses and SOHO observations help us to determine whether the observed variations of the tail lobe field are caused by solar-wind induced compression and expansion of the Jovian magnetotail [Southwood and Kivelson, 2001] or due to endogenic flux transport followed by reconnection and plasmoid release.

[6] During the sixth orbit around Jupiter, Galileo was at a distance between 50 R₉ and 85 R₉ from the planet in the Jovian magnetotail, as illustrated in Figure 1. Figure 2a displays 10 days of magnetic field measurements during this orbit in RTP coordinates where \( B_r \) is radial and positive outward, \( B_\theta \) perpendicular to the rotational plane and positive southward, and \( B_\phi \) azimuthal and positive with rotational direction. The semi-regular square-wave pattern in the radial and azimuthal magnetic field components (\( B_r, B_\phi \)) arises when Galileo crosses the current sheet due to the 10-hour rotation of Jupiter. The anti-correlation between the radial and azimuthal components indicates a swept-back
configuration of the magnetic field lines associated with the fast rotation of Jupiter. The theta component $B_\theta$ was on average close to 1 nT in the lobes, while it was about 2 nT when Galileo was near the current sheet crossing.

[7] On 28 March 1997 a large excursion of $B_\theta$ with a peak value about 9 nT occurred from UT 16:55 to UT 18:00 accompanied by an enhancement of the field strength, showing a localized reconnection event similar to the event given by Russell et al. [1998, Figure 3A]. Energetic particle intensity peaks are found in this interval in EPD measurements (not shown here). Before this reconnection event, the magnetic field strength had been gradually increasing for about three days, from 8.4 nT to 17 nT. The field strength quickly decreased after the reconnection event. During this interval, the Galileo spacecraft moved from about 68 $R_J$ to 58 $R_J$ from Jupiter. Since the Jovian lobe field magnitude varies with radial distance following a power law with an exponent of $-1.37$ in the region beyond 25 $R_J$ downtail [Kivelson and Khurana, 2002], the change of spacecraft position here could only contribute about 1.6 nT to the increase of lobe field magnitude and certainly could not produce the increase and decrease in field strength from March 26th through March 29th, that on Earth would be interpreted as the ejection of a plasmoid after a period of magnetic flux buildup, i.e., a growth phase and expansion phase.

[8] Similar variations are also seen on other orbits. During the ninth (not shown) and tenth orbits (Figure 3), typical tail field enhancements are found before the localized reconnection events at larger distances from Jupiter. Energetic particle bursts are observed at these times recorded in the list by Kronberg et al. [2005, Table 1]. Ulysses was 156° east and 4° north of Jupiter in Helio graphic Inertial (HGI) coordinates. The solar wind conditions were not as steady as those during the sixth orbit. Some enhancements of the tail field seem to correspond to the solar wind $P_{\text{dyn}}$ peaks. A solar wind $P_{\text{dyn}}$ enhancement occurred near a substorm on October 21st during the tenth orbit (Figure 3b). But the solar wind $P_{\text{dyn}}$ enhancement lasted less than 1.5 days, while the tail field enhancement lasted about 3 days, and occurred much later than the start of the growth phase. Using the Ulysses measurement of the solar wind speed of 400 km/s at 5 AU and the spacecraft position of 95 $R_J$ from the Jupiter, the response time for the magnetotail to the solar wind $P_{\text{dyn}}$ enhancement should be about 0.2 days, if the tail field increase were directly caused by the solar wind.
changes, rather than the endogenic magnetic flux transport. One CME candidate is the one on October 6th at CPA 273°/C176, but its linear speed was too small to reach Jupiter within 13 days to cause the $|B|$ increase starting on October 19th. In addition, the $P_{\text{dyn}}$ profile associated with CMEs usually starts with a sharp increase, which is not characteristic of any sudden enhancement on Jovian tail field strength during this interval. Therefore, during these enhancement events of Orbit C9 and C10, the Jovian magnetotail field must have been enhanced due to internal processes rather than external effects.

10 The change of solar wind $P_{\text{dyn}}$ does at times affect the Jovian magnetotail [Southwood and Kivelson, 2001] and these signatures are different than those identified as being a growth phase. Observations during Galileo’s eighth orbit show the almost simultaneous enhancements of the tail magnetic field and the time-shifted solar wind $P_{\text{dyn}}$ measured by Ulysses spacecraft 167° east and 2.5° north of Jupiter in HGI coordinates. The two measurements have a similar duration and waveform from June 8th to June 10th (Figure 4). These solar-wind induced tail field variations have a quite different signature from the gradual enhancements of the tail field during the growth phase seen on Orbit E6 and C10.

3. Summary and Discussion

11 The gradual enhancement of Jovian tail magnetic field strength before reconnection events indicates that a gradual loading process, a growth phase, is a part of a Jovian substorm. During this phase, the magnetic flux appears to be continuously added into tail, increasing the tail lobe field strength, thinning the plasma sheet and producing favorable conditions for tail reconnections. Similar magnetospheric variations occur during growth phases of terrestrial substorms. However, at Jupiter the mass-loaded flux tubes are transported into the magnetotail by centrifugal force, rather than by the solar wind as in terrestrial substorms. Thus, the growth phase of Jovian substorms is driven by an internal process. Typical duration of the
Figure 3. (a) Galileo observations of the three components and magnitude of the Jovian magnetotail field from 10/15 to 10/25, 1997. (The growth phase is shown in the shaded area.) (b, c) Ulysses measurements show the square root of time-shifted solar wind dynamic pressure at about 5 AU for the two solar rotations bracketing the observations at Jupiter.
growth phase in Jovian substorms is about 3 days which is consistent with the period of flow bursts [Krupp et al., 1998], and much longer than that of a terrestrial growth phase, ~1 hour. This time scale may be determined by the time scale of the internal mass loading process which depends on the source activity of the plasma disk.

[12] Changes of the solar wind $P_{\text{dyn}}$ can produce variations in the Jovian tail magnetic field by compressing or relaxing the Jovian magnetosphere. The compression of the Jovian magnetotail has a very similar waveform and duration to that in the solar wind $P_{\text{dyn}}$. The Ulysses and SOHO observations indicate that the variations of Jovian tail field during the growth phase events were not caused by changes of solar wind conditions.

[13] Jovian growth phases are not found before every localized tail reconnection event and no clear periodicity of this type of events is found in our investigation. However, tail reconnection following a growth phase is usually the strongest event and may produce larger-scale, global, influences on the Jovian magnetosphere. The time scales of these growth phases are quite similar, consistent with a quasi-steady internal process, e.g., the mass loading from the moons [Kronberg et al., 2007].

[14] Acknowledgment. The authors thank M. G. Kivelson, the principal investigator of the Galileo magnetic field data, for providing the data and for discussions of our interpretations.

References


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