Evidence for collisionless magnetic reconnection at Mars

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1. Introduction

Mars is a unique planetary plasma laboratory because it has no global magnetosphere, only strong, localized regions of crustal magnetic field [Acuña et al., 1998]. The dynamics of the magnetic field near Mars result from the rotation of the crustal fields and the way in which they press against the Interplanetary Magnetic Field (IMF), which is draped around the planet forming a two-lobed magnetotail [Ma et al., 2002; Nagy et al., 2004; Halekas et al., 2006]. The recent discovery of auroral activity [Bertaux et al., 2005] and observations that the topology and extent of the crustal fields change with IMF orientation [Brain, 2006] indicate that the Mars space environment is highly dynamic.

One potential cause is magnetic reconnection [Krymskii et al., 2002; Brain et al., 2006], a fundamental process controlling the dynamics and evolution of plasmas [Vasyliunas, 1975; Sonnerup, 1979] which would facilitate the changing structure of the magnetic field and particle and energy exchange between the solar wind and the atmosphere. All in-situ observations confirming fast collisionless reconnection in space have been made in or near the Earth’s magnetosphere [e.g., Paschmann et al., 1979; Sonnergup et al., 1981; Gosling et al., 2005] and until now, no observations of reconnection have been made at Mars. The non-global nature of the crustal fields implies that any interaction must be time dependent and localized, which one suspects might render reconnection unsustainable or unobservable. Here we show that reconnection does occur at Mars, specifically in the magnetotail current sheet. We have observed (a) the Hall magnetic field (generated by the current associated with the differential motion of the demagnetized ions and electrons) (b) current sheet filamentation (c) enhanced wave activity and (d) a ‘secondary’ magnetic island. Interpreted in conjunction with plasma simulations, these observations constitute a rather complete set of reconnection signatures.

2. Observations

Figure 1 shows data from 19 April 2001 when MGS occupied a nearly circular orbit with an altitude of ~400 km. Approximately one orbit of magnetometer (MAG) and electron reflectometer (ER) [Acuña et al., 1998] is shown. The ER observes a 14° × 360° strip of the sky; if \( B \) lies in the plane of the detector, it is possible, assuming gyrotropy, to determine the full PAD. When \( B \) does not lie in the detector plane, a partial PAD is constructed. The magnetic field is shown at 0.75s resolution in MSO coordinates, where the \( x \) direction points towards the Sun, the \( z \) direction is perpendicular to the orbital plane and \( \{x, y, z\} \) is a right handed triple. The \( |B| \) time series is colored red where, on the basis of existing magnetic field models [Cain et al., 2003], strong crustal fields are present. Electron fluxes are enhanced on the dayside due to shocked solar wind and photoelectrons. On the night-side, fluxes are much weaker except for the enhancement at 17:05 UT which occurs between two intervals of crustal fields (16:38–16:58 UT and 17:14–17:20 UT). This enhancement is associated with the magnetotail current sheet (the reversal in \( B_m \)).

The overall flux enhancement corresponds to a density of \( \sim 2 \text{ cm}^{-3} \). \( |B| \) is reduced in the center of the current sheet, at 17:04:55 UT.

The first piece of evidence for reconnection across the current sheet is the so-called Hall magnetic field structure, the bipolar variation in \( B_N \) (Figure 3a). Here, \( B \) is shown in boundary normal coordinates where \( N \) is normal to the current sheet, the \( L-N \) plane contains the main magnetic field reversal (the reversal in \( B_L \) is the main current sheet and except around 17:04:36 UT there is a constant normal magnetic field \( B_N \sim -10 \text{ nT} \) and L-N-M is a right handed triple. These coordinates were found by applying Minimum Variance Analysis [Sonnerup and Scheible, 1998] to the interval 17:04–17:06 UT; \( L = (-0.98 \ 0.19 \ -0.02) \), \( N = \)...
B_M has a peak-to-peak variation of 8 nT centered on a background guide field of ~3 nT. The B_M signature is indicative of Hall current loops [Sonnerup, 1979]. In recent years it has become clear that fast reconnection is a two-scale process where the ions and electrons decouple on scales corresponding to their relative inertial scales [Birn et al., 2001], and their relative motion produces currents and associated magnetic field signatures which are intimately related to fast reconnection [e.g., Mandt et al., 1994; Fujimoto et al., 1997; Nagai et al., 2001; Øieroset et al., 2001; Mozer et al., 2002].

The second observation supporting reconnection is current sheet bifurcation. Figure 3b shows B_L (black), a Harris current sheet model fit (dashed black) [Harris, 1962], and the current density j_M (red); B_L changes in two steps across the current sheet. Assuming that the current sheet is one-dimensional and time stationary, one can calculate the current density via Ampere’s law \( j_M = \frac{1}{\sqrt{\pi}} \cdot dB_L/dt \). Since v_N is unknown, j_M is shown in Figure 3b in arbitrary units. The current density is not maximized in a central peak but split into two main channels at 17:04:50 UT and 17:05:00 UT with a weaker channel in the center. Bifurcation is not typical of equilibrium current sheets, but is a feature of reconnection, observed both at the Earth [Runov et al., 2003] and in the solar wind [Gosling et al., 2005].

The third feature is the enhanced wave activity observed during the crossing. The wavelet transform of B_z shown in Figure 2f indicates that there are significant fluctuations up to 1 Hz which is above the proton gyrofrequency (= 0.15 Hz if \|B\| = 10 nT). Enhanced wave activity associated with reconnection has been reported at Earth [Bale et al., 2002; Petkaki et al., 2006].

The fourth feature is a secondary magnetic island, a loop-like structure whose signature is the bipolar perturbation in B_N between 17:04:30–17:04:45 UT. This island is unusual because there is also an enhancement in the B_L component, rather than the B_M component [Slavin et al., 2003]. Islands generated by magnetic reconnection are a relatively common feature of the Earth’s magnetotail current sheet [Slavin et al., 2003; Drake et al., 2006; Eastwood et al., 2007].
Figure 4a shows the orbit of MGS. The black and white pattern on the planet surface represents the positive/negative strength of the crustal magnetic fields [Connerney et al., 2001] and the red lines show the draping of the IMF. The color of the trajectory corresponds to time. Between 17:04 and 17:06 UT, MGS crossed the region enclosed by the box, which can be seen to lie at the midplane of the draped field configuration. Figure 4b shows this region in more detail; the morphology of the magnetic field is reconstructed from the observations and analysis. The boundary normal coordinates \{L, N, M\} are shown relative to MSO. Across the current sheet, \(B_L\) reverses and there is a \(+B_M/\beta B_N\) Hall perturbation. The island creates a \(+B_N/\beta B_M\) perturbation superposed on a \(-B_N\) normal field. Although there is a large crustal field region near the dusk terminator (encountered at \(\sim 17:15\) UT), it is not currently clear whether it is involved in the reconnection process.

### 3. Comparison With Simulations

To better understand the observations and put them in context, we show the results from a magnetic reconnection simulation performed using the particle-in-cell code p3d [Zeiler et al., 2002]. Figure 3c shows the out of plane current density from a Particle-In-Cell simulation of magnetic reconnection. The system is periodic in the x-z plane and uniform in the y direction \(\{L, N, M\} = \{-x_{\text{sim}}, -y_{\text{sim}}, z_{\text{sim}}\}\). The initial equilibrium consists of two Harris current sheets superimposed on a uniform ambient population with \(B_0^M = 0\) [Drake et al., 2006]. The initial Harris current sheet half width is 0.5 \(c/\omega_{\text{pe}}\) (based on the normalization scheme, \(c/\omega_{\text{pe}} \sim 200\) km) and has uniform initial electron and ion temperatures \((T_e/T_i = 5)\). The simulation domain is \(L_x L_z = 64, 32 \ c/\omega_{\text{pe}} - \) only part of the domain is shown. The simulation is in good agreement with the observations, reproducing the X-line, and the island. The main reconnection x-line is at \(x = 53 \ c/\omega_{\text{pe}}\) and on the left is a secondary island. A cut (black line) through the simulated magnetic field, skirting the island, is shown in Figure 3d. The components of \(B\) are labeled according to the boundary normal coordinate system. The simulated magnetic field is qualitatively consistent with the data – the peak in \(B_1\) at \(s = 36.5 \ c/\omega_{\text{pe}}\) is produced by the secondary island and the reversal in \(B_1\) around \(s = 43 \ c/\omega_{\text{pe}}\) corresponds to the current sheet. The positive/negative excursion of \(B_1\) at \(s = 36 \ c/\omega_{\text{pe}}\) is produced by the secondary island. The negative excursion of \(B_M\) around \(s = 47 \ c/\omega_{\text{pe}}\) is the Hall magnetic field produced by reconnection at the main X-line. The good correlation with the satellite data offers further support for the trajectory shown in Figure 4.

One interesting feature the simulation reveals, that could not easily be deduced from the observations, is that the leading edge of the island is coalescing with the downstream magnetic field. The positive \(B_M\) component
in the vicinity of the secondary island around \( s = 36 \ c/\omega_{pi} \) is the Hall magnetic field produced during coalescence; the key signature being that this field is confined within the separatrices (the lines where the magnetic field connect to the X-point). The pitch angle data (Figure 2b) show that the separatrix crossing, marked by the onset of anti-parallel electron flow, occurred at 17:04:20 UT. The Hall magnetic field (Figure 3a) is not observed until 17:04:30 UT, closer to the island, and does not extend to the separatrices. Thus, this Hall magnetic field must be linked to island coalescence. In Figure 4b, the blue ovals show regions of reconnection (centered on the X-line) and coalescence (centered on the left hand side of the island). Overall, the magnetic field structure of the simulation confirms that reconnection is collisionless. We note that the local ion-electron collision frequency is \( 10^{-5} \) Hz.

4. Conclusions

[13] We have presented observations strongly suggesting the existence of collisionless magnetic reconnection in Mars’ magnetotail, including the Hall magnetic field structure, bifurcated current sheets, wave activity, and secondary islands. Although some evidence for reconnection at Jupiter [Russell et al., 1998] and Saturn [Jackman et al., 2007] (in the form of magnetic dipolarizations) has been presented, our results constitute the first observation at another solar...
system body of the signatures of fast reconnection that appear in the vicinity of the diffusion region where reconnection is initiated. Furthermore, both the data and simulations suggest that magnetic island coalescence was occurring in tandem with the main reconnection process. Little or no experimental evidence for coalescence has been presented in the literature, even at Earth. It should be noted that MGS has no ion thermal plasma measurements, and so we predict the existence of reconnection ion jets, which ought to be observed by the next generation of spacecraft studying the Martian solar wind interaction.

[14] This result provides a mechanism for Mars’ recently discovered auroral activity [Bertaux et al., 2005], as accelerated, reconnecting, plasma can be deposited directly into the ionosphere, and naturally explains the changing boundaries of the closed crustal field regions [Brain, 2006]. These observations also show that reconnection is indeed a viable mechanism for the rapid disconnection of magnetotails from bodies with ionospheres such as comet tails [Russell et al., 1986]. We have presented here the strongest evidence for reconnection in the MGS dataset, an encounter close to the magnetic diffusion region where the magnetic field changes topology during reconnection. We have observed evidence for reconnection in a number of events indicating that this is not an uncommon process at Mars.

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References


