



## Evidence for collisionless magnetic reconnection at Mars

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[1] Using data from Mars Global Surveyor (MGS) in combination with Particle-In-Cell (PIC) simulations of reconnection, we present the first direct evidence of collisionless magnetic reconnection at Mars. The evidence indicates that the spacecraft passed through the diffusion region where reconnection is initiated and observed the magnetic field signatures of differential electron and ion motion – the Hall magnetic field – that uniquely indicate the reconnection process. These are the first such in-situ reconnection observations at an astronomical body other than the Earth. Reconnection may be the source of Mars' recently discovered auroral activity and the changing boundaries of the closed regions of crustal magnetic field.

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### 1. Introduction

[2] 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.

[3] 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; Sonnerup *et al.*, 1981; Gosling *et al.*, 2005] and until now, no observa-

tions 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

[4] Figure 1 shows data from 19 April 2001 when MGS occupied a nearly circular orbit with an altitude of  $\sim 400$  km. Approximately one orbit of magnetometer (MAG) and electron reflectometer (ER) [Acuña *et al.*, 1998] is shown. The ER observes a  $14^\circ \times 360^\circ$  strip of the sky; if  $\mathbf{B}$  lies in the plane of the detector, it is possible, assuming gyrotropy, to determine the full PAD. When  $\mathbf{B}$  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  $|\mathbf{B}|$  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  $B_x$ ) [Halekas *et al.*, 2006]. Figure 2 shows a two minute interval centered on the current sheet field reversal. It can be seen that the flux of 10 eV electrons is enhanced between 17:04:30–17:05:10 UT. The overall flux enhancement corresponds to a density of  $\sim 2 \text{ cm}^{-3}$ .  $|\mathbf{B}|$  is reduced in the center of the current sheet, at 17:04:55 UT.

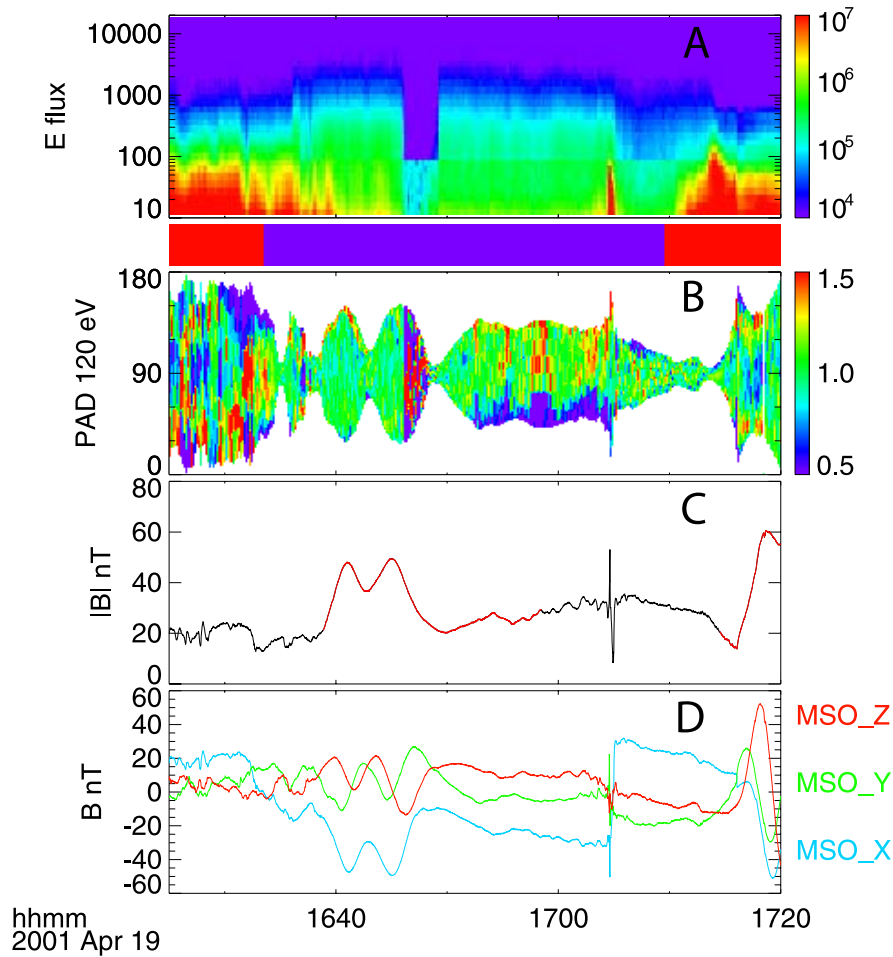
[5] The first piece of evidence for reconnection across the current sheet is the so-called Hall magnetic field structure, the bipolar variation in  $B_M$  (Figure 3a). Here,  $\mathbf{B}$  is shown in boundary normal coordinates where N is normal to the current sheet, the L-N plane contains the main 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;  $\mathbf{L} = (-0.98 \ 0.19 \ -0.02)$ ,  $\mathbf{N} =$

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**Figure 1.** Magnetometer and Electron Reflectometer data recorded by MGS on 19 April 2001. (a) Electron differential energy flux (in units of  $\text{eV}/(\text{s cm}^2 \text{ ster eV})$ ) between 10 eV and 20 keV. The color bar below shows the solar illumination and thus location of the spacecraft (red = illuminated  $\sim$  dayside). (b) Normalized Pitch Angle Distribution (PAD) of the 120 eV electrons. (c and d) Magnetic field strength and components. The spacecraft crossed the tail current sheet at 17:05 UT.

(0.19 0.95  $-0.26$ ),  $M = (-0.03 -0.26 -0.96)$  (relative to MSO).

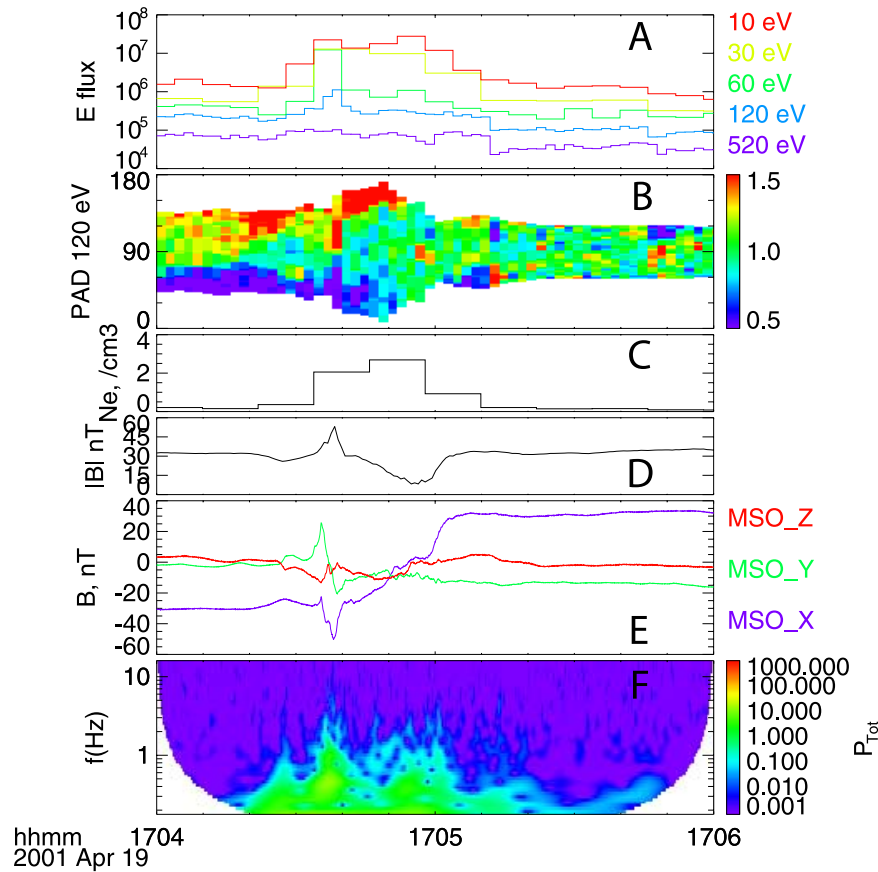
[6]  $B_M$  has a peak-to-peak variation of 8 nT centered on a background guide field of  $\sim 3$  nT. The  $B_M$  signature is indicative of Hall current loops [Sonnerup, 1979]. In recent years it has become clear that fast reconnection is a two-scale process where the ions and electrons decouple on 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].

[7] 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 ( $j_M = (1/v_N) \cdot dB_L/dt$ ). 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].

[8] 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].

[9] 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 2.** (a and b) Electron differential energy flux in 5 channels and PAD of 120 eV electrons. (c) Density of the electron plasma calculated by fitting the observations to a Maxwellian distribution assuming isotropy. (d and e) Magnetic field strength and components at 0.031s resolution in MSO coordinates. (f) Wavelet transform of the  $B_z$  time series.

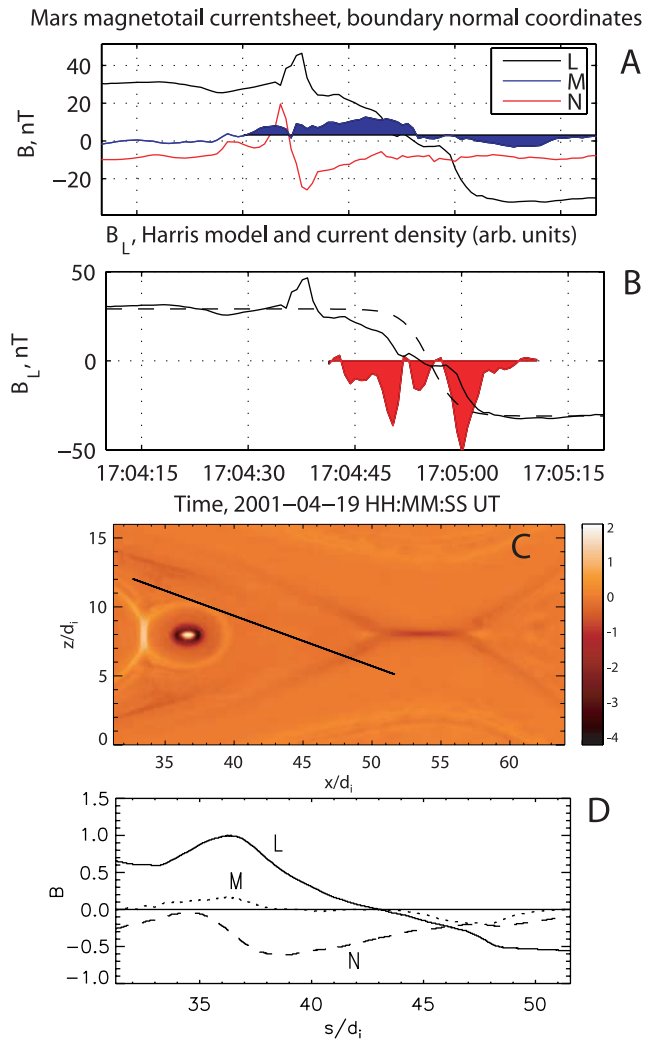
[10] Figure 4a shows the orbit of MGS. The black and white pattern on the planet surface represents the positive/negative strength of the crustal magnetic fields [Connerney *et al.*, 2001] and the red lines show the draping of the IMF. The color of the trajectory corresponds to time. Between 17:04 and 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  $+B_M/-B_M$  Hall perturbation. The island creates a  $+B_N/-B_N$  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

[11] 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 ( $\{L, N, M\} = \{-x^{\text{sim}},$

$-z^{\text{sim}}, -y^{\text{sim}}\}$ ). The initial equilibrium consists of two Harris current sheets superimposed on a uniform ambient population with  $B_{y0}^{\text{sim}} = 0$  [Drake *et al.*, 2006]. The initial Harris current sheet half width is  $0.5 c/\omega_{pi}$  (based on the normalization scheme,  $c/\omega_{pi} \sim 200$  km) and has uniform initial electron and ion temperatures ( $T_i/T_e = 5$ ). The simulation domain is  $L_x, L_z = 64, 32 c/\omega_{pi}$  – 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  $x = 53 c/\omega_{pi}$  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  $\mathbf{B}$  are labeled according to the boundary normal coordinate system. The simulated magnetic field is qualitatively consistent with the data – the peak in  $B_L$  at  $s = 36.5 c/\omega_{pi}$  is produced by the secondary island and the reversal in  $B_L$  around  $s = 43 c/\omega_{pi}$  corresponds to the current sheet. The positive/negative excursion of  $B_N$  at  $s = 36 c/\omega_{pi}$  is produced by the secondary island. The negative excursion of  $B_M$  around  $s = 47 c/\omega_{pi}$  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.

[12] 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



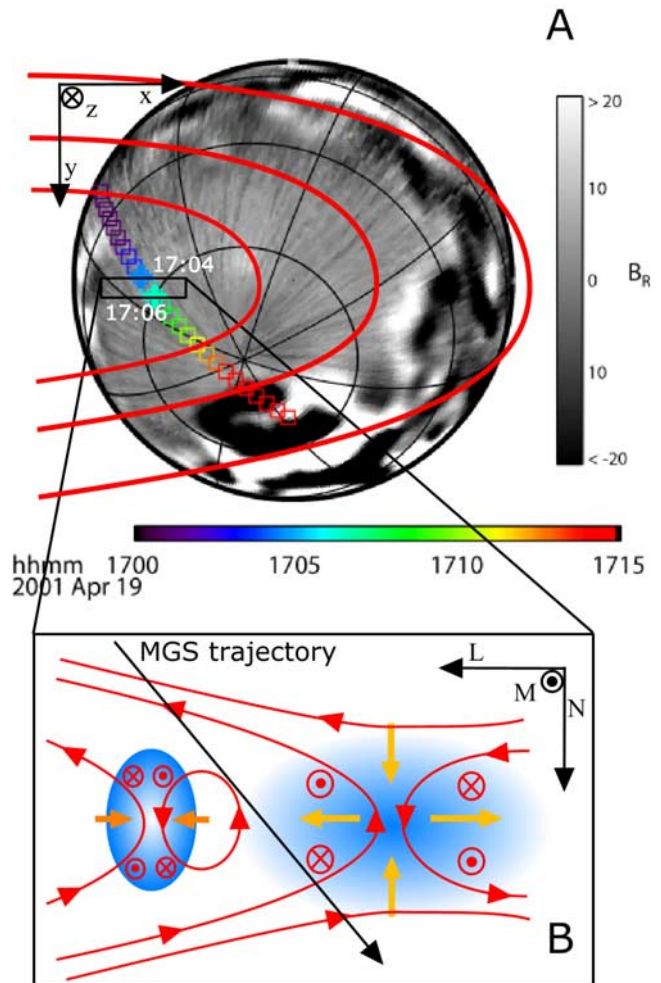
**Figure 3.** (a) Magnetotail crossing in boundary normal coordinates. (b)  $B_L$  (black), a Harris current sheet model fit (dashed black) and the current density  $j_M$  (red). (c) Out of plane current density from a Particle-In-Cell simulation of magnetic reconnection. (d) Variation in the magnetic field along the diagonal cut shown in Figure 3c. This cut corresponds to the trajectory of the spacecraft, as inferred from the data and shown in Figure 4.

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



**Figure 4.** (a) Orbit of MGS relative to Mars (looking along  $+z_{MSO}$  towards the southern hemisphere with the Sun to the right). Mars is shaded according to the radial component of the crustal field. The red lines indicate the draping of IMF. The color of the trajectory indicates the time. Between 17:04–17:06 UT, MGS crossed the region enclosed by the box. (b) Reconstruction of the magnetic field morphology in the vicinity of the reconnection site inferred from the observations. Across the current sheet,  $B_L$  reverses and there is a  $+B_M/-B_M$  Hall perturbation. The island creates a  $+B_N/-B_N$  perturbation superposed on a  $-B_N$  normal field.



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, reconnected, 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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