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We present an analysis of magnetic field and suprathermal electron measurements from the Mars Global Surveyor (MGS) spacecraft that reveals isolated magnetic structures filled with Martian atmospheric plasma located downstream from strong crustal magnetic fields with respect to the flowing solar wind. The structures are characterized by magnetic field enhancements and rotations characteristic of magnetic flux ropes, and characteristic ionospheric electron energy distributions with angular distributions distinct from surrounding regions. These observations indicate that significant amounts of atmosphere are intermittently being carried away from Mars by a bulk removal process: the top portions of crustal field loops are stretched through interaction with the solar wind and detach via magnetic reconnection. This process occurs frequently and may account for as much as 10% of the total present-day ion escape from Mars.

1. Introduction

Several distinct ion escape processes are believed to operate at Mars and similar unmagnetized bodies [*Hunten*, 1993], but it has proved difficult to distinguish between them using existing observations. Some processes, such as bulk plasma escape, have not been unambiguously demonstrated to occur. In contrast with ion pickup or ion outflow, where individual atmospheric ions are accelerated away from the planet by electric fields associated with flowing plasma or by ambipolar electric fields on open magnetic field lines, respectively, bulk escape involves the removal of coherent portions of the ionosphere en masse. This process has been proposed to occur at Venus via the formation of a Kelvin-Helmholtz instability at the interface between the ionosphere and solar wind [*Wolff et al*., 1980], and some observations suggest that it occurs [*Brace et al*., 1982]. An analogous process has been proposed for Mars [*Penz et al*., 2004], with few supporting observations [*Cloutier et al*., 1999].

Strong crustal magnetic fields at Mars influence how the solar wind interacts with the atmosphere in some regions, and perhaps globally. Crustal fields deflect the solar wind in some locations, preventing solar wind-related ionization of atmospheric neutrals. They also facilitate particle and energy exchange between the solar wind and atmosphere in small-scale regions analogous to Earth's polar cusps [*Brain et al*., 2007]. Simulations suggest that crustal fields provide a net shielding effect for planetary ions, on the order of ~30% [*Ma et al*., 2002]. Here we present observational evidence that crustal fields also enable bulk plasma escape processes occurring through magnetic shear between the solar wind and closed crustal field lines.

2. Observations

Figure 1a shows 38 minutes of magnetic field observations recorded by the Mars Global Surveyor (MGS) spacecraft as it orbited Mars at altitudes near 400 km in March 2002. A large amplitude signature in the magnetic field was observed from 04:51:30 to 04:59, with the field strength peaking near 180 nT at 04:55. Although small differences of 15-60 nT between measurements and a crustal magnetic field model [*Cain et al*., 2003] can be explained by the compressed solar wind magnetic field which drapes around the conducting ionosphere on the day side of the planet, it is not likely that the large amplitude, short-duration feature can be explained in this manner.

MGS should not have measured substantial crustal field signatures at this time. The orbit geometry for the event (Fig 1b) shows that MGS observed the feature a few minutes before the spacecraft encountered strong crustal fields. Shocked solar wind plasma is expected to flow anti-sunward, so that crustal fields were immediately upstream during the event.

Smooth rotations in the vector field components accompany the increase in field strength, suggestive of a magnetic flux rope [*Russell and Elphic*, 1979]. Magnetic flux ropes are common in a wide variety of solar system plasmas [e.g. *Cloutier et al*., 1999; *Russell and Elphic*, 1979; *Slavin et al*., 2009], and can form as a result of magnetic reconnection [*Drake et al*., 2006]. Reconnection and associated flux ropes have been previously reported for Mars in the current sheet that forms in the plasma wake [*Eastwood et al*., 2008; *Halekas et al*., 2009]. The field profiles expressed in a minimum variance coordinate system (Fig 1c) are similar to those shown for previously observed flux ropes throughout the solar system [*Russell and Elphic*, 1979; *Lepping et al*., 1990] with an almost circular polarization in the plane of maximum and intermediate variance (i-j plane), and a thinner arc shape in the i-k plane (Fig 1d). We conclude that the structure observed by MGS is a large field amplitude flux rope. The 180 nT field strength measured in this flux rope is, to our knowledge, the highest reported in any flux rope sampled in situ, anywhere in the solar system.

Electron energy distributions recorded in sunlight before, during, and after the flux rope observation (Fig 2) contain distinctive peaks near 500 eV and 20-60 eV. These (unresolved) peaks have been attributed to electrons created via ionization of neutral atmospheric species (oxygen and CO_2) by solar soft x-rays and solar UV photons, respectively [*Mitchell et al.*, 2000; *Frahm et al.*, 2010], indicating that ionospheric plasma is present throughout the event. The flux of electrons is generally expected to increase with decreasing solar zenith angle. However, the electron fluxes in the central rope are comparable to or exceed the fluxes measured at lower solar zenith angles. This excess may be explained by temporal or spatial variations, but the coincidence with the enhanced magnetic field strength strongly suggests that there is additional plasma in the central portion of the flux rope relative to the surrounding regions.

The regions surrounding the central flux rope (labeled 1, 2, 4) all contain highly anisotropic pitch angle distributions (Fig 2). The angular distribution of electrons is more isotropic in the core of the flux rope (interval 3). Electrons occupying open field lines at most pitch angles should rapidly gyrate away; therefore, the isotropic distributions in interval 3 indicate that they occupy closed field lines [*Brain et al.*, 2007]. We infer that the plasma is physically isolated from the surrounding regions encountered by MGS.

3. Discussion

The spacecraft traversed ~1200 km when crossing the flux rope, at an angle of ~25º to the rope's central axis (determined from minimum variance analysis). If we assume it was stationary, the rope's radius was then ~250 km. Fits to the observations (shown in Fig 1c) using a simple force free symmetric flux rope model [*Lepping et al.*, 1990] yield a best-fit diameter of 140 km. The model results confirm that the structure is larger than typical flux ropes previously observed in the ionosphere of Venus or Mars, but the substantial difference between the two estimates also suggests that the flux rope may not be force-free, so that pressure is not conserved throughout the rope. Therefore, it may not be in steady state with its surroundings. The model results also indicate that the rope's peak (axial) field strength is ~200 nT and that the spacecraft passed ~60 km from its center. However, the rope is not likely to be stationary. If we assume that it is carried with the 5-15 km/s plasma flow expected for this region then the rope could be as large as 350-1300 km.

During the time of the event, the upstream solar wind pressure was nearly four times larger than its median value, and the orientation of the upstream Interplanetary Magnetic Field (IMF) rotated by ~180° during the two hour period containing the observation. Periods of similarly large solar wind pressure are not uncommon for the MGS dataset, but the combination of high solar wind pressure and recent reorientation of the IMF suggest that external conditions may have contributed to the formation of the rope and its characteristics (such as large size and field strength).

The event is not unique. Further examination of four weeks (~340 orbits) of MGS magnetic field observations reveals 190 clear examples of flux ropes in the southern hemisphere, downstream from Martian crustal fields. The flux ropes range in peak magnetic field amplitude from a few nT to nearly 200 nT. A fraction of the weaker examples may be only coincidentally associated with crustal fields, and may instead be Venus-like ionospheric flux ropes, previously reported at Mars [*Cloutier et al.*, 1999; *Vignes et al.*, 2004]. However, in a separate search of the entire MGS mapping orbit dataset (June 1999 – October 2006) we identified at least 135 spacecraft orbits for which there is a possible flux rope structure having peak field magnitude in excess of a crustal field model prediction by 100 nT or more. The process that formed the flux rope in Figure 1 clearly occurs frequently.

The observations presented here are consistent with MGS having sampled crustal magnetic field lines that had been stretched tailward from the day side through interaction with the solar wind (Fig 3). The field lines may be attached to the planet at the time of observation or may have recently detached, similar to plasmoids in Earth's magnetotail. Regardless, as crustal fields are stretched long distances tailward they will form a thin current sheet that is likely to reconnect and detach. The ionospheric plasma inside the structure will be carried away from the planet in a bulk removal process.

It is difficult with a single spacecraft to unambiguously determine whether a flux rope is magnetically detached. However, global simulations of the solar wind interaction with Mars show evidence for large-scale magnetic flux ropes detached from crustal fields [*Harnett*, 2009]. Further, at least a few of the examples identified so far in MGS observations show possible evidence for current sheets between the flux rope and upstream crustal fields, as if reconnection has occurred. Figure 4 shows a strong (~120 nT) flux rope downstream from crustal magnetic fields on May 23, 2005, at ~14:30.

From 14:38-14:40, two depressions in the magnetic field magnitude are observed at the location where an increase in magnetic field magnitude due to crustal magnetic fields is expected. Application of minimum variance analysis to the two depressions reveals that at least one of them is a current sheet, with a characteristic change in sign of one of the magnetic field components (from +20 to -20 nT). The presence of a current sheet between crustal fields and the downstream flux rope supports the interpretation that the flux rope is detached.

We can obtain an upper limit estimate of the observed loss from the event shown in Figure 1, assuming that MGS encountered a cylindrical structure filled with planetary plasma. The total number of particles carried away by the rope is given by the product of the density of particles inside the rope (n) and the rope's volume. The density is estimated by direct integration of the measured electron energy spectrum over all energy channels of the instrument, assuming charge neutrality and that the electron flux sampled in the field of view of the instrument is representative of the entire ambient electron distribution. This integration yields densities of 1.5-2.5 cm^{-3}. However, the instrument does not measure electrons with energies <10 eV and it is possible that the electrons are relatively cold, so that the actual density in this location maybe as high as 5-10 cm^{-3}. The volume of the rope can be expressed in terms of the time MGS spent crossing the rope (~450 s), the velocity of the rope relative to the spacecraft (5-15 km/s), and the angle that the spacecraft trajectory makes with the rope's central axis (25°). Using these parameters, we obtain a total loss of $\sim 3.6 \times 10^{25}$–7.3×10^{26} ions which, over the time that it took the rope to pass MGS is equivalent to a loss rate of $\sim 7.9 \times 10^{22}$–1.6×10^{24} ions/s.

The upper end of the range in estimated loss rate from this short term event is comparable to estimates of the long term average ion escape rate at Mars (from all processes) during solar minimum [*Lundin et al.*, 2009]. This estimate is particularly sensitive to the rope velocity, which cannot be determined from the observations and may have been greater during this high pressure period, so the actual loss rate could be higher. We note also that due to the circular orbit geometry of MGS the rope could extend much further downstream than MGS was able to observe. If so, then many more ions escaped during this event than we are able to account for. Regardless, during the time period of the MGS observations, ion loss via the flux rope may have contributed significantly to the global escape rate of planetary ions.

We can crudely estimate the total contribution of flux ropes to ion loss at Mars by noting that strong (>100 nT) flux ropes have been identified in ~1% of MGS orbits. MGS was in a position to observe flux ropes from southern crustal fields ~15% of the time. If the loss rate from each strong rope is comparable to the long-term average, then the total contribution of flux ropes to ion loss could be as high as ~5-10% of the total ion loss. Therefore, this previously unobserved intermittent bulk atmospheric removal process may significantly contribute to the total ion escape from Mars.

Acknowledgments

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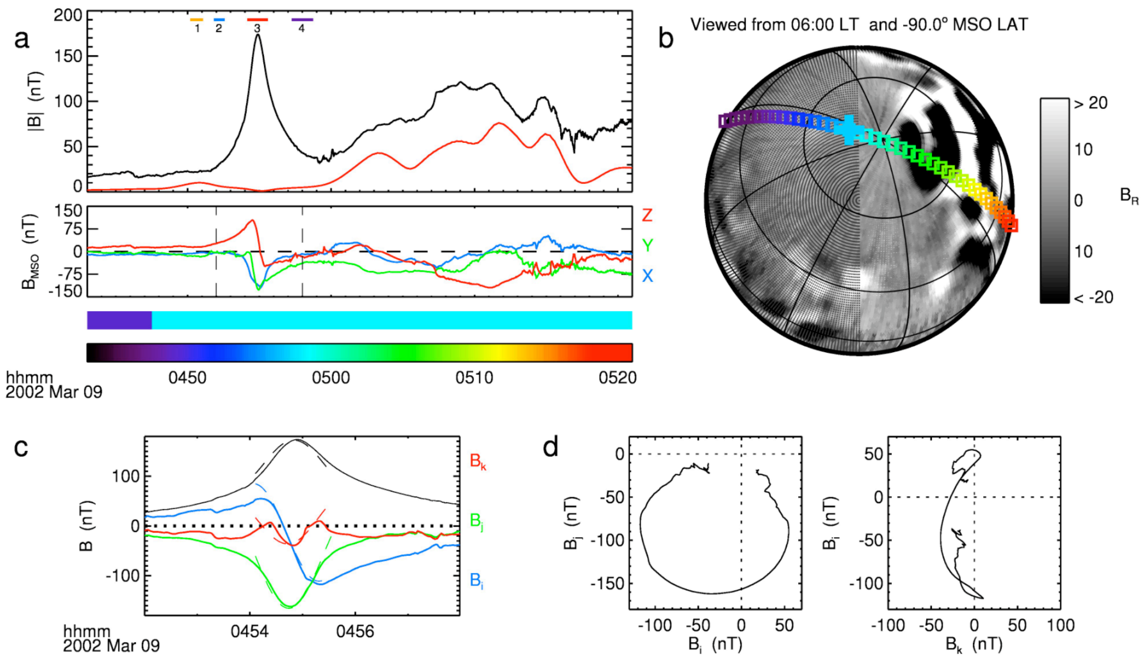

Figure 1: (a) Time series magnetic field amplitude (top) and vector field in Mars-Solar-Orbital coordinates (bottom) recorded by MGS over a 38 minute period. Expected crustal field amplitudes are shown in red in the top panel. Color bars indicate whether MGS was illuminated (light blue) or in eclipse (purple) and observation time. Numbered periods are identified for use with Figure 2. (b) The MGS orbit track is indicated by the squares colored according to observation time. The blue cross marks the location of the large magnetic field structure. The globe is shaded according to the expected radial component of the crustal field, and viewed from above the South Pole, with the Sun to the right. (c) Vector field for the time period between the vertical dashed lines in panel a, expressed in minimum variance coordinates. The black trace shows the field amplitude. Fits to a flux rope model are shown as dashed lines. (d) Hodograms of the field shown in panels c.

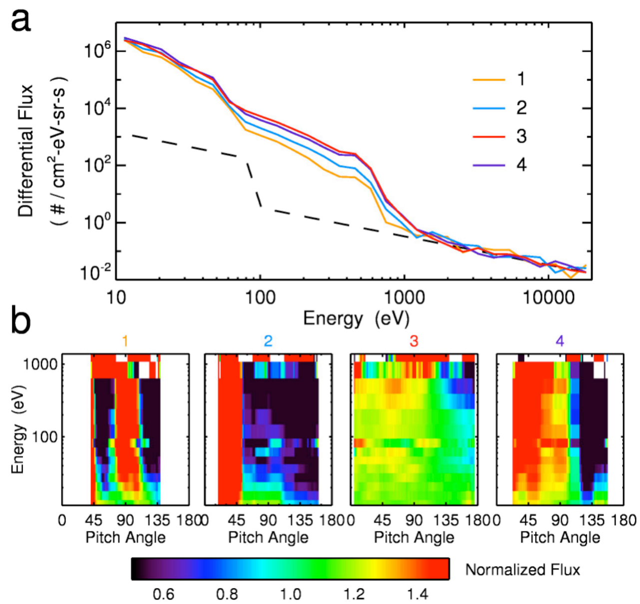

Figure 2: Electron energy and angular distributions during the event in Figure 1. (a) Averaged electron energy distributions for the four numbered periods identified in Figure 1a, colored accordingly. The dashed line indicates the instrumental background level. (b) Average electron pitch angle distributions as a function of energy for the same four numbered periods. Pitch angle distributions at each energy are normalized.

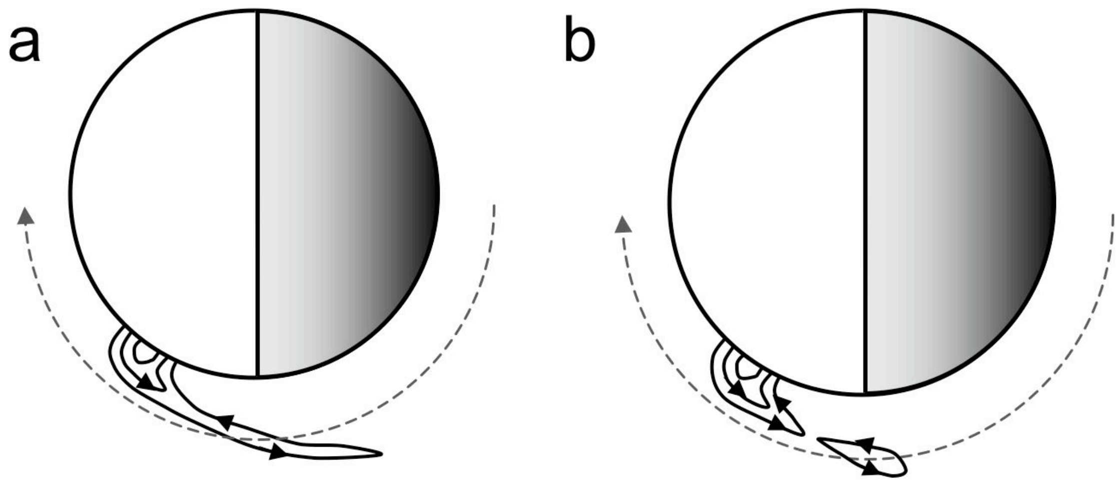

Figure 3: Cartoon of possible field line geometries for the event in Figure 1. The Sun is to the left, and the MGS orbit trajectory is shown as a dashed line, with the spacecraft moving from right to left. (a) Crustal field lines are still attached to the planet, and have been stretched tailward long distances by the solar wind; (b) Loops of crustal magnetic field have detached, carrying ionospheric plasma away from Mars.

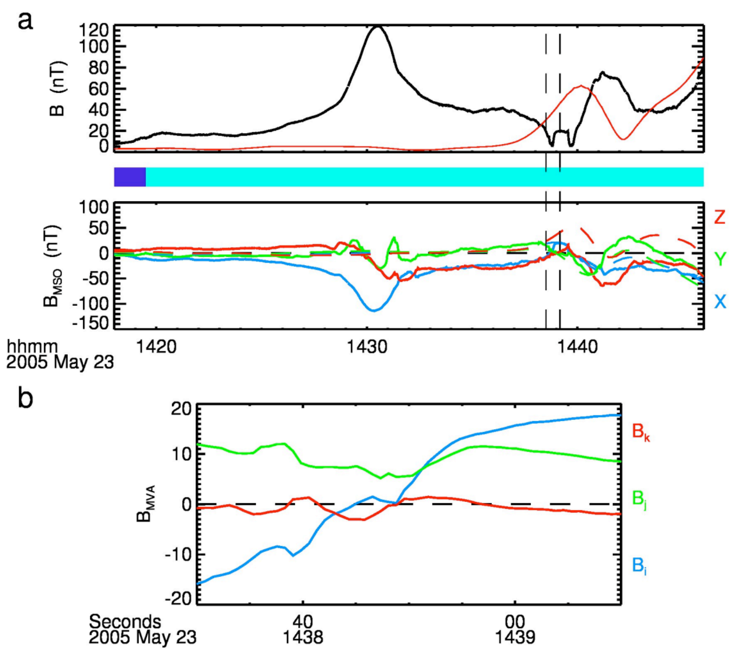

Figure 4: Strong flux rope downstream from crustal magnetic fields on May 23,2003, with a current sheet. Panels a and b are analogous to Figure 1 panels a and c.