Estimation of Ionospheric Plasma Content inside Martian Magnetic Flux Ropes Based on MAVEN Observations. T. Hara[1], D. L. Mitchell[1], J. P. McFadden[1], J. S. Halekas[2], J. R. Espley[3], J. E. P. Connerney[3], G. A. DiBraccio[3], L. Andersson[4], D. A. Brain[4], and K. Seki[5], [1]Space Sciences Laboratory, University of California, Berkeley, CA, 94720, United States (hara@ssl.berkeley.edu), [2]Department of Physics and Astronomy, University of Iowa, Iowa City, IA, 52242, United States, [3]NASA Goddard Space Flight Center, Greebelt, MD, 20771, United States, [4]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, 80303, United States, [5]Solar-Terrestrial Environment Laboratory, Nagoya University, Aichi, 4648601, Japan.

Introduction: Although Mars lacks a global intrinsic magnetic field, it possesses strong localized crustal magnetic fields [1]. The rapid changing interplanetary magnetic field (IMF) embedded in the solar wind interacts with the asymmetric crustal magnetic fields which rotate with the planet relative to the solar wind. The electromagnetic environment around Mars is thus expected to be highly complicated and dynamic. Insitu spacecraft measurements, such as Phobos-2 and Mars Express, have recorded that planetary ions are energized through the direct interaction of the solar wind with the upper atmosphere, resulting in ion escape into interplanetary space [2, 3]. However, the role of the crustal magnetic fields in the atmospheric escape from Mars is not yet well understood.

It is thought that Martian crustal magnetic fields influence atmospheric escape in several different ways. One remarkable space physics phenomenon associated with the Martian crustal magnetic fields is magnetic flux ropes. Flux ropes are characteristic twisted magnetic field structures, and could intermittently carry significant large amounts of atmosphere away from Mars if they detach from the surface. Indeed, large-scale magnetic flux ropes downstream from the strong Martian crustal magnetic fields were observed by Mars Global Surveyor (MGS) [4]. However, quantitative contribution to an atmospheric escape from Mars due to magnetic flux ropes has not been fully understood yet because of ambiguities that arise from the estimation of their shape and size from single spacecraft measurements and the absence of any ion detectors onboarded MGS.

Method: Recently, we attempted to estimate lower limits on ionospheric plasma content contained inside the Martian flux ropes observed by MGS based on the Grad-Shafranov reconstruction (GSR) technique [5, 6]. The GSR technique is capable of reconstructing the two-dimensional magnetohydrostatic structure from the single-spacecraft data and also provides us with various spatial characteristics of flux ropes, including their shape (lower limits of their radii and lengths), axial orientation, and chirality (handedness) of the flux rope magnetic field.

It should be noted that the comprehensive spacecraft plasma and magnetic field data are essential to apply the GSR technique to the magnetic flux ropes [7]. Hence, we had to impose additional assumptions for an application of the GSR technique, due to the lack of ion observation by MGS in the previous studies. MAVEN carries a suitable package of plasma instruments to investigate the Martian ionospheric plasma

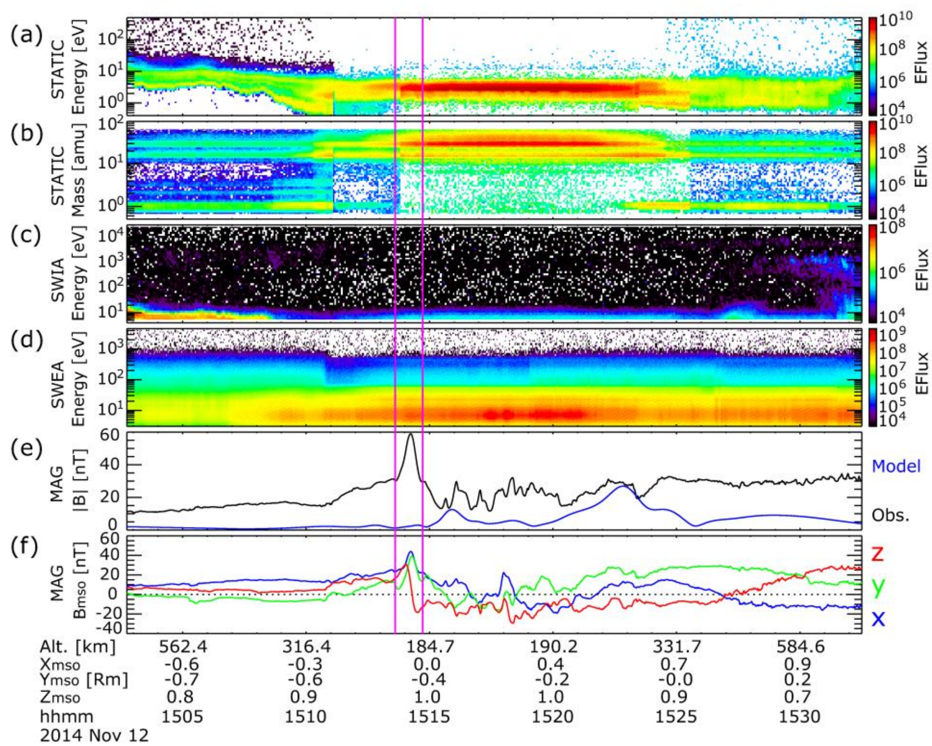

Figure 1: Overview of the Martian magnetic flux rope event measured by MAVEN on Nov. 12, 2014.

properties, including number density, bulk velocity, and temperature. Hence, flux rope spatial structures could be estimated more accurately and ion escape rates owing to flux ropes can be better evaluated via the GSR technique. In this paper, we first apply the GSR technique to the Martian magnetic flux rope by using the comprehensive plasma and magnetic field data obtained from MAVEN. Moreover, we first evaluate lower limits on plasma content included inside the Martian magnetic flux ropes based on the MAVEN ion observations.

Observations: Figure 1 shows the summary time-series plots of the Martian magnetic flux rope event measured by MAVEN on Nov. 12, 2014: (a) STATIC ion energy, (b) ion mass (species), (c) SWIA ion energy, (d) SWEA electron energy, and (e) the strength and (f) vector magnetic field. During the time interval between 15:13:36 and 15:14:43 (between two magenta vertical lines), the observed magnetic field strength (black) is strongly enhanced compared to the modeled crustal magnetic field (blue) in Figure 1e. Figure 1f indicates that vector magnetic field is smoothly rotating during the event, which is consistent with the feature of the magnetic flux rope. Since this signature is observed in the vicinity of the terminator region of ionosphere at the northern pole, STATIC mostly detected ionospheric-origin planetary heavy-ion population, such as O^+, O_2^+, CO_2^+ (Figure 1b), and SWEA also observed ionospheric photoelectrons with energies around above 20 eV (Figure 1d). According to the minimum variance analysis (MVA), the hodogram for the event (not shown here) in the MVA coordinate system shows that the vector magnetic field rotates in a circular manner, which is an expected feature of magnetic flux ropes.

GSR Results: When we apply the GSR technique to the observed magnetic flux rope, we adopt the O_2^+ density and temperature calculated by STATIC data, because STATIC ion mass data indicates that O_2^+ is the most dominant population during the flux rope observations in this study. It is also assumed that the observed flux rope is approximately stationary, which means that the spacecraft velocity is the dominant component causing apparent movement of the flux rope relative to the MAVEN spacecraft.

Figure 2 shows that the axial two-dimensional magnetic field map of the observed flux rope recovered by the GSR technique. The MAVEN spacecraft was traveling along the *x* direction from left to right at *y*=0. The overlaid magenta dashed curve on Figure 2 is our determined boundary to estimate the volume of the magnetic flux rope. The axial orientation of the flux rope derived from the GSR technique is [0.43, 0.90, -0.03] in the MSO coordinate system. We then estimate the cross section of the recovered flux rope. The equivalent radius is derived from the estimated cross section, under the assumption that the shape is strictly circular. It is about 22.3 km. The length along the flux rope axis is estimated from the MAVEN flight distance. We assume that the reconstructed spatial structure is maintained at least over the time interval when MAVEN was inside the flux rope. The estimated axial length is about 276.2 km. The average number densities of planetary heavy ions are estimated by STATIC to be about 1.6×10^3 cm^{-3} for O^+, and 1.3×10^4 cm^{-3} for O_2^+. Based on the GSR results, the lower limits on the ionospheric plasma content inside the Martian flux rope are about 6.9×10^{23} ions for O^+, and 5.7×10^{24} ions for O_2^+. Given the ionospheric plasma content inside the flux rope is completely removed from the upper atmosphere within the duration that MAVEN samples this structure, ion escape rates can be estimated by dividing the ionospheric plasma content inside the flux rope by the duration of the event. This result indicates that potential ion escape rates of the flux rope can instantaneously contribute to approximately 1-10 % of the global average ion escape rate (including all candidate escape processes) during the solar minimum [3]. These results derived from the GSR technique are consistent with our previous studies [5, 6]. Further investigations with respect to the field topology, i.e., whether the observed flux rope detaches from (remains attached to) the surface will be discussed, based on the MAVEN data.

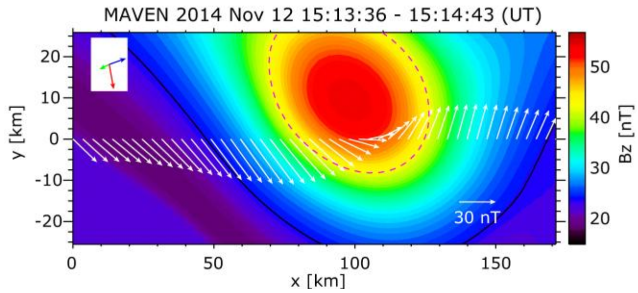

Figure 2: The reconstructed 2-d axial magnetic field Bz map obtained from the GSR technique using MAVEN plasma and magnetic field data.

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