In Situ Detection of Kinetic-size Magnetic Holes in the Martian Magnetosheath

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Abstract

Depression in magnetic field strength with a scale below one proton gyroradius is referred to as a kinetic-size magnetic hole (KSMH). KSMHs are frequently observed near Earth’s space environments and are thought to play an important role in electron energization and energy dissipation in plasma. Recently, KSMHs have been evidenced in the Venusian magnetosheath. However, observations of KSMHs in other planetary environments are still lacking. In this study, we present the in situ detection of KSMHs in the Martian magnetosheath using MAVEN for the first time. The distribution of KSMHs is asymmetric in the southern–northern hemisphere and no obvious asymmetry in the dawn–dusk hemisphere. The observed KSMHs are accompanied by increases in the electron fluxes in the perpendicular direction, indicating the presence of electron vortices. These features are similar to the observations in the Earth’s magnetosheath and magnetotail plasma sheet and the Venusian magnetosheath. This implies that KSMHs are a universal magnetic structure in space.

Unified Astronomy Thesaurus concepts: Mars (1007); Planetary magnetospheres (997); Solar system planets (1260); Planetary dynamics (2173); Magnetic fields (994)

1. Introduction

Magnetic field depressions in the total magnetic field strength are usually called magnetic holes. Magnetic holes with scales larger than a proton gyroradius, referred to as mirror modes, are frequently observed in the solar wind (Zhang et al. 2008; Tsurutani et al. 2011; Volwerk et al. 2020; Yu et al. 2021), Earth’s magnetosphere (Tsurutani et al. 2011; Balikhin et al. 2009), and other planetary magnetospheres (e.g., Cattaneo et al. 1998). These large-scale magnetic holes are usually generated by ion temperature anisotropy via the mirror mode instability (Hasegawa 1969).

Magnetic holes with a scale smaller than a proton gyroradius are commonly referred to as kinetic-size magnetic holes (KSMHs). Because KSMHs can heat or accelerate electrons and dissipate energy in turbulent plasmas, KSMHs have drawn attention in recent years. KSMHs are widely observed in the Earth’s magnetosphere, including the magnetosheath (e.g., Yao et al. 2017; Huang et al. 2017a, 2017b, 2018; Liu et al. 2019, 2020) and the magnetotail plasma sheet (e.g., Ge et al. 2011; Sundberg et al. 2015; Gershman et al. 2016; Huang et al. 2019). A variety of interesting phenomena occur inside KSMHs, including electron vortices (Huang et al. 2017a, 2017b), electron perpendicular temperature increase (Yao et al. 2017; Huang et al. 2017a, 2017b), electron-scale whistler waves, electron cyclotron waves, and electrostatic solitary waves (Huang et al. 2018; Yao et al. 2019). There are several mechanisms for the generation of KSMHs, including the theory of electron solitary waves (Ji et al. 2014), electron mirror instability (Pokhotelov et al. 2013), tearing instability (Balikhin et al. 2012), and the model of electron vortex magnetic holes as coherent structures in plasma turbulence (Haynes et al. 2015; Roytershteyn et al. 2015).

Recently, Goodrich et al. (2021) presented the first evidence of KSMHs in the Venusian magnetosheath using Parker Solar Probe. Whether KSMHs exist in other planetary environments is still unclear. In the present study, we revisit the observations from the Mars Atmosphere and Volatile EvolutioN (MAVEN) in the Martian magnetosheath and find a large number of KSMHs accompanied by electron vortices for the first time. These observations indicate that KSMHs are a universal structure in magnetized space plasmas.

2. Instruments and Methods

To investigate KSMHs, we use magnetic field data with a sampling of 32 Hz from magnetometer (MAG; Connerney et al. 2015), ion data with a sampling of 4 s from Supra-Thermal And Thermal Ion Composition (STATIC; McFadden et al. 2015), and electron data with a sampling of 4 s from Solar Wind Electron Analyzer (SWEA; Mitchell et al. 2015) on board MAVEN. With a field of view of 360° × 90°, STATIC is able to provide fluxes, temperature, and velocity vectors of ions owing to its large mass resolution. It is noted that ion density and velocity vectors are derived from STATIC measurements, whereas ion temperature is derived from the MAVEN Insitu Key Parameters. SWEA measures the energy and angular distributions of the electrons from 5 to 5 keV in the solar wind and magnetosheath.

To identify KSMHs accurately, the following criteria are used in the present study: (1) each component of the magnetic field should remain in its direction; (2) the depression of the magnetic field DepthMH should be more than 10%, where

\[ \text{Depth}_{\text{MH}} = 1 - \frac{B_{\text{min}}}{B_{\text{background}}} \]

\( B_{\text{min}} \) is the minimum value of the magnetic field in the magnetic hole, and \( B_{\text{background}} \) is the average of the magnetic field near the magnetic hole; (3) the standard deviation of the magnetic field outside the structure should be less than that inside; (4) the length of the spacecraft crossing the magnetic hole \( L_{\text{MH}} \) should be less than one proton gyroradius \( \rho_{H+} \), where

\[ L_{\text{MH}} = |V_{H+} \times \Delta t| \]

and \( V_{H+} \) is the background proton bulk velocity and \( \Delta t \) is the duration of the spacecraft passing through the magnetic hole.

3. Results

Figure 1 shows an example of KSMH on 2019 January 26. Figure 1(a) presents the energy fluxes of proton. The proton...
fluxes in solar wind gather around 1 keV. The energy of proton fluxes gradually expands in foreshock, and the proton fluxes visibly expand in the magnetosheath, which indicates that protons are heated crossing the bow shock. This event occurred in the Martian magnetosheath, where the proton bulk velocity is less than that in the upstream quiet solar wind. This event occurred in the Martian magnetosheath, where the proton bulk velocity is less than that in the upstream quiet solar wind (not foreshock; Figure 1(c)), the magnetic field is more turbulent (Figure 1(e)), and the density of heavy ions, such as O\(^+\), remains much less than that of protons (Figure 1(d)). The gray shadow in the left panels of Figure 1 marks one KSMH, which is magnified in the right panels.

The MAVEN spacecraft observed a depression in magnetic field strength without reversals in the three components of the magnetic field (Figure 1(h)), implying the existence of a magnetic hole. MAVEN entered the magnetic hole at 10:25:32.944 UT and exited at 10:25:33.319 UT, yielding the duration \(\Delta t = 0.375 \text{s}\). Based on the assumption of moving together between the magnetic hole and the plasma flow, one can estimate the size of the magnetic hole \(L_{\text{MH}}\) as 80.93 km. With the temperature of background proton \(T_{\text{H+}} = 141 \text{ eV}\), the proton gyroradius \(\rho_{\text{H+}}\) is estimated to be 359 km. Thus, the size of the magnetic hole is much less than one proton gyroradius, implying that MAVEN detects one KSMH here. As shown in Figure 1(f), the fluxes of electron (50–200 eV) in the perpendicular direction have significant enhancement inside this KSMH, which is similar to the observations of the KSMHs in Earth’s magnetosheath (e.g., Huang et al. 2017a, 2017b, 2018) and plasma sheet (e.g., Huang et al. 2019). It should be pointed out that the sampling rate of SWEA is much lower than that of MAG, and the time duration of this KSMH is less than the sampling rate of SWEA. Thus, the measured fluxes of the electron belong to not only the KSMH but also one part of outside of KSMH. However, comparing the background electron fluxes, the enhancement of the electron fluxes in the perpendicular direction is obvious and can still represent the characteristics of this KSMH.

To reconstruct KSMHs, we estimate the radius \(R_{\text{MH}}\) and maximum current density \(J_0\) in these structures based on the simple cylindrically symmetric current vortex model proposed by Goodrich et al. (2021). The current density in the magnetic hole can be described as \(J = J_0 \sin(\pi r/R)\) while \(r \leq R\), where \(r\) is the radial distance from the center of the magnetic hole, \(R\) is the radius of the magnetic hole (i.e., the distance from the center to the outer edge of the magnetic hole), and both \(J_0\) and \(R\) are constant. Then, the magnetic field is obtained using Ampere’s law, \(B_i(r) = B_0 - \Delta B_i(r)\), where \(\Delta B_i(r) = \mu_0 \int R_j R |J(r)| \, r \, dr \cdot B_i(r)\) is the observed largest variation component derived from the minimum variance analysis (MVA; e.g., Sonnerup & Scheible 1998), and \(B_0\) is the magnetic field \(B_i(r)\) at the edge of the magnetic hole (i.e., \(r = R\)). To obtain the best-fitting results for \(J_0\) and \(R\), we employ the minimum mean square error method and set up a rule to restrict the minimum magnetic field in the model \(B_{\text{model}}\) within \(5\%\), which is \(J_{\text{model}} - B_{\text{min, model}} [|B_{\text{min}}|] \leq 5\%\).

Figure 2 shows the observed magnetic field inside the KSMH shown above and the fitted result derived by the model. One can see that the fitted curve agrees well with the observed magnetic field. The estimated radius of the KSMH \(R_{\text{MH}}\) is 85.80 km, which is also much smaller than \(\rho_{\text{H+}}\), and the maximum current density \(J_0\) is 1.10 \(\mu\text{A m}^{-2}\).
According to the criteria in the previous section and the aforementioned restriction that is used in the fitting process, 102 KSMH structures are successfully selected in the Martian magnetosheath from 2015 January 1 to 2019 December 31. It should be noted that we try to present unambiguous KSMH structures that are consistent with the current vortex model. However, this process may miss some KSMH structures that are not consistent with the simple model.

Figure 3 presents the spatial distribution of all KSMH events. One can conclude several distinct features. Asymmetry exists in the southern–northern hemisphere (61.7% on the $+z$-axis and 38.3% on the $-z$-axis; Figure 3(a)), and no obvious asymmetry exists in the dawn–dusk hemisphere ($y$-axis; Figure 3(b)). Although several events seem to appear below the magnetic pileup boundary, the obstacle boundary that separates the magnetic pileup region from shocked solar wind, it is easy to confirm that these events are all in the magnetosheath by checking the plasma properties and the background magnetic field, which means that all identified KSMH events occur in the Martian magnetosheath. In addition, no KSMH event was observed yet in the low-latitude or nose region on the dayside (Figure 3(d)).

Statistical studies on the parameters of KSMHs were conducted, including $L_{MH}/\rho_{H+}$, $R_{MH}/\rho_{H+}$, Depth$_{MH}$, $J_0$, $\text{Flux}_\perp /\text{Flux}_\parallel$, and $\text{Flux}_\perp_{\text{inside}} /\text{Flux}_\perp_{\text{outside}}$, where $\text{Flux}_\perp_{\text{inside}}$ ($\text{Flux}_\perp_{\text{outside}}$) is the electron flux with a pitch angle between $60^\circ$–$120^\circ$ ($135^\circ$–$180^\circ$) inside (outside) of the magnetic holes, and $\text{Flux}_\parallel$ is half of the electron flux with a pitch angle between $0^\circ$–$45^\circ$ and $135^\circ$–$180^\circ$. Since the time resolution of SWEA is practically higher than the time duration of the KSMHs, it is almost impossible to obtain the data inside/outside of the magnetic holes precisely. Thus, the one sampling of electron fluxes covering the whole KSMH is regarded as that inside the magnetic hole, and the average of the last and next samplings is that outside the magnetic hole.

Figure 4 shows the statistical results of the parameters of all KSMH events. The $L_{MH}$ normalized by $\rho_{H+}$ are mostly approximately 0.25 (Figure 4(a)), and the normalized estimated radii $R_{MH}$ are mostly less than 0.5 (Figure 4(d)). The depression of the magnetic field seems to gather at approximately 55% (Figure 4(b)). Most of the maximum current densities derived from the model are less than $1.2 \, \mu \text{A m}^{-2}$ (Figure 4(e)), whereas there exist several cases with a considerably strong current (up to $\sim 6 \, \mu \text{A m}^{-2}$). The electron fluxes in the perpendicular direction inside KSMHs are higher than those outside KSMHs (the ratio could be up to 2.5; Figure 4(c)). Moreover, the electron fluxes in the perpendicular direction are much higher than those in the parallel direction inside KSMHs (Figure 4(f)). This implies that the electron fluxes in the perpendicular direction are enhanced inside KSMHs, which causes a significant increase in the electron perpendicular temperature therein.

4. Discussions and Conclusions

As mentioned in the 1, there are several mechanisms for the generation of KSMHs in space plasmas. However, due to the low time resolution of both ion and electron data provided by MAVEN, one cannot directly determine which mechanisms are responsible for the KSMHs in the Martian magnetosheath. According to our statistical study, the existence of KSMHs is proven in the Martian magnetosheath by MAVEN.
observations. All observed KSMHs are accompanied by obvious enhancements of the electron fluxes at $\sim 90^\circ$ compared to the fluxes in the parallel direction inside KSMHs and in the perpendicular direction outside KSMHs, indicating that the electrons are trapped by the KSMHs. The trapped electrons can form an electron vortex, which carries a strong current vortex to induce a magnetic field decrease inside the KSMHs (e.g., Haynes et al. 2015; Huang et al. 2017a). This infers that the KSMHs in the Martian magnetosheath may be described by the electron vortex magnetic hole model. However, due to the low time resolution of the electron data, only one data point is available during the crossing of KSMHs. Thus, one cannot directly identify the electron vortex inside KSMHs through bipolar signatures in one or two components of electron velocity.

Based on the simple cylindrically symmetric current vortex model, the current and radius of the KSMHs are derived. An intense current inside KSMHs of up to $6 \mu$A m$^{-2}$ is found. As for the case shown in Figure 1, the electron velocity is estimated as $1375$ km s$^{-1}$ using $J_0 = 1.1 \mu$A m$^{-2}$, $n_e \sim n_i \sim 5$ cm$^{-3}$, and the assumption that the currents are mainly carried by the electrons. Such a large electron velocity is much higher than the ion velocity (i.e., $\sim 300$ km s$^{-1}$) in this KSMH, indicating decoupling between the ions and the electrons. This decoupling can cause the Hall effect and lead to the Hall electric field therein.

In summary, KSMHs have been successfully identified in the Martian magnetosheath by MAVEN for the first time. These KSMHs are possibly accompanied by electron vortices, which are characterized by enhancements in electron fluxes in the perpendicular direction with respect to the ambient magnetic field. These KSMHs are likely to be explained by the electron vortex magnetic hole model in turbulent plasma. KSMHs are frequently detected in the Earth’s magnetosheath and plasma sheet and have recently been detected in the Venusian magnetosheath. Our study demonstrates the existence of KSMHs in the Martian magnetosheath. Thus, KSMHs may be universal magnetic structures under different plasmas

\[ r = \sqrt{y^2 + z^2} \]

**Figure 3.** The spatial distribution of all KSMHs in Mars Solar Orbital (MSO) coordinates, respectively, in the (a) $x$--$z$ plane, (b) $x$--$y$ plane, (c) $y$--$z$ plane, and (d) $x$--$\rho$ plane, where $\rho = \sqrt{y^2 + z^2}$. The red dots represent positions of KSMH events. Two dashed lines mark the bow shock (BS) and magnetic pileup boundary (MPB) separately (Vignes et al. 2000). All axes are in units of Mars radii ($R_M$).
conditions in space plasma, which are indicative of a universal microphysical plasma process.

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Figure 4. Statistical results on parameters of KSMH events. (a) $L_{MH}/\rho_{H}$, (b) $\text{Depth}_{MH}$, (c) $\text{Flux}_{\text{inside}}/\text{Flux}_{\text{outside}}$, (d) $R_{MH}/\rho_{H}$, (e) $J_{e}$, and (f) $\text{Flux}_{\text{inside}}/\text{Flux}_{\text{outside}}$. $L_{MH}$ is the length of the spacecraft crossing the KSMHs, $\rho_{H}$ is the proton gyroradius, $R_{MH}$ is the estimated radius, $\text{Depth}_{MH}$ is the depression of magnetic field, $J_{e}$ is the maximum current density derived from the model, $\text{Flux}_{\text{inside}}$ ($\text{Flux}_{\text{outside}}$) is the electron fluxes with a pitch angle between $60^\circ$–$120^\circ$ inside (outside) of the structure, and $\text{Flux}_{||}$ is half of the electron fluxes with a pitch angle between $0^\circ$–$45^\circ$ and $135^\circ$–$180^\circ$. 

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