Kinetic-size magnetic holes (KSMHs) in the terrestrial magnetotail plasma sheet are statistically investigated using the observations from the *Magnetospheric Multiscale* mission. The scales of KSMHs are found to be smaller than one ion gyroradius or tens of electron gyroradii. The occurrence distributions of KSMHs have dawn–dusk asymmetry (duskside preference) in the magnetotail, which may be caused by the Hall effect. Most events of KSMHs (71.7%) are accompanied by a substorm, implying that substorms may provide favorable conditions for the excitation of KSMHs. However, there is a weak correlation between KSMHs and magnetic reconnection. The statistical results reveal that for most of the events, the electron total temperature and perpendicular temperature increases while the electron parallel temperature decreases inside the KSMHs. The electron temperature anisotropy ($T_{e\perp}/T_{e\parallel} > 1$) is observed in 72% of KSMHs. Whistler-mode waves are frequently observed inside the KSMHs, and most (92%) KSMHs associated with whistler waves have enhancements of electron perpendicular distributions and satisfy the unstable condition of whistler instability. This suggests that the observed electron-scale whistler waves, locally generated by the electron temperature anisotropy, could couple with the electron-scale KSMHs. The observed features of KSMHs and their coupling to electron-scale whistlers are similar to the ones in the turbulent magnetosheath, implying that they are ubiquitous in the space plasmas. The generation of KSMHs in the plasma sheet could be explained by an electron vortex magnetic hole, magnetosonic solitons, and/or ballooning/interchange instabilities.

**Key words:** planets and satellites: magnetic fields – plasmas – turbulence – waves

1. Introduction

Magnetic holes (MHs) are widely observed in space and astrophysical plasmas (Turner et al. 1977), such as solar wind (e.g., Zhang et al. 2008), planetary magnetosheaths (e.g., Tsurutani et al. 2011; Huang et al. 2017a, 2017b, 2018; Yao et al. 2017; Breuillard et al. 2018), and magnetospheric plasma sheets (e.g., Ge et al. 2011; Sun et al. 2012; Sundberg et al. 2015; Gershman et al. 2016). MHs are characterized by significant magnetic depressions and their spatial scales vary from less than one $\rho_i$ (ion gyroradius) to thousands of $\rho_e$, which corresponds to temporal scales from seconds to tens of minutes. The MHs with scales larger than $\rho_e$ are believed to be a consequence of nonlinear evolution of the mirror instability (e.g., Chisham et al. 1999; Passot & Sulem 2006; Califano et al. 2008; Soucek et al. 2008; Ahmadi et al. 2017), or seen as solitary structures (e.g., Stasiewicz 2004) or nonlinear Alfven(n) waves (e.g., Tsurutani et al. 2005).

Recently, more attention has been paid to kinetic-size magnetic holes (KSMHs) with the scales less than an ion gyroradius, or even close to an electron gyroradius (e.g., Ji et al. 2014, Sundberg et al. 2015; Gershman et al. 2016; Yao et al. 2016, 2017; Huang et al. 2017a, 2017b, 2018; Shustov et al. 2019) due to that such MHs can effectively affect the electron dynamic and energy exchange between the plasma and the field. Various possible generation mechanisms of KSMHs are proposed, which include magnetosonic solitons (Ji et al. 2014; Li et al. 2016), tearing instability (Balikhin et al. 2012), and self-evolution of decaying turbulence (named as electron vortex MH, Haynes et al. 2015). Abundant electron-scale wave activities are observed and associated with KSMHs, such as electron cyclotron harmonic waves (Zhang et al. 2017) and whistler waves (Huang et al. 2018), indicating the evidence of the coupling between electron-scale waves and electron-scale structures in space plasmas. Thus, these MHs may play an important role in energy dissipation, electron acceleration, change of local plasma properties, and energy exchange between ions and electrons (Huang et al. 2017a, 2018; Zhang et al. 2017).

To investigate the properties of KSMHs in the terrestrial magnetotail plasma sheet, including the occurrence distributions, electron properties, and waves in the KSMHs, we present a statistical investigation that takes advantage of high-time resolution field and plasma measurements from the *Magnetospheric Multiscale* (MMS) mission.

2. Data and Event Selection

The MMS mission is a solar-terrestrial probe mission comprising four identical spacecraft flying in a tetrahedral formation. This mission uses the terrestrial magnetosphere as a
laboratory to study the microphysics of three fundamental plasma processes: magnetic reconnection, energetic particle acceleration, and turbulence (Burch et al. 2015). In this study, we used magnetic field data measured by the Fluxgate Magnetometer instruments with a sampling frequency of 128 Hz in burst mode (Russell et al. 2016), and the plasma measurements from Fast Plasma Instrument (FPI) with a resolution of the electron data of 30 ms and resolution of the ion data of 150 ms in burst mode (Pollock et al. 2016).

The criteria used to identify MHs are given below: (1) $B_{min}/B = 0.9$, where $B_{min}$ is the minimum magnetic field magnitude inside an MH, and $B$ is the average magnetic field magnitude within a 6 s time interval; (2) $\omega = 15^\circ$, $\omega$ is the magnetic shear angle between two boundaries of an MH. To ensure we are detecting KSMHs, a short window of 30 s time interval is used in the data survey. We perform the statistical study from 2017 May to September during magnetotail phase of MMS mission. At least 53 events are successfully selected.

### 3. MMS Observations of KSMHs in the Plasma Sheet

#### 3.1. Case Study

An example of the identified KSMH associated with whistler waves on 2017 May 28 is shown in Figure 1. The vectors of the magnetic field (Figure 1(b)), ion velocity (Figure 1(d)), electron velocity (Figures 1(g)), and current density (Figure 1(h)) are presented in $LMN$ coordinates ($L = [0.47, -0.25, 0.85]$, $M = [0.56, -0.66, -0.50]$, $N = [0.68, 0.71, -0.17]$ in GSM coordinates), which are determined by the minimum variance analysis (MVA) of the magnetic field (Sonnnerup & Scheible 1998). The duration of the MH is 0.69 s with magnetic amplitude depression ($B_{min}/B$) of $\sim 0.45$. The scale of the hole is estimated by $D_N = V_n \times dt = 522$ km ($\sim 0.27 \rho_i$, or $\sim 13.4 \rho_e$), where $V_n$ is 756 km s$^{-1}$ from the timing analysis based on the magnetic field from four MMS spacecraft, $dt \approx 0.69$ s is the duration of the crossing of the hole, $\rho_i \approx 1927$ km and $\rho_e \approx 39$ km are the proton and electron gyroradii estimated using the background plasma parameters, respectively. This confirms the kinetic size of the observed holes. One can see that electron temperature (especially perpendicular temperature, Figure 1(f)) and electron velocity (Figure 1(g)) clearly increase in the KSMH. It is interesting to note that the bipolar variation in $V_{en}$ component, which may indicate the existence of an electron vortex in the cross section of KSMH (similar to the observations in the magnetosheath in Huang et al. 2017a, 2017b, 2018). No significant changes are found in ion measurements during the crossing of KSMH, which may be due to the short time duration of MH or the noises on these measurements. The current’s densities are estimated by the curlometer method (i.e., $J = \nabla \times B/m$; Dunlop et al. 1988) and using the direct FPI plasma measurements (i.e., $J = n q(V_i - V_e)$, where $n$ is the plasma...
density, \( q \) is the charge, \( V_i \) and \( V_e \) are the velocities of ion and electron, respectively, shown in Figure 1(h). It can be seen that the current densities obtained by the two methods have the same trend and polarity and have some differences due to the noises from the FPI instruments. We observe intense currents in the KSMH with bipolar signatures in the \( J_i \) and \( J_e \) components (Figure 1(h)), while the total current \( J \) significantly increases with a dip in the center of KSMH. Considering the bipolar signatures in the \( V_i \) and \( V_e \) components of the electron velocity, one can deduce that the major current carriers are the electrons in the KSMH.

We performed the singular value decomposition (SVD) method (Santolik et al. 2003) to derive power spectral densities of the magnetic field and electric field and the properties of wave emissions. The results are shown in Figure 1 panels (j)–(n). One can see that magnetic (Bpsd) and electric (Epsd) field power spectrum densities significantly increase between 0.1 \( f_{ce} \) and 0.5 \( f_{ce} \) (\( f_{ce} \) is the electron cyclotron frequency) in the MH (marked by black ellipses in Figures 1(j) and (k)). The corresponding ellipticities approach 1 (Figure 1(l)) with large polarization degrees (~1 in Figure 1(n)), implying that the waves are right-hand polarized, and the corresponding propagation angles \( \theta_k \) are smaller than 20° (Figure 1(m)), meaning that the waves are quasi-parallel propagating with respect to the background magnetic field. Thus, the wave emissions in this KSMH are likely to be carried by a right-hand polarized and quasi-parallel whistler mode.

Figures 1(o)–(r) present the omni-directional electron fluxes and electron pitch angle distributions (PADs; from 0.2 to 20 keV). The electrons have a dominant energy from ~0.4 to 20 keV, as the typical feature in the plasma sheet (Figure 1(r)). The field-aligned electron phase space densities are observed at low energy, from 0.2 to 2 keV, in the outside and inside the KSMH, while the perpendicular phase space densities increase at higher energy, from 2 to 20 keV, before and during the crossing of the KSMH. There is a slight increase in perpendicular electron phase space densities inside the KSMH, which causes the electron temperature anisotropy (Figure 1(f)). This is favorable for the excitation of the observed whistler waves in the KSMH.

Figure 2 shows another example of the KSMH without the observations of whistler waves on 2017 July 20. Magnetic field (Figure 2(b)), electron and ion velocity (Figure 2 panels (d) and (g)), and current (Figure 2(h)) are presented in \( LMN \) coordinates \( (L = [0.67, 0.62, 0.41], M = [0.69, −0.31, −0.66], N = [−0.28, 0.72, −0.64] \) in GSM coordinates) derived by the MVA method. The magnetic amplitude depression \( B_{min}/B \) of this hole is about 0.85, and the duration of the hole is about 1.6 s. The estimated size is about 49 km (~0.08 \( \rho_L \) or ~8.8 \( \rho_L \) where ion gyroradius \( \rho_i = 601 \) km, and electron gyroradius \( \rho_e = 5.6 \) km), implying that this hole is a kinetic-size structure. We observe an increase in electron density (Figure 2(e)), a slight increase in electron parallel temperature (Figure 2(f)), a decrease in electron perpendicular temperature, and no significant change in ion measurements inside KSMH. During the crossing of KSMH, the electron velocity \( V_{el} \) decreases and the temperature increases. The total current \( J \) significantly increases with a dip in the center of KSMH. Considering the bipolar signatures in the \( J_i \) and \( J_e \) components of the electron velocity, one can deduce that the major current carriers are the electrons in the KSMH.
component has a bipolar variation from negative to positive, and the \( V_{\text{en}} \) component has a peak in the KSMH. While the \( J_l \) component also exhibits a bipolar signature, \( J_m \) has a peak (Figure 2(h)), and total current \( J_t \) significant increase in the KSMH, indicating that the intense currents in the KSMH are carried by the electrons. Figures 2(o)–(r) present the electron PADs and omni-directional fluxes. One can clearly see an enhancement in the electron parallel phase space densities in the

**Figure 3.** Histograms of the sizes of the KSMHs normalized by electron gyroradius (a) and ion gyroradius (b).

**Figure 4.** Statistical occurrence distributions of the KSMHs in the \( X_{\text{GSM}}-Y_{\text{GSM}} \) plane (a), \( Y_{\text{GSM}}-Z_{\text{GSM}} \) plane (b), and the occurrence distributions as a function of \( Y_{\text{GSM}} \) (c) and \( Y_{\text{GSM}} \) (d).
energy range from 80 to 3 keV inside KSMH. The results derived by the SVD method show no distinct whistler-mode waves during the crossing of KSMH.

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3.2. Statistical Results

A total of 53 events in the terrestrial magnetotail plasma sheet are analyzed in our statistical study. Figure 3 displays the scales of all KSMHs normalized to the ion gyroradius $\rho_i$ and electron gyroradius $\rho_e$. One can see that the scales of KSMHs are much smaller than $\rho_i$ (mainly between 0.04 and 0.25 $\rho_i$, which corresponds to $3 \sim 20 \rho_i$, Figure 3(a)), thus demonstrating that all of these MHs are kinetic-size structures.

The occurrence distributions of KSMHs within the magnetotail plasma sheet are presented in Figure 4. The KSMHs can be observed in a large area extending from $-13 R_E$ to $-25 R_E$ in the Sun–Earth direction and from $-15 R_E$ to $18 R_E$ in dawn–dusk direction, and more frequently detected in the north (i.e., northern hemisphere of the magnetotail in Figure 4(b)). It is clear that the distribution of the KSMHs has a dawn–dusk asymmetry (mainly concentrated on the duskside, $Y_{GSM} > 0$ in Figure 4(c)) and a south–north asymmetry (mainly concentrated in the north, $Z_{GSM} > 0$ in Figure 4(d)). Actually, we have checked the MMS orbit and ruled out the possibility that the dawn–dusk asymmetry of the occurrence distributions is due to the MMS orbit inclination.

Figure 5 presents the geomagnetic conditions and the environmental context when MMS detected the KSMHs in the magnetotail. As can be seen in Figure 5(a), 38 events are accompanied by the substorm (71.7%) and 15 events (28.3%) occurred in the quiet period, implying that the substorm may provide favorable conditions for the excitation of KSMHs. Moreover, we found that 43.4% of the events were occurring when the AE index was less than 200 nT, and 62.3% of the events were occurring when the AE index was less than 300 nT (not shown here). This indicates that the KSMHs are more likely to distribute in the weak period of the geomagnetic activity. Considering that magnetic reconnection is considered to be the major contributor to the origin of the bursty bulk flow in the plasma sheet, we investigated the plasma velocity $V_\|/V_\perp$ accompanied by KSMH events (Figure 5(b)). One can see that the values of $V_\|$ of the events are mostly less than $300 \text{ km s}^{-1}$ (79.3%), and only five events (9.4%) have $V_\|$ larger than $400 \text{ km s}^{-1}$, implying that there is a weak correlation between the KSMHs and the reconnection.

To investigate the electron properties associated with KSMHs, we performed a statistical study of electron temperature outside (i.e., background) and inside the KSMHs in Figure 6. We find that the total temperature and perpendicular temperature inside the KSMHs are mostly larger than those outside the KSMHs (83% and 89% respectively, Figure 6 panels (a) and (b)), implying that the total and perpendicular temperatures increase inside the KSMHs. However, the electron parallel temperature inside the KSMHs is generally smaller than that outside the KSMHs (Figure 6(c)). These features are similar to the previous observations in the turbulent magnetosheath by Huang et al. (2018). The ratios between electron perpendicular temperature and parallel temperature inside KSMHs are larger than 1 (up to 1.35) for 71.7% of events, suggesting the existence of electron temperature anisotropy ($T_{e\perp}/T_{e\parallel} > 1$) inside KSMHs. Figure 7 also presents the statistical results of electron PADs for all events and the events associated with whistler waves. We found that 71.7% of the events have perpendicular distributions, 24.5% of the events have field-aligned distributions, while a few events have isotropic distributions (3.8%). Furthermore, we analyzed the link between whistler waves and corresponding electron PADs inside KSMHs. In total, 24 KSMH events were successfully found to be associated to whistler waves. The vast majority of the whistler events (91.7%) correspond to electron perpendicular distributions inside KSMHs, and only two whistler events (8.3%) have field-aligned distributions. Moreover, we calculated the instability threshold for whistler anisotropy...
instability given by Gary & Wang (1996) for the events with the observations of whistler waves, i.e., $R_w = \beta_{\parallel}^{0.55} (T_{\perp}/T_{\parallel} - 1) - 0.36$. The plasma environment is unstable to whistler instability when $R_w > 0$ and stable when $R_w < 0$. The values of $R_w$ are larger than 0 in 20 events. This indicates that the electron temperature anisotropy is likely to be responsible for the local excitation of whistler waves inside KSMHs for most of the events. For the other whistler events that correspond to stable conditions ($R_w < 0$), the whistler waves may have been generated in other regions and then propagated into the KSMHs.

4. Discussions and Summary

In this study, we investigated a series of KSMHs in the terrestrial magnetotail plasma sheet. The occurrence distributions of KSMHs have dawn–dusk asymmetry (higher occurrence on the duskside). Similar dawn–dusk asymmetries have been found in many phenomena in the magnetotail, such as magnetic reconnection (Eastwood et al. 2010), fast plasma flows (Lotko et al. 2014), flux ropes (Slavin et al. 2005), and Hall electric field (Lu et al. 2019). This asymmetry may be caused by the nonuniform spatial distribution of the ionospheric Hall conductance or asymmetric external driving (Zhang et al. 2012; Lotko et al. 2014). However, recent global hybrid simulations and three-dimensional particle-in-cell simulations without any asymmetric effect from the ionosphere or...
externally driving have shown that the Hall electric field is caused by the unmagnetized ions, the latter being unable to co-move with the electrons (i.e., Hall effect) in the magnetotail (Lu et al. 2016, 2018, 2019). This Hall effect is stronger on the duskside and generates a thin current sheet asymmetry (Lu et al. 2019). The dusk-side preference of the KSMHs in the plasma sheet may be caused by this Hall effect.

The mirror instability condition can be stated as \( R = \left( T_{\|}/T_{\perp}\right)/(1 + 1/\beta_e) > 1 \) (e.g., Southwood & Kivelson 1993). Considering that the scales of the KSMHs are smaller than the ion gyroradius and close to electron gyroradius, we only test the electron mirror instability condition using the background plasma and field measurements. The results show that the \( R \) values of all events are smaller than 1 (not shown here), implying that the background plasma environment is electron mirror instability stable. Thus, the electron mirror instability could not be used to explain the generation of KSMHs in the plasma sheet. Due to the fact that the ion temperature is much larger than the electron temperature in the plasma sheet, one can rule out the possibility that field-swelling instability (Pokhotelov et al. 2013) excites the observed KSMHs. Recently, a statistical study of KSMHs in the magnetotail using THEMIS observations is particularly focused behind dipolarization fronts (Shustov et al. 2019). They suggested that these KSMHs are generated by the ballooning/interchange instability from the dipolarization fronts. In our statistical events, it is found that 11 KSMH events (21%) are detected behind dipolarization fronts, suggesting such KSMHs may be generated by the ballooning/interchange instabilities. Particle-in-cell simulations have shown that electron vortex MHS, characterized by the size of the order of the electron scale and electron vortex formed by trapped electrons, can be spontaneously generated in turbulent magnetized plasmas (Haynes et al. 2015). They also showed that the electron vortex MHS have the features of an increasing electron density, temperature, and perpendicular temperature. In our observations, 71.7% of KSMHs have perpendicular distributions, and the electron vortex is observed inside 68% of such KSMHs. This indicates that half of the KSMHs can be explained by electron vortex MHS. In addition, electron magnetosonic solitons based on the EMHD model are used to describe the features of KSMHs (Li et al. 2016), and it is found that the solitons can explain the generation of the KSMHs in the plasma sheet with the scale size from 10 to 20 \( \rho_e \) (Yao et al. 2016). Thus, the generations of some KSMHs observed by MMS may be explained by magnetosonic solitons.

The increase of the electron temperature and perpendicular temperature is observed in the KSMHs for most of the events, which is similar to the observations in the turbulent magnetosheath by Huang et al. (2017a, 2018). Such increases may be due to the heating or Betatron acceleration of the electrons by the compression of the KSMHs during their evolutions, as suggested by Ahmadi et al. (2018). The increase of electron parallel temperature for the event in Figure 2 and other events may be caused by Fermi acceleration during the shrinking of magnetic flux inside the KSMHs. The systematic investigation of the generation mechanism of the electron distributions inside the KSMHs will be performed in the future via kinetic simulations.

In summary, we statistically investigated KSMHs with scales of tens of electron gyroradii and related electron characteristics and wave activities in the terrestrial magnetotail plasma sheet. The occurrence distributions of KSMHs have dawn–dusk asymmetry (higher occurrence in the duskside), which may be caused by the Hall effect in the magnetotail. There is a good correlation between the KSMHs and the substorm but a weak relationship between the KSMHs and magnetic reconnection, suggesting that the substorm may provide favorable conditions for the excitation of the KSMHs. The electron total and perpendicular temperatures increase, and the electron parallel temperature decreases inside most (>80%) of the KSMHs. This leads to the electron temperature anisotropy \( (T_{\|}/T_{\perp}) > 1 \) in the KSMHs. The increase of the electron temperature within the KSMHs indicates that the KSMHs are likely to heat or accelerate the electrons. Whistler waves are observed inside 24 KSMHs, and most of (91.7%) the KSMHs with whistler waves observed have enhancements on electron perpendicular distributions, implying that the whistler waves inside the KSMHs could be locally excited by the electron temperature anisotropy. Considering that similar observations of whistler waves-KSMHs have been reported in the turbulent magnetosheath (Huang et al. 2018), our results suggest that the coupling between electron-scale whistler waves and the electron-scale structures may be ubiquitous in space plasmas.

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