Supporting Information for "Characteristics of Kelvin-Helmholtz Waves as Observed by the MMS from September 2015 to March 2020"

Rachel Rice[1], Katariina Nykyri[1], Xuanye Ma[1], Brandon Burkholder[2]

[1]Embry-Riddle Aeronautical University, Department of Physical Sciences, Center for Space and Atmospheric Research

[2]University of Maryland Baltimore County, Goddard Planetary Heliophysics Institute

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The magnetosheath is characterized by cold, dense plasma flowing tailward with the shocked solar wind. The magnetosphere, on the other hand, is comprised of hot, tenuous plasma which is relatively stagnant. Thus, we have 3 plasma parameters, density, temperature, and tailward velocity, which may be used to easily and automatically distinguish the magnetosheath and magnetopause. Due to the mixing and heating which occurs within the KH vortex, and the possibility of reconnection dragging less dense magnetosphere tailward with sheath-like speeds, no one parameter will be sufficient to separate the regions. Instead, we look for a combination of two or three parameters which will allow for the automated identification of the magnetosheath and magnetosphere. Table 1 lists all of the parameters we considered and their relative values in each region.

Corresponding author: Rachel Rice, ricer4@my.erau.edu

Condsider a ratio of density and temperature, n/T. In the cold, dense magnetosheath, n/T is large. In the hot, tenuous magnetosheath, n/T is small.

In the magnetosheath the GSM$-X$ component of velocity is typically large and negative, flowing with the shocked solar wind. The GSM$-X$ component of velocity is typically small, either positive or negative, in the magnetosphere. For simplicity we define the tailward velocity such that it is strictly positive, $v_{tail} = |v_X - \max v_x|$. The product of density and tailward velocity, nv_{tail} is large in the magnetosheath and small in the magnetosphere.

We may combine the previous two parameters in to a single ratio, nv_{tail}/T. This is large in the magnetosheath and small in the magnetosphere.

Next consider specific entropy, $S = T/n^{2/3}$. In the cold dense magnetosheath S is small. In the hot, tenuous magnetosphere, S is large.

Recalling our definition of tailward velocity, we may also consider ratios of the specific entropy and tailward velocity, S/v_{tail} and v_{tail}/S. In the sheath, S/v_{tail} is small, and it is large in the magnetosphere. In the magnetosheath v_{tail}/S is large, and in the magnetosphere it is small.

When using the above parameters, we first determined a mean magnetopause value for each event. Then created cutoff values for each region based on the magnetopause value. Mean values of density and temperature in each isolated region were compared with typical values for the magnetosheath and magnetosphere. Mean values of density, velocity, and magnetic field were also used to calculate growth rates (GR), unitless growth rates (UGR), and unstable solid angles (USA).

In order to determine the magnetopause value, we first sort a given parameter in ascending order. A percentage of the largest and smallest values are collected, and the mean of these extreme values is labeled the magnetopause value, mp. We use a subset, rather than all, of the data for a given event, to avoid any effects from the spacecraft spending more time in one region than the other.

The percentage of data used to determine mp was varied from including the largest and smallest 2.5% (5% total) of all data to including the largest and smallest 25% (50% total) of all available data points. Once mp is determined, we can then use it to set cutoff values defining the magnetosheath and magnetosphere.

In the region in which a given parameter is expected to be large, cutoff values were varied from $1.0 * mp$ to $1.9 * mp$. The most restrictive cutoff values ($> 1.7 * mp$) were ruled out because they did not return a reasonable number of data points in both regions. Fore some events, no MMS observations fit the more restrictive criteria. The more relaxed cutoffs ($< 1.3{*}mp$), included too much mixed plasma from regions already strongly affected by the KHI. The inclusion of such mixed plasma had a significant but unpredictable effect on the final results. Marginal cutoff values from $1.4{*}mp$ to $1.6{*}mp$ all produce comparable results. Within this range of cutoff values, density and temperature show only small variations and match well with expected values for both the real spacecraft and simulated data.

In the region in which a given parameter is expected to be small, cutoff values were varied from $0.1 * mp$ to $1.0 * mp$. The more relaxed cutoffs ($> 0.7 * mp$) included too much plasma already affected by mixing and heating processes in the KHI. The most restrictive cutoff values ($< 0.3{*}mp$) are too restrictive, yielding little to no plasma in the region. The marginal cutoff values ($0.4{*}mp$ to $0.6{*}mp$), again seem to be the best choice. However, the mean density and temperature of the regions identified using these cutoffs were not reasonable for any of our tested parameters. A check against simulation data also showed poor agreement with the known values. Thus, no parameter performed well to identify the region in which it is expected to be small.

The percentage of data used to determine mp and the cutoff values were varied in parallel. Plots of the density and temperature for each identified region were created for all combinations of mp and cutoff values. Figure 1 shows an example of these plots for the magnetosheath density of the KHI encounter on 15 October 2015. The parameters which are expected to be large in the sheath (n/T, nv_{tail}, nv_{tail}/T, and v_{tail}/S), return density values from ≈ 9 to 12 /cc, in line with expectations for the sheath. Parameters which are small in the magnetosheath (S and S/v_{tail}) return density values less than 6 /cc, which is lower than expected for the typical sheath.

Likewise Figure 2 shows an example of these plots for the magnetosphere density of the KHI encounter on 15 October 2015. The parameters which are expected to be large in the magnetosphere (S and S/v_{tail}), return density values ≈ 0.5 /cc, in line with expectations for the magnetosphere. Parameters which are small in the magnetosheath (n/T,

nv_{tail}, nv_{tail}/T, and v_{tail}/S) return density values between 1 and 2 /cc, which is higher than expected for the typical magnetopshere.

We found of the percent of data used to determine the magnetopause value has only a small affect on the mean values of density (as can be seen in Figures 1 and 2) and temperature of each region and on the final calculations of GR, UGR, and USA. As such, we chose to use the smallest and largest 12.5% (25% total) of all data for a given parameter when determining the magnetopause value. This ensures we are not only considering outliers (as would be the case using too little data), but should not be strongly effected if the spacecraft spends more time on one side of the boundary than the other (as would happen if we used all available data).

Because no parameter performed well for the region in which it is expected to be small, we must use two separate parameters: one large in the magnetosheath and one large in the magnetosphere. We chose nv_{tail}/T as our sheath parameter and S as our magnetosphere parameter. Both of these parameters produce consistent results over the range of marginal cutoff values ($1.4 * mp$ to $1.6 * mp$), suggesting they are robust and not overly sensitive to the selection of our cutoff value. Thus, in order to balance the desire to select the most pure plasma from each region and the need to have a meaningful number of data points in each region, we settled on the cutoff value $1.5 * mp$.

Once selected, the parameters and cutoff values were also tested on simulation data. Both nv_{tail}/T and S performed well, isolating regions in which plasma parameters agreed well with the known values. This can be seen in Figure 3, where the density as determined by our method is plotted in blue for the duration of the simulations, and the known initial value is marked in black. The density of the regions isolated with these parameters is within 0.15/cc of the initial value for the duration of the NIMF simulation, and within 0.3/cc of the initial value for the duration of the PSIMF simulation, which indicates our methodology will work well even for the late stage KHI with significant mixing.

Our new methodology was also compared with a region sorting technique previously published in *Moore et al.* [2017]. In that study, histograms of the most common energy channel in each time step are used to determine the typical energy value of the magnetosheath and magnetosphere. The log mean average of energy in both regions is considered representative of the mixed plasma region. Each time step is sorted into the region to which its weighted mean energy is closest. For KHI where the magnetosheath and magnetospheric energies are well separated, this method works well and produces similar results as the new method presented here, as can be see in Figure 4 for the example events used in the main text. In all cases, the new method sorts more plasma into the mixed region than the Moore method, which we prefer as the resulting regions are more representative of the "pure" magnetosheath and magnetosphere.

We use the KHI event observed on 26 September 2017, shown in Figure 5, as an example of the selection of only pure magnetosheath. Plots of the MMS orbit show it skimming the the magnetopause boundary primarily on the magnetosphere side with only a brief excursion to the magnetosheath. Solar wind density is ≈ 8 /cc, yielding a pure magnetosheath density of $\approx$ 32 /cc according to MHD shock physics. MMS observes such high density only at the very end of the interval, suggesting that MMS observes pure sheath only at the end of the interval and is otherwise in mixed and magnetospheric plasma. As can be seen in Figure 6, the new method identifies only the portion of the MMS observations where density is nearly 30 /cc as pure sheath. The Moore method selects an early portion of the data as magnetosheath plasma based on its energy, but the density and temperature are more consistent with mixed plasma. This is preferable in our work, as our goal is to calculate GR, UGR, and USA using data from only pure magnetosheath and magnetosphere plasma.

In both simulations and real MMS data, it is important to remember the growth rate is dependent upon the path of the satellite through the instability (or the geometry of the cut in simulation space). Figure 7 demonstrates the effect of cut geometry on growth rate for both the NIMF and PSIMF simulations. Simulation data was recorded along four cut geometries as shown in the bottom panels of Figure 7. One cut is perpendicular to the boundary (black), one is parallel to the boundary on the magnetosheath side (cyan), another is parallel to the boundary on the magnetosphere side (magenta), and the final cut is between perpendicular and parallel to the boundary (red). Data from each cut was used to calculate the KHI growth rate at every time step as shown in the top panels of Figure 7 (colors in the growth rate plot correspond with each cut). The perpendicular and intermediate cuts are able to capture pure plasma on either side of the boundary at all time steps, and produce similar results which match well with the observational values from the real events on which they are based. The parallel cuts do not capture both regions of plasma until the KHI is well developed, and as such produce much lower growth rates until later in the simulations.

Our method of separating the regions requires the satellite observes both the magnetosheath and magnetosphere, and works best when the regions are observed for roughly equal times. We can use our method to separate the regions in skimming cuts which observe much more of one region than the other, but such cuts are likely to underestimate the growth rate.

Figures 1 to 7

Tables 1 and 2

Table 1. Tested parameters and the relative values in the magnetosheath and magnetosphere.

Parameter	Magnetosheath	Magnetosphere
n/T	large	small
nv_{tail}	large	small
nv_{tail}/T	large	small
S	small	large
S/v_{tail}	small	large
v_{tail}/S	large	small

Table 2. Normalization constants for the 2D MHD simulations.

Quantity	Northward	Parker spiral
Magnetic field B_0 (nT)	71.5	30.23
Number Density n_0 (/cc)	12.36	2.78
Length scale L_0 (km)	640	640
Velocity V_A (km/s)	443	395.21
Time t_0 (s)	1.35	1.62

Caption for Long Table 1

MMS observed 45 KHI from September 2015 to March 2020. Onset IMF orientation and magnitude, average IMF orientation and magnitude, solar wind flow speed, Alfvén Mach number, temperature, and density are determined using 1 minute OMNI data, which is available for 44 of the 45 events. Here, "onset" refers to the time at which KHI first observes the KHI, as we cannot predict how long the KHI may have been operating before MMS observes it. The OMNI data we report is convected to the bow shock nose, but not to the KHI observation point. Additional transit times to the observation point is estimated using the magnetosheath velocity, are typically small, and have little to no effect on the observed SW conditions.

Caption for Long Table 2

Boundary normal directions were determined using the maximum variance of the convective electric field (MVA-E) technique. The outward pointing normal for a stationary boundary is the direction of maximum variance in the $\mathbf{v}\times\mathbf{B}$ electric field. The Minimum Faraday Residue (MFR) method determines the normal direction and velocity of a moving boundary. The normal direction is well determined when the maximum eigenvalue of the variance matrix is significantly larger than the intermediate eigenvalue for MVA-E, yielding an eigenvalue ratio of 5 or greater. Likewise, the MFR normal direction is well determined when the intermediate eigenvalue of the residue matrix is significantly larger than the minimum eigenvalue. In all cases, the velocity of the boundary is small, as is expected for events in which the velocity is primarily tangential to the boundary, like the KHI. MVA-E and MFR thus produce similar normal directions, but MVA-E has larger eigenvalue ratios. For this reason, we use MVA-E in our analysis.

References

Moore, T. W., K. Nykyri, and A. P. Dimmock (2017), Ion-scale wave properties and enhanced ion heating across the low-latitude boundary layer during Kelvin-Helmholtz instability, *Journal of Geophysical Research: Space Physics*, *122*, 11,128–11,153, doi:10.1002/2017JA024591.

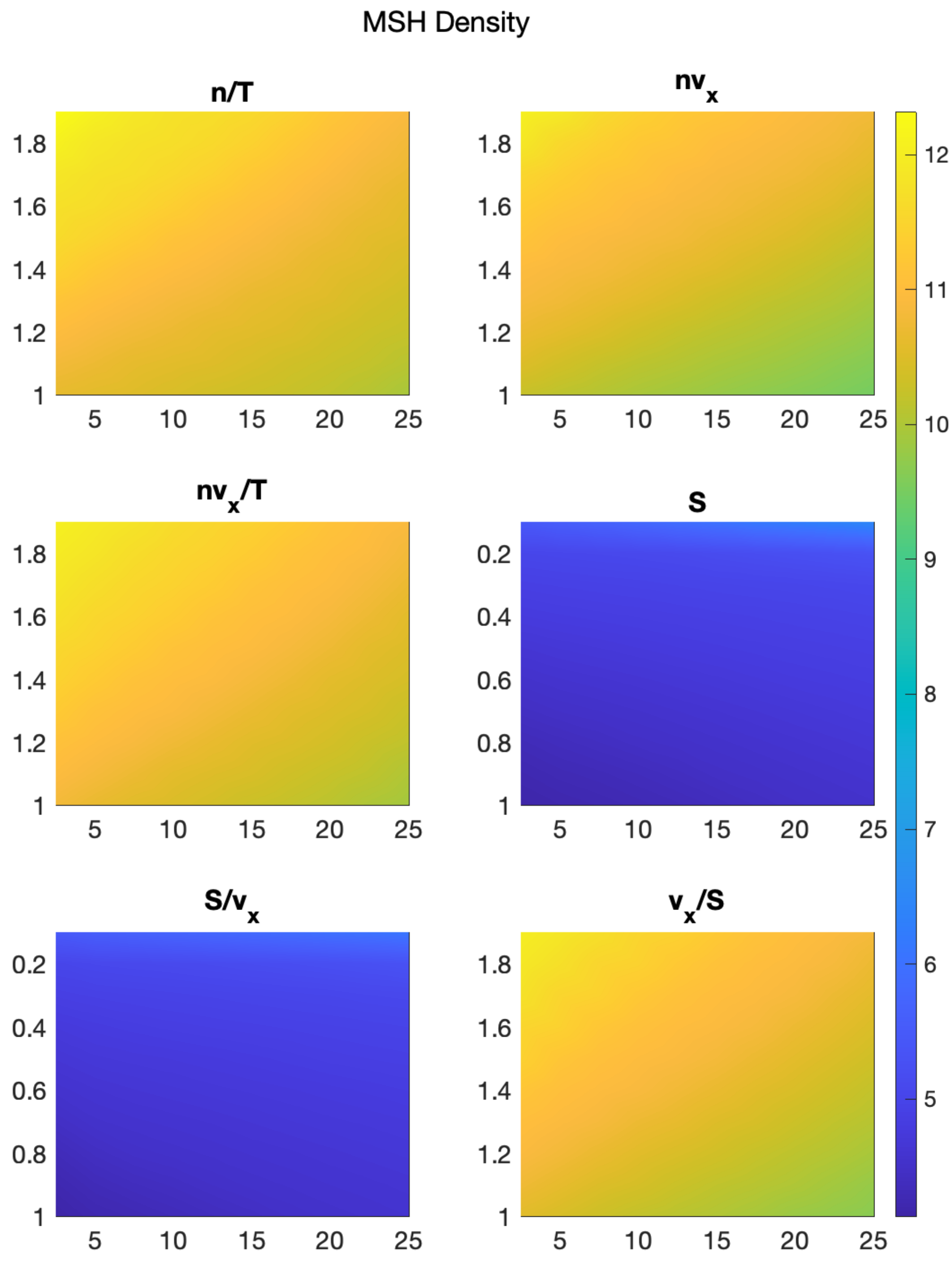

Figure 1. Magnetosheath density for all parameters and combinations of magnetopause values and cutoff values. The percent of data used to determine the magnetopause value increases from right to left on the X-axis. Cutoff values become more restrictive from bottom to top along the Y-axis. The parameters which are large in the sheath (n/T, nv_{tail}, nv_{tail}/T, and v_{tail}/S) return more reasonable values than the parameters which are small in the sheath (S and S/v_{tail}).

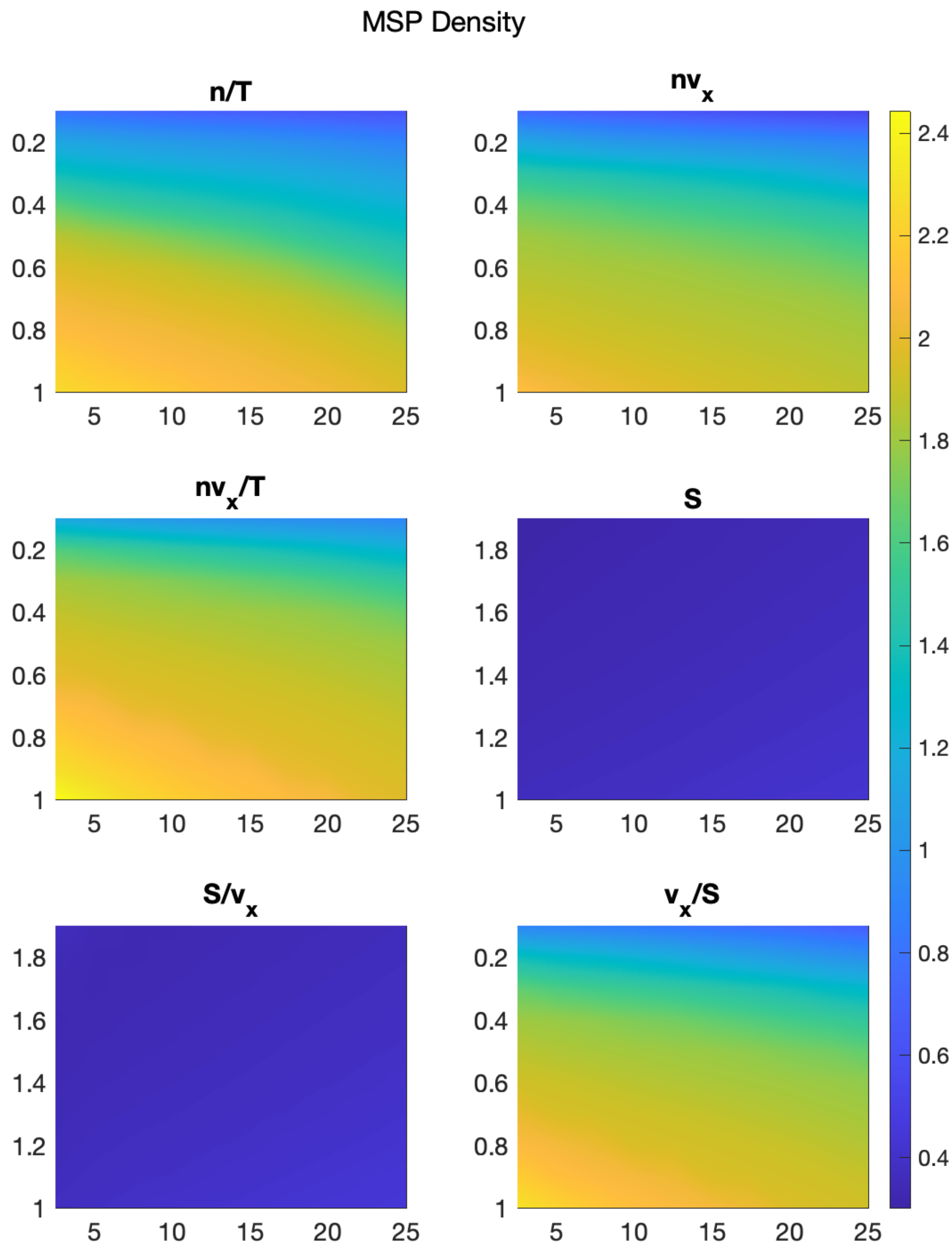

Figure 2. Magnetosphere density for all parameters and combinations of magnetopause values and cutoff values. The percent of data used to determine the magnetopause value increases from right to left on the X-axis. Cutoff values become more restrictive from bottom to top along the Y-axis. The parameters which are large in the sheath (S and S/v_{tail}) return more reasonable values than the parameters which are small in the sheath (n/T, nv_{tail}, nv_{tail}/T, and v_{tail}/S).

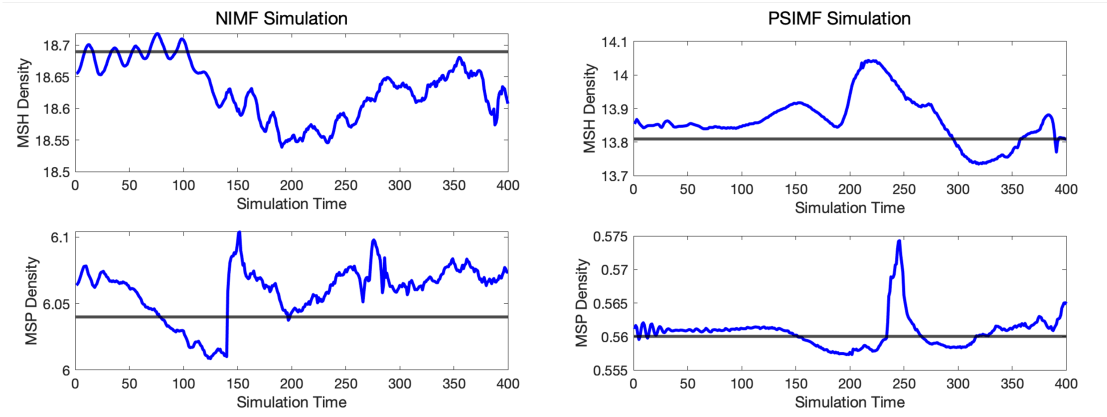

Figure 3. Magnetosheath (top row) and magnetosphere (bottom row) density as determined using our automated region sorting method for the NIMF (left) and PSIMF (right) simulations are plotted as a function of simulation time in blue. For the duration of both simulations, these values match well with the known initial value in each region, shown in back.

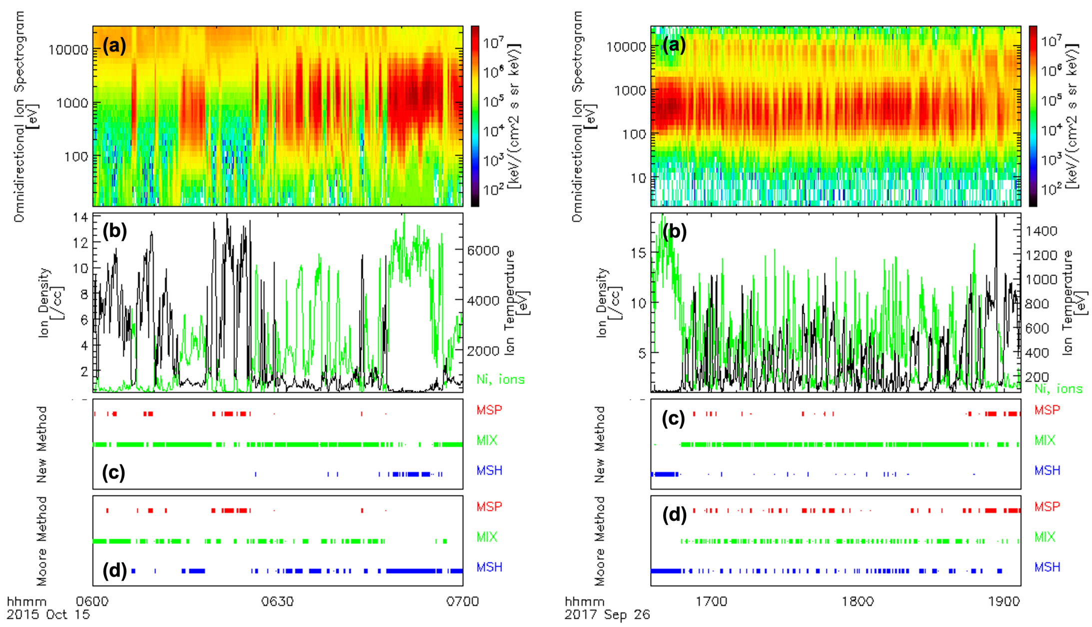

Figure 4. Omnidirectional ion energy (top), ion density and temperature (upper middle), regions as determined using the method developed in this study (lower middle), and regions as determined using methods presented in *Moore et al.* [2017] (bottom). The new region sorting method places more plasma in the mixed regions than the Moore method, but the results are comparable.

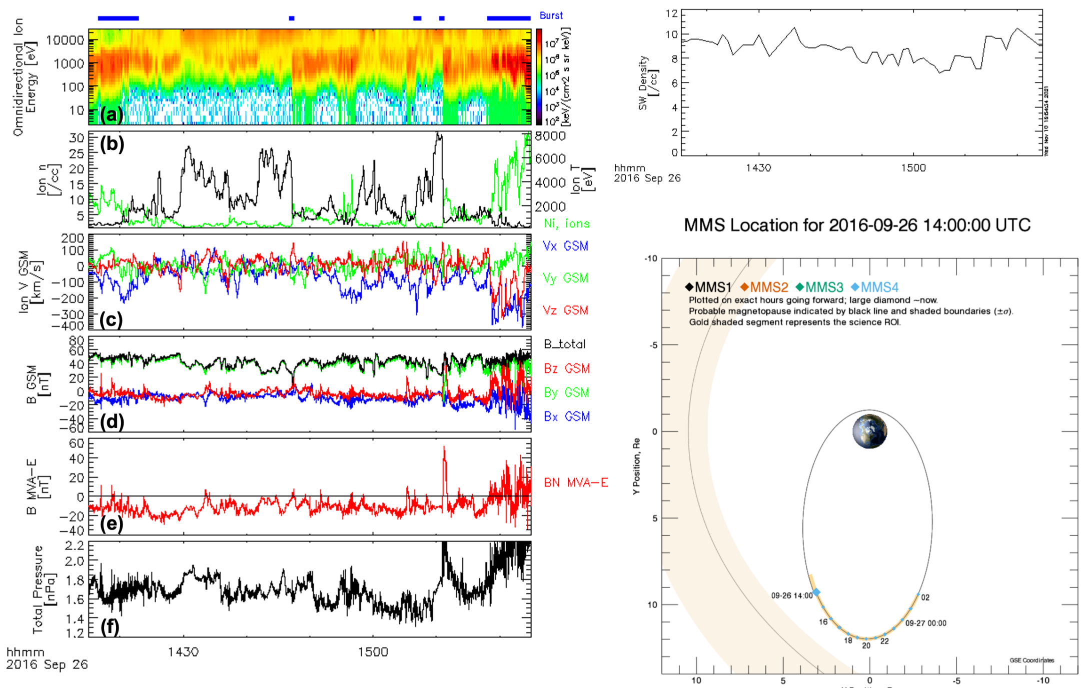

Figure 5. MMS observations of the KHI event on 26 September 2016. Solar wind density was high, between 8 and 10 /cc, pushing the magnetopause boundary further in than the approximation shown. MMS skimmed the magnetopause boundary, primarily on the magnetospheric side, with a brief excursion to the pure magnetosheath at the end of the inteval.

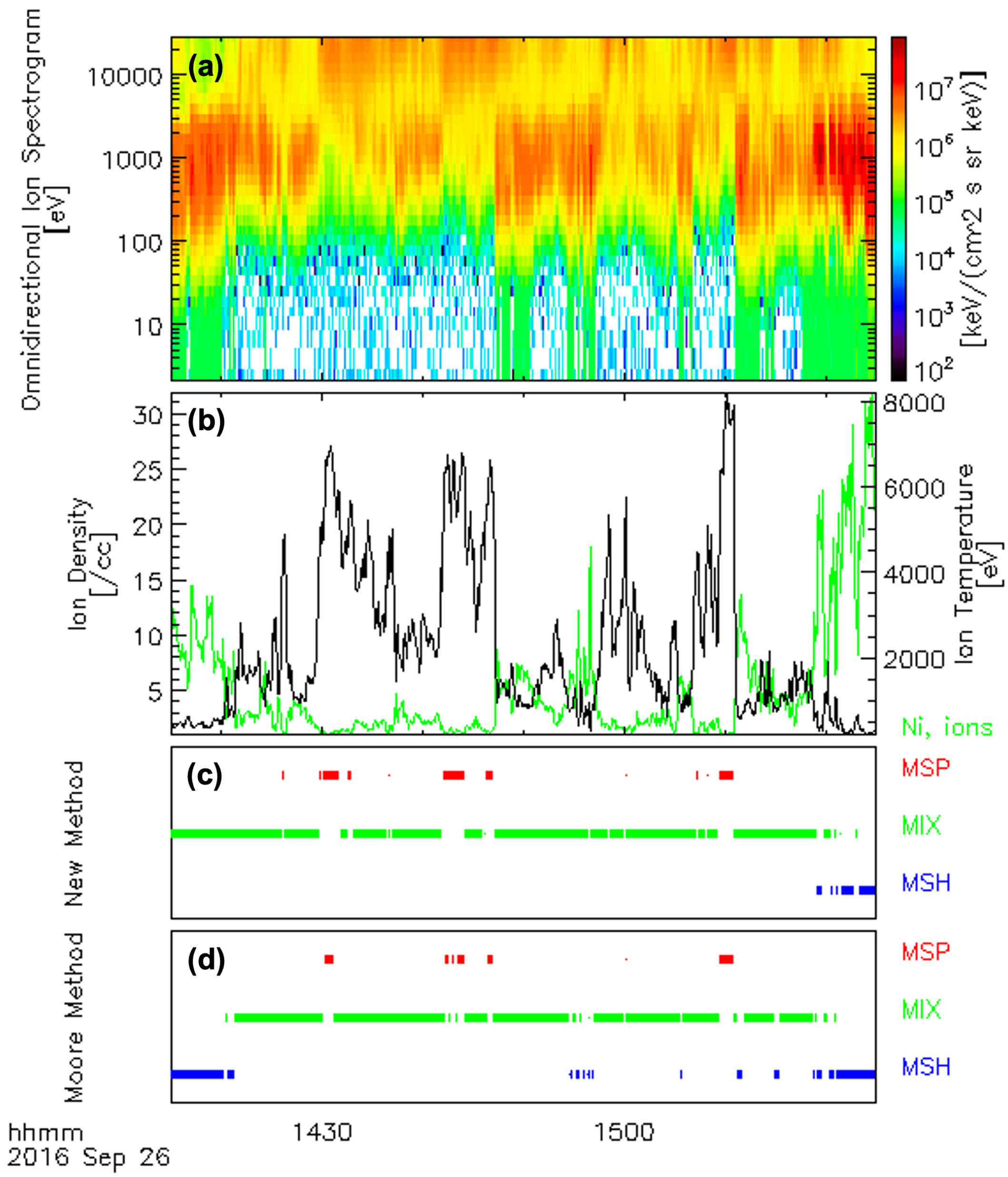

Figure 6. MMS observations of the KHI event on 26 September 2016 and the regions sorted using the new method presented in this paper and *Moore et al.* [2017]. SW density and MHD shock physics dictate a sheath density of $\approx$ 30 /cc, as is observed at the end of the interval. The new region sorting method corresponds well with this expectation, but the Moore method also identifies an earlier timespan with about half the expected sheath density. The new method is better at isolate only the pure sheath and sphere regions, resulting in more plasma being classified as "mixed."

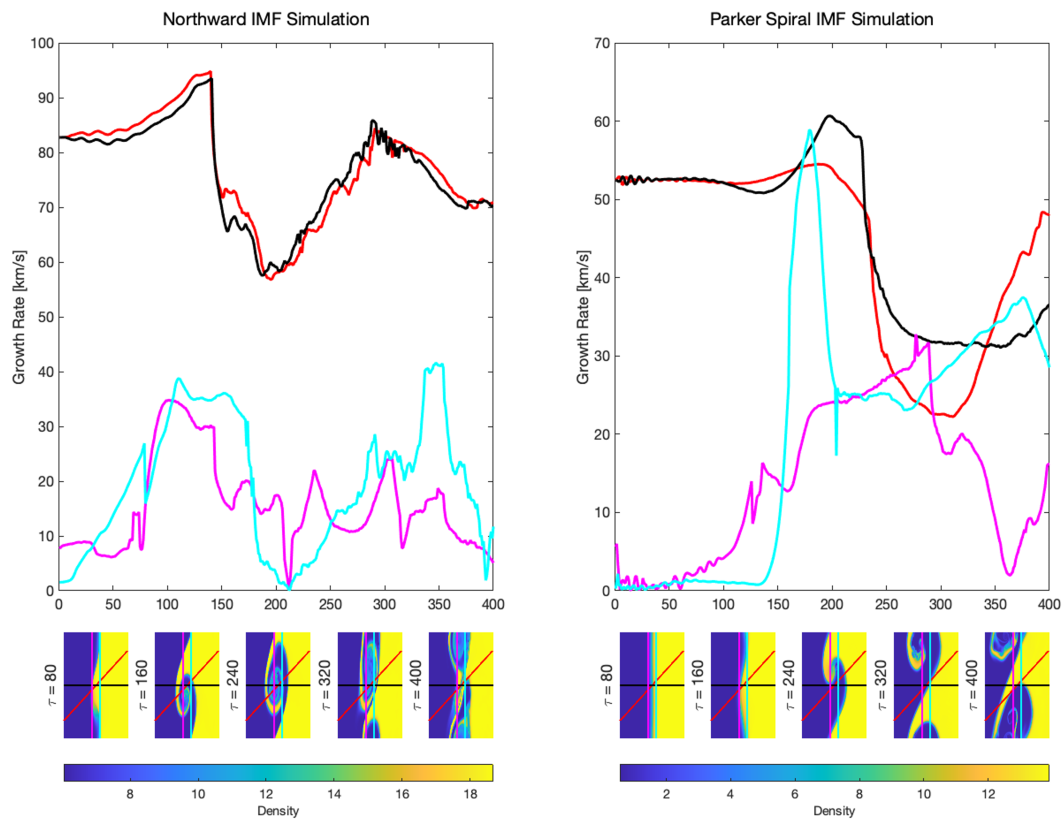

Figure 7. Cut geometry can have a significant effect on the growth rate. Cuts which spend nearly equal time on both sides of the boundary tend to have larger growth rates than cuts which merely skim the instability, spending significantly more time in one region than the other. For both the NIMF (left) and PSIMF (right) simulation, growth rates are calculated at each time step for the four cuts shown in the bottom panels. Colors in the growth rate plot correspond to the color of the cut shown in the simulation space.