Large amplitude electrostatic proton plasma frequency waves in the magnetospheric separatrix and outflow regions during magnetic reconnection

K. Steinvall[1,2], Yu. V. Khotyaintsev[1], D. B. Graham[1], A. Vaivads[3], M. André[1], C. T. Russell[4]

[1]Swedish Institute of Space Physics, Uppsala, Sweden
[2]Space and Plasma Physics, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[3]Division of Space and Plasma Physics, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden
[4]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA, USA

Key Points:

- Large amplitude electrostatic waves are found in the magnetospheric separatrix region
- The waves are driven by an ion acoustic instability due to the presence of cold ions
- The ion acoustic waves may heat cold magnetospheric ions and dissipate parallel currents

Corresponding author: Konrad Steinvall, konrad.steinvall@irfu.se

Abstract

We report Magnetospheric Multiscale observations of large amplitude, parallel, electrostatic, proton plasma frequency waves on the magnetospheric side of the reconnecting magnetopause. The waves are often found in the magnetospheric separatrix region and in the outflow close to the magnetospheric ion edge. Statistical results from five months of data show that these waves are closely tied to the presence of cold (typically tens of eV) ions, found for 91% of waves in the separatrix region, and that plasma properties are consistent with ion acoustic wavegrowth. We analyze one wave event in detail, concluding that the wave is ion acoustic. We provide a simple explanation for the mechanisms leading to the development of the ion acoustic instability. These waves can be important for separatrix dynamics, by heating the cold ion component and providing a mechanism to damp the kinetic Alfvén waves propagating away from the reconnection site.

Plain Language Summary

The magnetopause is the magnetic boundary shielding the Earth's magnetosphere from the shocked solar wind plasma of the magnetosheath. Magnetic reconnection, a fundamental plasma process, locally breaks this boundary, leading to energization and mixing of magnetospheric and solar wind plasma. During the reconnection process, the plasma is highly unstable and many different kinds of waves appear. In this Letter we investigate the large amplitude electrostatic waves with frequencies around the proton plasma frequency which are often found in spacecraft observations of magnetic reconnection. We find that the waves can appear when cold (tens of eV) magnetospheric ions are present at the magnetopause, and are generated by an ion acoustic instability between the cold ions and the fast flowing electrons often observed during magnetic reconnection. The waves might heat the cold ions and couple to the large scales by dissipating parallel currents.

1 Introduction

The magnetopause is the boundary between the Earth's magnetosphere and the shocked solar wind plasma of the magnetosheath. Plasma waves are often found in the vicinity of the magnetopause (e.g. Fairfield, 1976; Gurnett et al., 1979; LaBelle et al., 1987; Tang et al., 2019), and appear to be intimately connected to magnetic reconnection (Khotyaintsev et al., 2019), a fundamental plasma process where changes in magnetic field topology result in plasma mixing and explosive energy conversion from mag-

netic energy to kinetic and thermal energy (e.g. Birn & Priest, 2007). Though magnetic reconnection is a well studied subject some fundamental aspects are still not understood, and studying wave dynamics might be crucial to fully understand the cause and effects of magnetic reconnection (Khotyaintsev et al., 2019; Wilder et al., 2019).

The separatrix region is defined as the kinetic boundary separating the inflow and outflow regions of magnetic reconnection (Lindstedt et al., 2009). As such, this region is characterized by recently reconnected magnetic field lines, complex distribution functions, and large parallel currents (Khotyaintsev et al., 2006). At the reconnecting dayside magnetopause, which is the focus of this Letter, the complexity is even greater due to the variable plasma composition, where the typically tenuous magnetosphere, which can contain both hot ($\sim$ 1 keV) and cold ($\sim$ 10 eV) plasma (André & Cully, 2012; Lee & Angelopoulos, 2014), is mixing with the dense $\sim$ 100 eV magnetosheath plasma. The end result is that the plasma is unstable to the generation of various waves, which are observed both in simulations and spacecraft data. Examples include beam and loss cone driven whistler waves (Graham, Vaivads, et al., 2016; Uchino et al., 2017), electron holes (Farrell et al., 2002; Graham et al., 2015), Langmuir waves (Vaivads et al., 2004; Wilder et al., 2016; Zhou et al., 2016), ion acoustic waves (Uchino et al., 2017), and electron acoustic waves (Ergun, Holmes, et al., 2016).

Early observations from the Magnetospheric Multiscale (MMS) mission (Burch et al., 2016) reported the presence of electrostatic waves with large amplitude parallel (to the magnetic field) electric fields ($E_{\parallel}$) in the magnetospheric separatrix region close to the electron diffusion region (Ergun, Holmes, et al., 2016). The waves could be found with frequencies both below and significantly above the ion plasma frequency f_{pi}. By comparing observations with simulations, the high frequency waves were argued to be consistent with electron acoustic waves driven by the interaction of a cold magnetospheric electron beam with a warmer electron beam of magnetosheath origin, while the mechanism behind the lower frequency waves observed in the MMS data could not be determined unambiguously. Uchino et al. (2017) used Time History of Events and Macroscale Interactions during Substorms (THEMIS) (Angelopoulos, 2008) data to investigate waves found in the innermost open boundary layer during dayside magnetopause reconnection. The authors presented one wave event similar to the low frequency waves found by Ergun, Holmes, et al. (2016) and concluded that the wave was generated by an ion acoustic in-

stability. However, to the best of our knowledge, no statistical study of these low frequency waves has yet been published.

In this Letter we use data from MMS to study the large amplitude, electrostatic, ion plasma frequency waves observed in and around the magnetospheric separatrix region during ongoing magnetic reconnection, looking to answer the questions: What is the instability generating these waves? What effect do these wave have on the separatrix plasma dynamics? We present and analyze one wave event in Section 2 where we use wave properties and dispersion analysis to conclude that the wave is driven by an ion acoustic instability between cold magnetospheric ions and electrons carrying the strong parallel currents often found in the separatrix region (Khotyaintsev et al., 2006), likely associated with kinetic Alfvén waves propagating away from the reconnection site (Dai et al., 2017; Dai, 2018; Huang et al., 2018). The wave amplitude is large enough to trap parts of the cold ion distribution, and the instability implies the dissipation of parallel currents. We then investigate the waves from a statistical perspective in Section 3 and find that the waves have properties and are found in plasmas which are qualitatively consistent with ion acoustic wavegrowth. These ion acoustic waves can be important for separatrix dynamics by providing a mechanism to dissipate the strong parallel currents present there, thereby coupling Debye scale wave activity to large scale plasma dynamics.

2 Wave observation example

In this section we start by discussing large amplitude waves observed by MMS during a crossing of the reconnecting magnetopause on the 24th of October 2015. The waves are similar to the ones reported by Ergun, Holmes, et al. (2016) in that they are electrostatic, have large $E_{\parallel}$, nonlinear waveforms, and frequencies close to f_{pi}. We then analyze one wave in detail, placing it in the context of magnetic reconnection, and determine its generation mechanism and effect on the plasma dynamics.

We present an overview of this magnetopause crossing in Fig. 1. This event has previously been analyzed in the context of reconnection in the presence of cold ions by Toledo-Redondo et al. (2017). Initially, MMS is located in the magnetosphere. At around 07:03:48 UT, highlighted by the red shaded area, MMS crosses the electron edge (Gosling et al., 1990; Lindstedt et al., 2009) as seen by the sudden appearance of low energy magnetosheath electrons and reduction of high energy magnetospheric electrons (Fig. 1b). Shortly af-

ter, around 07:03:51, MMS crosses the ion edge (green shaded region) where the first ions of magnetosheath origin are observed (Fig. 1c) and enters the outflow region while remaining close to the ion edge. During this time, strong parallel currents are observed $j_{\parallel} \approx 500$ nA/m^2 (Fig. 1f), together with waves (Fig. 1g) with amplitudes reaching up to 200 mV/m. There are no corresponding magnetic field fluctuations (not shown), meaning the waves are electrostatic. The frequencies of the waves are slightly below the ion plasma frequency f_{pi} (Fig. 1h), which indicates that ion dynamics are likely to play a role in the generation mechanism.

In order to investigate the generation mechanism and understand how these waves interact with the plasma, we zoom in to the large amplitude waves marked by the dashed vertical line in Fig. 1, and plot the 1 and 2-dimensional velocity distribution functions (VDFs) for ions (Figs. 2a,f-h) and electrons (Figs. 2b,i-k). The VDFs have been integrated over the entire velocity range of FPI. In the case of ions, two components are clearly visible. The cold component with $v_{\parallel} \approx -20$ km/s corresponds to the cold magnetospheric ions seen in Fig. 1c whereas the hotter component with $v_{\parallel} \approx -500$ km/s and the characteristic D-shape in Fig. 2f corresponds to transmitted magnetosheath ions moving along reconnected field lines south of the x-line (Cowley, 2013), consistent with the southward ion outflow in Fig. 1e. The gradual disappearance of low speed magnetosheath ions starting after ∼05:04:01 in Fig. 2a indicates that the spacecraft is moving closer to the magnetospheric ion edge. The electron VDF primarily contains magnetosheath electrons, and is slightly shifted in the $-v_{\parallel}$ direction, corresponding to the positive $j_{\parallel}$ in Fig. 1f. The different plasma components and their distinct parallel bulk velocities constitute a system where there are several positive slopes in the VDFs, and Landau resonance could lead to spontaneous growth of different waves.

Before moving on to dispersion analysis, we briefly discuss the electrostatic properties of the wave shown in Figs. 2c-e. In particular we want to determine the wave's phase velocity $\boldsymbol{v}_\phi = v_\phi \hat{\boldsymbol{k}}$ for two reasons. The first reason is that v_ϕ depends on the generation mechanism, and thus serves as a diagnostic to determine what instability generated the wave. The second reason is that once v_ϕ is known, the electrostatic potential can be calculated as $\Phi = \int \delta E v_\phi dt$. In this case we are particularly interested in Φ since the waveform of δE is non-linear, raising two questions which require Φ to answer: Is there a net potential change $\Delta\Phi$ associated with the waves? Is the non-linear waveform due to electron or ion trapping? Since the wave is electrostatic, $\boldsymbol{k} \times \delta\mathbf{E} = 0$, and we can

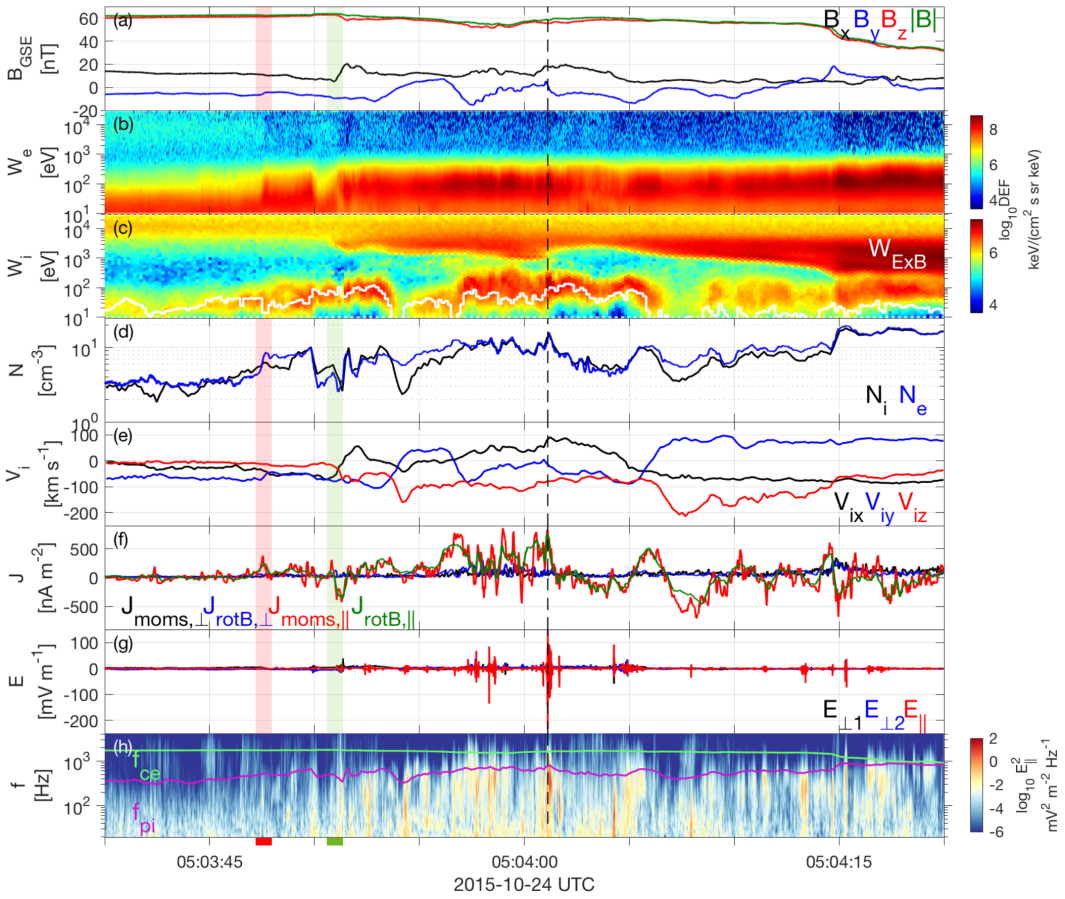

Figure 1. Overview of wave observation from MMS3. (a) Magnetic field data from the Fluxgate magnetometer (Russell et al., 2016) in the geocentric solar ecliptic (GSE) coordinate system. (b,c) Differential energy flux (DEF) from Fast Plasma Investigation (FPI) (Pollock et al., 2016) for electrons and ions. The white line in the ion spectrum is the energy corresponding to the $\mathbf{E} \times \mathbf{B}$ drift. (d) Ion and electron density from FPI. The observed deviation from quasi-neutrality is artificial, mainly due to cold ions with energies below FPI's energy threshold. (e) Ion velocity from FPI in GSE. (f) Currents in magnetic field aligned coordinates calculated using $\nabla \times \mathbf{B}$ and FPI plasma moments. (e) Electric field from the Electric field Double Probes (EDP) (Lindqvist et al., 2016; Ergun, Tucker, et al., 2016) in field aligned coordinates. (h) Spectral power density of $E_{\parallel}$ where the green and purple lines correspond to the electron cyclotron and the ion plasma frequencies, respectively. The verical red and green bars show roughly the location of the electron and ion edges.

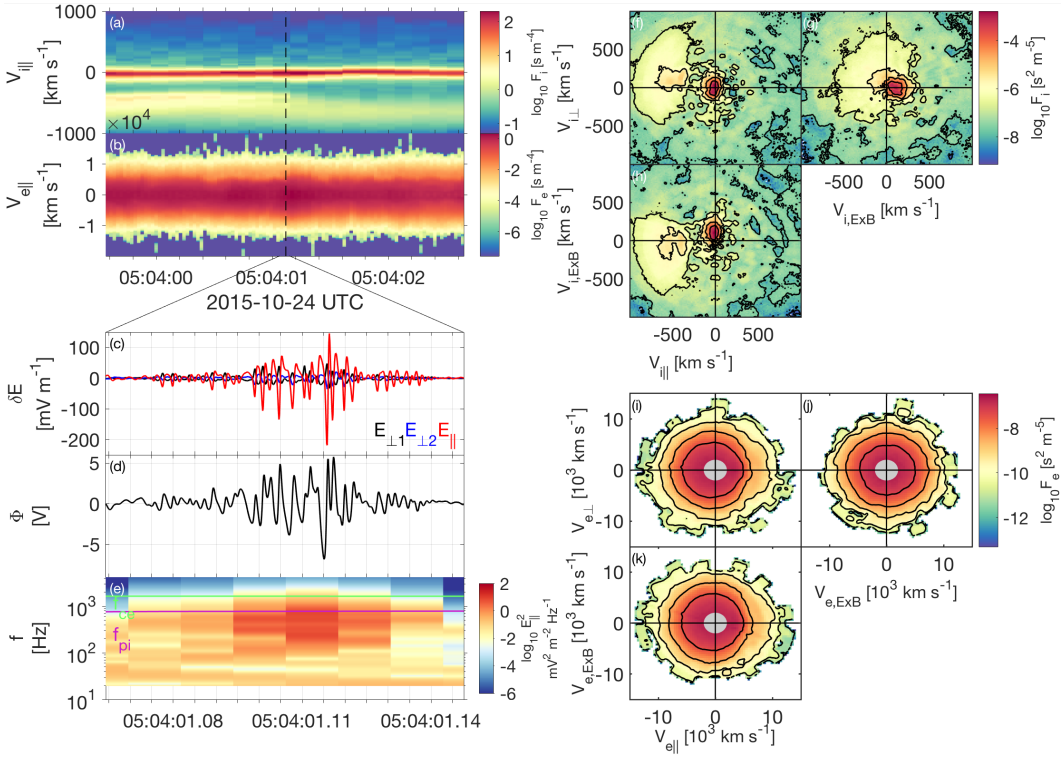

Figure 2. Particle distribution functions and wave properties observed by MMS3. (a,b) 1-dimensional ion and electron velocity distribution functions (VDFs). (c) Waveform of **E** high-pass filtered at 100 Hz. (d) Electrostatic potential of the wave. (e) Spectral power density of $E_{\parallel}$. (f-h) 2-dimensional VDFs of ions sampled at 05:04:01.078. (i-k) 2-dimensional VDFs of electrons sampled at 05:04:01.108, marked by the vertical dashed line in panels (a) and (b). The central area of the 2-dimensional electron VDFs corresponding to energies not resolved by FPI are blocked out.

determine $\hat{\boldsymbol{k}}$ using maximum variance analysis of $\delta\mathbf{E}$. We find that $\pm\hat{\boldsymbol{k}}$ is field aligned within the uncertainty. We determine v_ϕ and the sign of $\hat{\boldsymbol{k}}$ using cross-spectral analysis of the electric field between the axial EDP probes (Graham, Khotyaintsev, et al., 2016) and obtain $v_\phi \approx -100$ km/s. We emphasize that this speed estimate has a large uncertainty and should be interpreted only as a rough estimate. The sign, implying anti-parallel propagation, is determined with much greater confidence. The slow v_ϕ indicates that the instability generating this wave is most likely an interaction between either the two ion components, or the cold ions and the electrons. We calculate and plot Φ in Fig. 2d. Note that when calculating Φ, $\delta E_\parallel$ is high-pass filtered at 100 Hz while Φ is unfiltered, and any $\Delta\Phi$ related to the waves would appear in Fig. 2d. We conclude that there is no significant potential change across the waves, $\Delta\Phi = 0$, and that the peak value of around $\Phi = 5$V corresponds to an ion trapping range $v_{tr,i} = v_\phi \pm \sqrt{2e\Phi/m_i}$ of around $(-130, -70)$ km/s, and equivalently an electron trapping range of around $(-1100, 900)$ km/s in the spacecraft frame. The waves are thus capable of trapping parts of both the cold ion and electron components, which for example might lead to heating of the cold ions and local flattening of the electron VDF.

We are now in a position to set up and solve the one-dimensional electrostatic dispersion relation (Fried & Conte, 1961)

$$D(\omega, k) = 0 = 1 + \chi_{i,\mathrm{cold}} + \chi_{i,\mathrm{beam}} + \chi_{i,\mathrm{bg}} + \chi_e, \tag{1}$$

where $\chi_s(\omega, k)$ is the susceptibility of plasma component s. In addition to the plasma components we discussed previously, we include a hot background ion component $\chi_{i,\mathrm{bg}}$, corresponding to the hot magnetospheric ions in Fig. 1c. In Fig. 3a we show the observed reduced 1-dimensional VDFs for ions and electrons as the gray circles and dots respectively, and the Maxwellian fits by the solid lines. For the fits, we used the densities (units of cm^{-3}) $n_{i,\mathrm{cold}} = 11.076$, $n_{i,\mathrm{beam}} = 0.48$, $n_{i,\mathrm{bg}} = 0.08$, $n_e = 11.636$, thermal speeds (in km/s): $v_{th;i,\mathrm{beam}} = 180$, $v_{th;i,\mathrm{cold}} = 35$, $v_{th;i,\mathrm{bg}} = 900$, $v_{th;e} = 4160$, and parallel drift speeds (in km/s): $v_{d;i,\mathrm{cold}} = 20$, $v_{d;i,\mathrm{beam}} = -580$, $v_{d;i,\mathrm{bg}} = -330$, $v_{d;e} = -410$. The corresponding temperature ratio between the cold ions and the electrons is $T_{i,\mathrm{cold}}/T_e \approx 0.13$. Solving Eq. (1) numerically we find positive wavegrowth for the solution in Fig. 3b. The black(red) line corresponds to the real(imaginary) frequency $\omega(\gamma)$, and the circles mark the point of largest γ. The negative ω implies propagating in the anti-parallel direction, as was found in observations, and the phase speed at maximum growth marked by the dashed line in Fig. 3a is $v_{\max(\gamma)} = -102$ km/s, close to the observed v_ϕ. $v_{\max(\gamma)}$

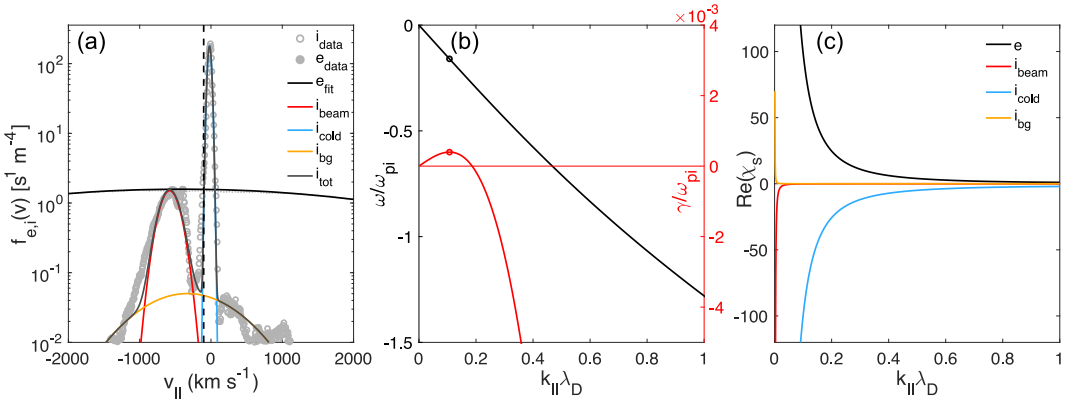

Figure 3. Dispersion analysis. (a) Observed and fitted reduced VDFs. The dashed line corresponds to the phase speed of the fastest growing wave. (b) Dispersion relation. The circles mark the points corresponding to the highest growth rate, and λ_D is the Debye length. (c) Real part of the susceptibilities of the plasma components for the solution in (b).

coincides with a positive slope of the drifting electron VDF, thus driving the wave via Landau resonance. In Fig. 3c, we plot the real part of the different χ_s and confirm that the wave is due to the electrons and cold ions. The imaginary parts of χ_s (not shown) show similar results. The ion-ion instability is stabilized by the electrons in this case. We thus conclude that an ion acoustic instability is the source behind the observed waves.

In summary, for this event we find $E_{||}$ waves with frequency close to f_{pi} in the reconnection outflow, near the magnetospheric ion edge. The analyzed wave is propagating slowly ($v_\phi \approx 100$ km/s) in the anti-parallel direction, carries no $\Delta\Phi$, and can trap parts of the electron and cold ion distributions. Dispersion analysis shows that the plasma is unstable to an ion acoustic instability between the dominating cold ions and the drifting electrons.

3 Statistics

Armed with the knowledge from the previous section, we would like to see if the ion acoustic instability can explain the wave observations also on a statistical level. To investigate this, we scan through 5 months of MMS data when the four spacecraft are close to the dayside magnetopause (September through November 2015, and October through November 2016), searching for magnetopause crossings where waves with $E_{||} > 20$ mV/m

and maximum power within the frequency band $[0.5, 2]f_{pi}$ are observed on the magnetospheric side. We find that when the waves are observed in the separatrix region between the ion and electron edges, cold ions are present for 91% (233/255) of the events. The waves where no cold ions are present tend to be either solitary waves or have a very small number of wave periods, and we exclude these from the following analysis. The wavevectors are typically close to field aligned, and the median wave normal angle is 16°. We are unfortunately not able to determine v_ϕ on a statistical level. This is primarily because B_z is generally the dominant magnetic field component, and the axial EDP probes are not ideal for interferometry due to their short separation and floating potential difference compared to the spin-plane probes used to calculate the spacecraft potential (Graham et al., 2015). However, when we are able to roughly estimate v_ϕ using either the spin-plane or axial probes, we typically find v_ϕ to be small $\sim$ 100 km/s, similar to the example in Fig. 2. Since cold ions are present during most wave observations they are most likely essential for the generation mechanism, motivating a statistical investigation into the plasma composition. In order to easily compute the moments of the cold ion component we take the wave events where the energy, $W_{E\times B}$, corresponding to the $\mathbf{E}\times\mathbf{B}$ drift is close to the differential energy flux peak of the cold ions. We then compute the cold ion moments by integrating the distribution function from the lowest energy to roughly $2.1W_{E\times B}$ to ensure that we capture the whole cold ion distribution and ignore any hot plasma. We only do this calculation when there is a clear energy separation between different ion components, resulting in 95 events gathered from 21 different orbits. In Fig. 4a we present the results. There is a clear trend that these waves are primarily found when the cold ions dominate $n_{i,\mathrm{cold}}/n_i \gtrsim 0.6$, the cold ion temperature is much smaller than the electron temperature $T_{i,\mathrm{cold}}/T_e \lesssim 0.4$, and when there is a significant parallel drift between the cold ions and electrons. These features are all consistent with the ion acoustic instability which, in the simple model of a two component plasma, requires $T_i \ll T_e$ to avoid Landau damping, and energy for wavegrowth is provided by the drifting electrons (Baumjohann & Treumann, 1996).

Here we limited ourselves to waves found in the magnetospheric separatrix region, excluding waves such as those in Fig. 1, found close to the ion edge in the outflow. This is because the inclusion of magnetosheath ions often makes it difficult to isolate the cold ion component (Li et al., 2017). However, we want to make it clear that the waves are

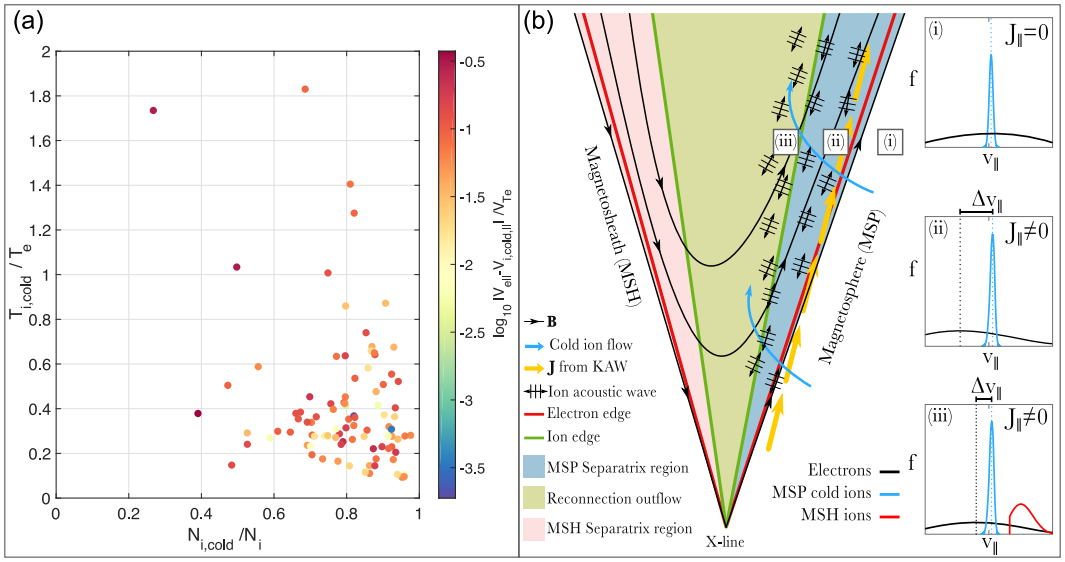

Figure 4. (a) Cold plasma properties for waves observed in the magnetospheric separatrix region. (b) Illustration showing where in the reconnection picture the ion acoustic waves are observed and the process leading to their formation. The boxes (i), (ii), and (iii) show where the distribution functions in the right column are observed. The separatrices are the outermost drawn field lines.

also often found in the parts of the outflow where cold magnetospheric ions are still the dominant ion component, that is, close to the magnetospheric ion edge.

4 Discussion

With this Letter we aimed at answering two main questions regarding the large amplitude electrostatic waves with frequencies near f_{pi} which MMS often observes at the reconnecting magnetopause. What is their generation mechanism? How do they affect the plasma?

Regarding the generation mechanism, there are three main pieces of evidence that, when combined, strongly points to the ion acoustic instability as the culprit. The first piece is the fact that the waves seem to be strongly connected to the ion scales, having frequencies around f_{pi}, and phase speeds in the ion range rather than electron range. This suggests that an electron-electron instability is unlikely to be the source, and that ions are important. The second piece is the fact that 91% of the waves are found when cold ions are dominating and have temperatures well below the electron temperature, giving

a strong indication that the cold plasma component is essential. The third piece is the fact that for the example event in Fig. 2, Eq. (1) predicts a growing ion acoustic wave. It is important to note that due to the dynamic nature of the separatrix region, the electron flow is highly variable (as seen by the currents in Fig. 1f), and waves that are growing in one instance of time may be stable or even damped in the next, also consistent with the localized, patchy, waveforms observed. This is reflected in the large variation of speeds shown in Fig. 4a. One result of this is that waves are frequently observed in plasma where the waves should be either marginally stable or slightly damped according to the numerical dispersion analysis. These electron variations, and the fact that the VDFs are not Maxwellian (contrary to the Maxwellianity assumption used in the analytical model) but often much more complex, makes a direct comparison between theory and observation difficult and not conclusive. However, these observations combined lets us conclude that the ion acoustic instability is very likely the source of these waves.

To answer the second question, regarding the effect of the waves, we need to take a step back and put the information into the context of magnetic reconnection. For the ion acoustic instability, the source of the free energy is the fast electron flow, which corresponds to the large $j_{\parallel}$ observed in the separatrix region. The underlying mechanism leading to the formation of $j_{\parallel}$ is the dynamics of a kinetic Alfvén wave (KAW) propagating away from the x-line (Vaivads et al., 2010; Huang et al., 2018; Dai, 2018). For the event in Fig. 1 there is some evidence of KAW-dynamics. Starting roughly from the ion edge crossing, there is a clear correlation between v_{ix} and B_x, as well as between v_{iy} and B_y. At around 03:55 we see a large increase of $j_{\parallel}$ which is associated with an 18.5 nT increase of B_y and a 12.5 mV/m decrease of E_x. The field ratio E_x/B_y corresponds roughly to 1.2 times the Alfvén speed, and the field directions correspond to Poynting flux directed away from the x-line. These features are consistent with KAWs propagating away from the x-line (Shay et al., 2011; Huang et al., 2018). Analysing the B_x increase at around 03:50 yields similar conclusions. By reducing $j_{\parallel}$ the ion acoustic instability thus effectively damps the KAWs, thereby providing a coupling between Debye and larger scale physics.

Observations of ion acoustic waves during ongoing magnetic reconnection has previously been reported in a study by Uchino et al. (2017), looking to answer the question of which waves are present in the innermost open boundary layer. The authors could not directly measure the cold plasma properties due to instrument limitations, and had to

instead rely on various assumptions and indirect measurements. Here we confirm with directly measured cold plasma properties that the ion acoustic instability can lead to wave generation during dayside magnetopause reconnection. Furthermore our statistical results show that the ion acoustic instability is likely to be, also in general, responsible for the large amplitude, ion plasma frequency waves often observed by MMS in the magnetospheric separatrix region.

Finally, we present a schematic picture of the separatrix region (similar to Lindstedt et al. (2009)) in Fig. 4b highlighting the kinetic boundaries, to illustrate the generation of ion acoustic waves during reconnection when cold ions ($T_i \ll T_e$) are present in the magnetosphere. When reconnection is ongoing the cold plasma in the magnetosphere (i) is convecting (blue arrows) toward the magnetopause. Here, the lack of free energy prevents wavegrowth. As the plasma convects further, it passes the KAW propagating in the direction of the Alfvén edge out from the ion diffusion region (Vaivads et al., 2010), and its associated current (orange arrows) which has a large field-aligned component. This $j_\parallel$ corresponds to a $v_\parallel$ shift between electrons and the cold ions as seen in (ii). There is thus a positive slope in the electron distribution function, enabling the ion acoustic wave to grow via Landau resonance. Throughout the separatrix region we find both parallel and anti-parallel currents as shown in the example of Fig. 1, intermittently enabling wavegrowth. Field aligned currents are also present in the outflow region (iii), again resulting in Landau resonant growth of ion acoustic waves. However, as we move deeper into the outflow, the denser and hotter magnetosheath ions starts to dominate, leading to Landau damping. This explains why we predominantly see these waves on the magnetospheric side. The end result of this picture is that ion acoustic waves are forming throughout the magnetospheric separatrix region, dissipating parallel currents, and damping KAWs.

5 Conclusions

We investigate the electrostatic, proton plasma frequency waves with $E_\parallel$ amplitudes reaching up to hundreds of mV/m that are frequently found on the magnetospheric side of the magnetopause, often in relation to reconnection events. From dispersion analysis we conclude that the waves are due to an ion acoustic instability between the electrons and cold magnetospheric ions in the separatrix region. We support this conclusion statistically by analyzing waves from 5 months of MMS data, finding 91% of the waves

to be observed when cold ions are present. Cold ions, typically with thermal energies in the range 10-100 eV dominate the density $n_{i,\mathrm{cold}}/n_i > 0.6$, and have temperatures lower than the electrons, typically below 0.4 T_e. This temperature ratio is favourable for ion acoustic waves. Energy for wavegrowth is provided by significant parallel currents.

We conclude that these waves are ion acoustic waves formed when cold magnetospheric ions are convected into the separatrix region, where parallel currents drive the plasma unstable an ion acoustic instability. These ion acoustic waves can be important for separatrix dynamics on both small and large scales. On small scale the waves are capable of trapping cold ions, possibly leading to heating, and on a larger scale they are dissipating parallel currents associated with kinetic Alfvén waves propagating away from the ion diffusion region.

Acknowledgments

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