Origin of whistler waves during asymmetric guide field reconnection

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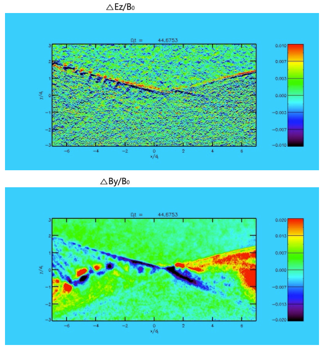
Background and Motivation

- We investigate asymmetric guide field reconnection to understand kinetic physics of electrons in the Earth's magnetopause, by means of 2D particle-in-cell (PIC) simulation.
- Velocity distribution functions (VDF) in the parallel and perpendicular planes of the local magnetic field indicate kinetics of plasma particles including various properties of electron beams (gyrotropy/nongyrotropy, polarity, intensity, etc.).
- MMS observations of the Earth's magnetopause (Le Contel et al. 2016, Wilder et al. 2016, Cao et al. 2017, Zhou et al. 2018, Burch et al. 2018, Yoo et al. 2019) show that there are whistler waves in the electron/ion diffusion region and near/on the separatrices during asymmetric magnetic reconnection.
- PIC simulations (Fujimoto and Sydora, 2008, Chen et al. 2015) for symmetric reconnection show whistler instabilities due to both temperature anisotropy and electron beams.

Where are whistler waves excited in asymmetric reconnection?

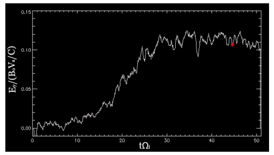
What physics (nongyrotropy, anisotropy, electron beams) is important in whistler waves in asymmetric reconnection?

Wave propagation on the separatrices in the magnetosphere side and the electron diffusion region (EDR)



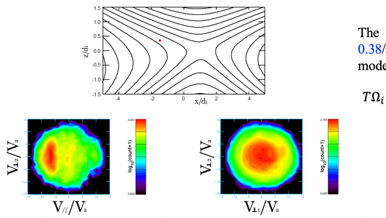
Electromagnetic wave propagation is found clearly in the separatrices at the magnetosphere side.

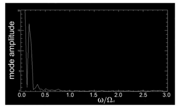
The range of wavelength is from $0.4d_i$ to $0.8d_i$. The frequency range is from 0.1 to 0.2 in the electron cyclotron frequency based on the local magnetic fields.



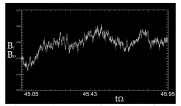
Reconnection rate

Whistler wave activity during reconnection





FFT frequency spectrum



By fluctuation as a function of time

The period of the dominant B_y wave is $0.38/\Omega_i$, which matches the FFT dominant mode frequency $0.17\Omega_e$ as

$$T\Omega_i = \frac{2\pi\Omega_i}{\omega} = \frac{2\pi\Omega_i}{0.17\Omega_{el}} \simeq 0.34$$

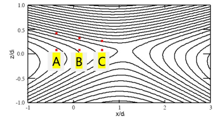
$V_{//}$ is parallel to the local magnetic field

$$V_{\perp 1} = b\times(V_e\times b)$$

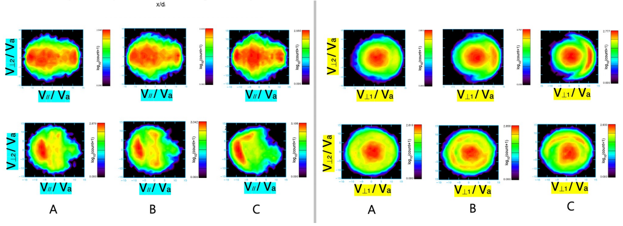
$$V_{\perp 2} = -V_e\times b$$

where V_e is the electron fluid velocity

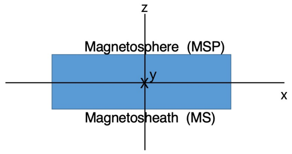
VDFs inside the EDR



The VDFs show strong electron beams (red colored area) in the negative direction of $V_{//}$ at the bottom panels. On the separatrix, the VDFs in the $(V_{\parallel},V_{\perp 2})$ plane are similar. The size of the crescent becomes smaller away from the X line ($V_{\perp 1}$, $V_{\perp 2}$ plane).

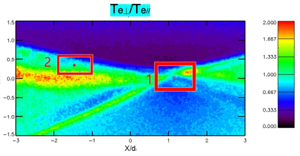


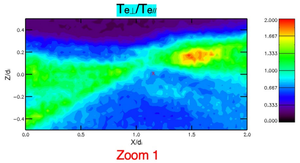
2D PIC simulation parameters



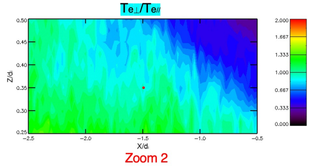
- Mass ratio ; 200
- Guide field ; $0.3B_0$
- Temperature ratio T_i/T_e ; 2
- Ratio of the plasma frequency to the electron cyclotron frequency ω_{pe}/Ω_e; 2
- Alfvén speed $V_a = C/20\sqrt{2}$
- 1 grid = $0.025\ d_i$
- Lx X Lz $=51.2d_i$ X $25.6d_i$

Temperature anisotropy during reconnection





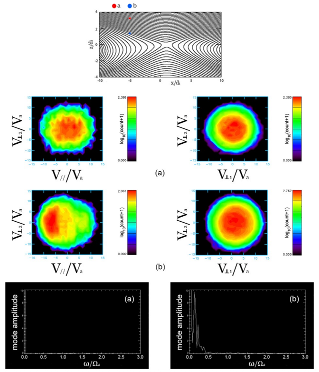
Zoom 1



Zoom 2

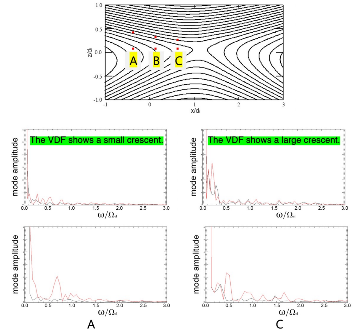
The temperature anisotropy is found in the EDR in the 2D temperature plot. The Tperp is smaller than Tpara over the separatrix in the magnetosphere side. At the red point, where we investigate the wave activity, Teperp /Tepara = 0.890.

No electron beam, no wave activity



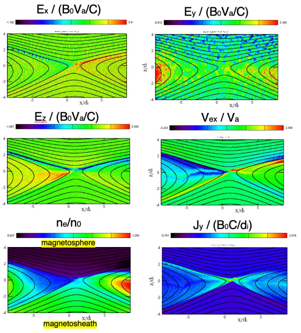
Fast Fourier transform (FFT) shows no wave excitation when there is no electron beam in the VDF at the location (a)-red point in the 2D plot. FFT in the location (b)-blue point (on the separatrix) presents large wave excitation, where there is an electron beam. The VDF in the blue point shows the electron beam with $V_{//}$=-10Va ~ -5Va.

FFTs inside the EDR



These FFT plots (B_y (red) and B_z (black)) show the wave activity is not concentrated on the separatrix near the X line. They are quite different from the case near the edge of the EDR away from the X line, where the wave activity is concentrated on the separatrix (slide # 10).

The wave activity is decreasing when the size of the crescent becomes smaller on the separatrix near the X line.



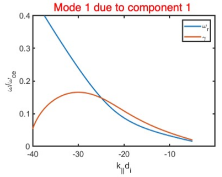
Contour plots of field quantities

Electric fields show the Hall electric field and the reconnection field.

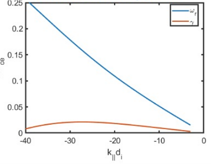
Electrons outflow from the x line along the separatrices in the magnetosphere side and inflow toward the x line along the separatrices in the magnetosheath side.

The electron outflows are asymmetry between the positive and negative x area and stronger in the negative x area due to the guide field.

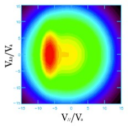
Mode 1 due to component 1



Mode 2 due to component 2



Modeled VDF



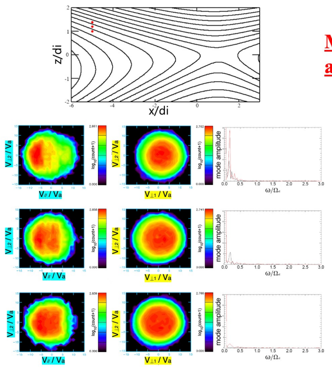
Linear numerical dispersion analysis about the wave

$T_{e1\parallel} = 1.91 m_e V_{al}^2$, $T_{e2\parallel} = 30.9 m_e V_{al}^2$,
$T_{e1\perp} = 14.6 m_e V_{al}^2$, $T_{e2\perp} = 35.4 m_e V_{al}^2$,
$T_{i\parallel} = 40.5 m_e V_{al}^2$, $T_{i\perp} = 79.2 V_{al}^2$,
$V_{al} = 0.0345c$, m_i/m_e=200, $\omega_{pel}/\Omega_{el} = 2.05$,
$Vel_{e1//} = -6.97V_{al}$, $Vel_{e2//} = -1.33V_{al}$, $Vel_{i//} = -0.530V_{al}$

Component 1 : highly anisotropic fast electron beam
Component 2: background slow electron beam

The two unstable modes (mode 1 & 2) have the maximum growth rates at the wavenumbers kd_{il}=29.5 and 27.3, respectively, and the real frequencies ω=0.24Ω_{el} and 0.16Ω_{el} , respectively, which are consistent with the wavenumber kd_{il}=25.2 and the frequency ω=0.17Ω_{el} in the simulation.

The WHAMP result shows that the whistler waves are excited by the temperature anisotropy in the fast electron beam (mode1) and the Landau resonance in the background slow electron beam (mode 2) .



Midplane electrons decrease the wave activity at the edge of the EDR

The VDFs show that the midplane components are larger away from the separatrix. FFTs (B_y (red) and B_z (black)) show less wave activity where there are more midplane electrons in the VDF at the edge of the EDR. The wave activity is concentrated on the separatrix at the edge of the EDR.

Conclusions

- We found the whistler mode in the electromagnetic waves in asymmetric guide field reconnection.
- The whistler waves we found are excited by the electron beam instability and temperature anisotropy.
- Midplane ($V_{//}$=0) electrons in VDFs are also the key to control the wave activity.
- The wave activity is concentrated on the separatrix near the edge of the EDR.
- The wave activity is not concentrated on the separatrix and decreasing when the size of the crescent becomes smaller on the separatrix near the x line.