Generation of helium and oxygen EMIC waves by the bunch distribution of oxygen ions associated with weak fast shocks in the magnetosphere

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Energy source for magnetospheric EMIC waves

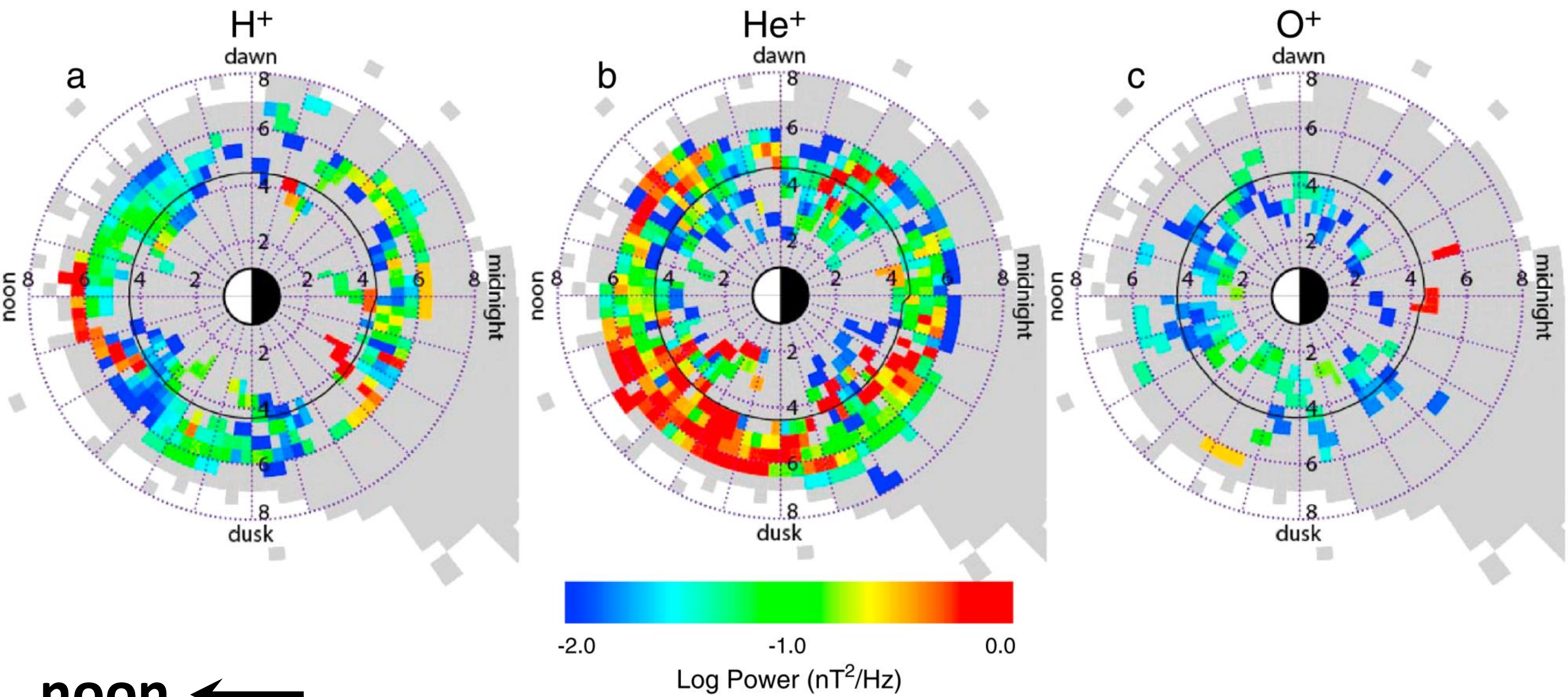
A. Injection of minor energetic ions mixed with background ions (Kennel & Petschek, 1966)
   (a) Background ions with $T_\perp/T_\parallel \approx 1$
   (b) Injected ions with $T_\perp/T_\parallel \approx 2-5$

B. Adiabatic compression of magnetospheric plasma by sudden impulses (Olson & Lee, 1983)
   (a) Increase of $T_\perp$, $T_\parallel$ and plasma beta
   (b) $T_\perp/T_\parallel \approx 1.5-3$ for all ion species

C. Heating by shocks in magnetosphere caused by interplanetary shocks or dynamic pressure enhancement (K. H. Lee and L. C. Lee, 2016)
   (a) Protons ($T_\perp/T_\parallel \approx 1-1.6$)
   (b) Helium He^+ ($T_\perp/T_\parallel \approx 3-6$)
   (c) Oxygen O^+ (bunch in $\boldsymbol{v}_\perp$ space)

Observations of EMIC waves

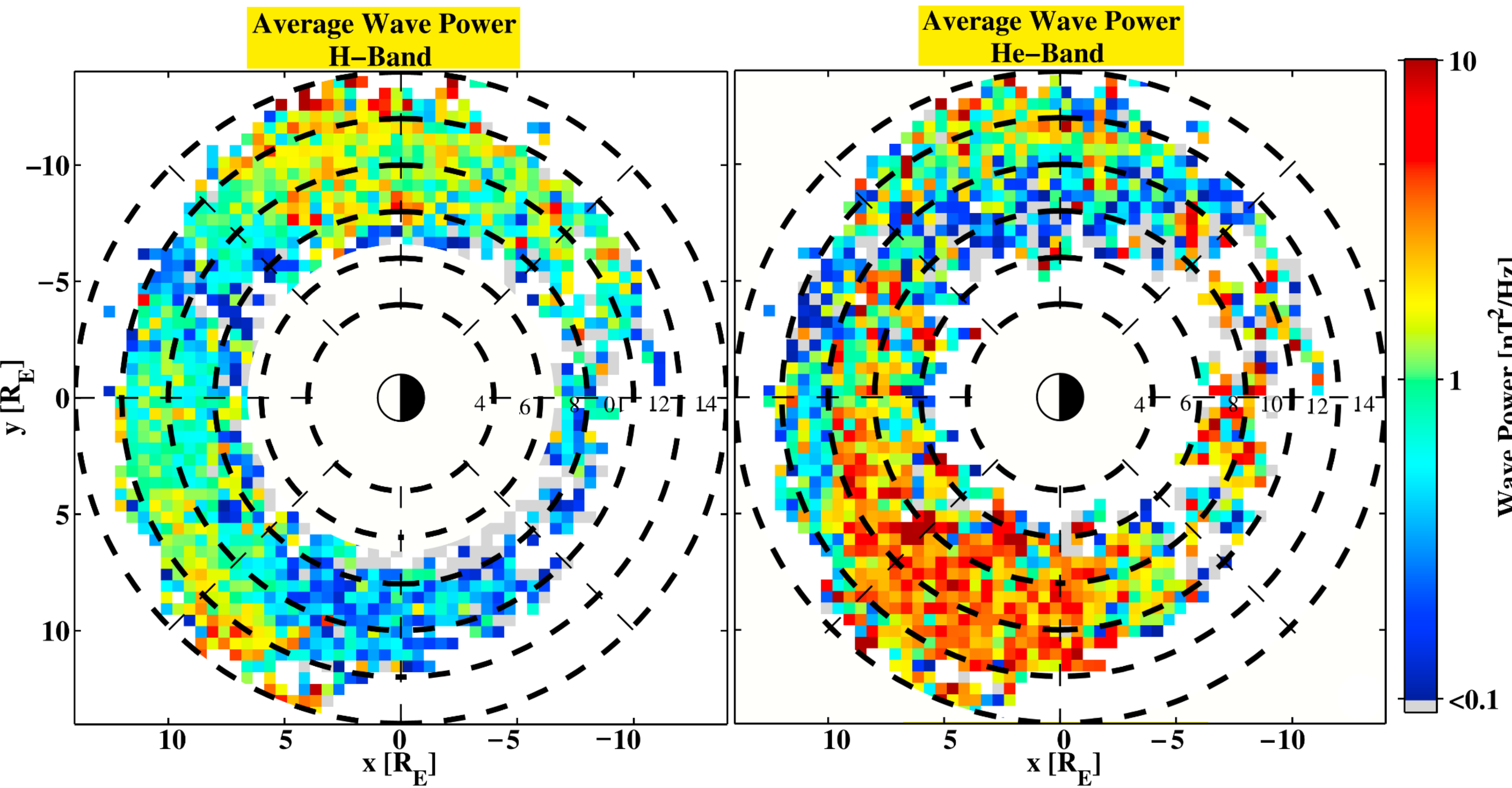
(Van Allen Probes, L≲6)



noon ←

Saikin et al., 2015

Observations of EMIC waves
(THEMIS , 6≲L≲14)



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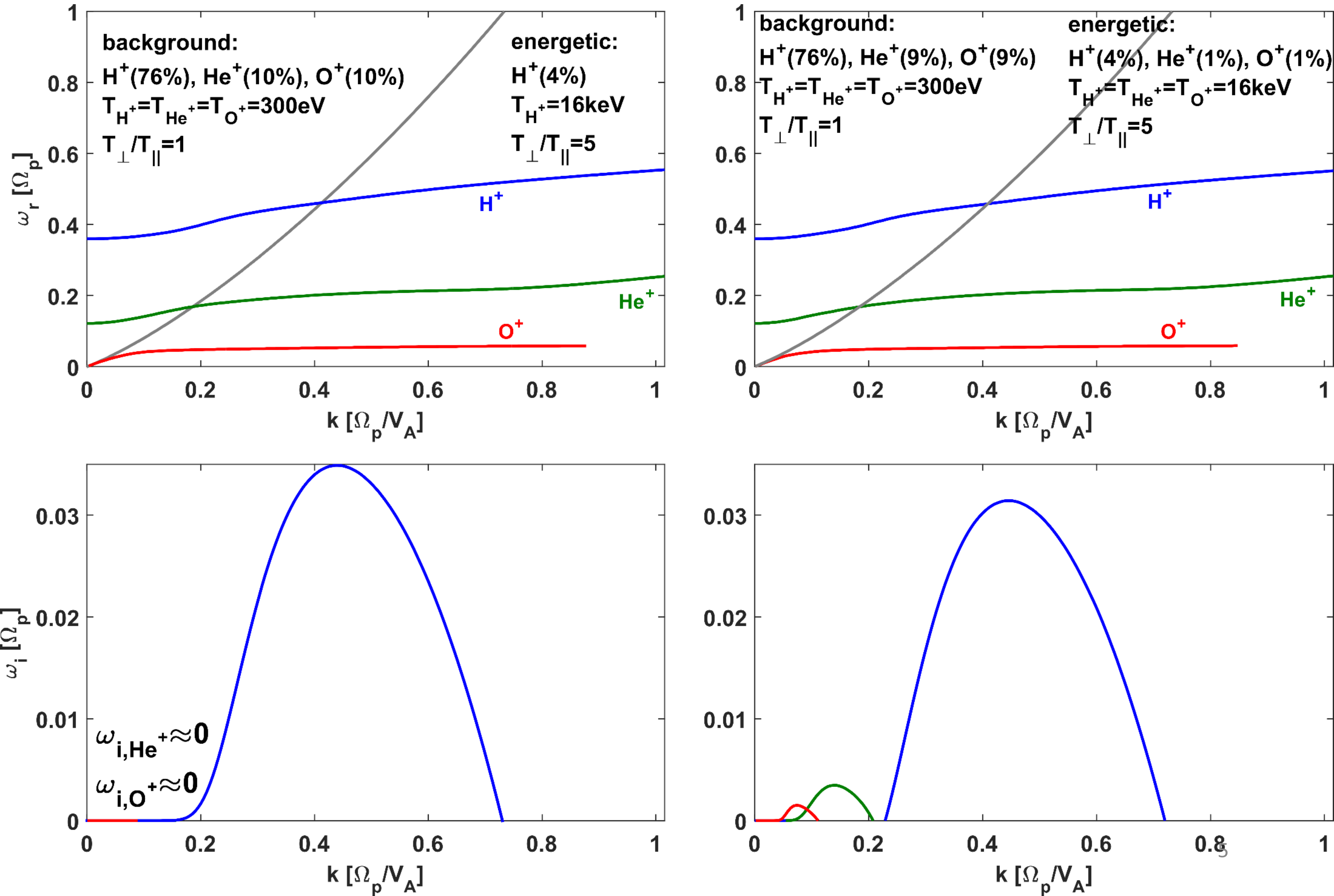
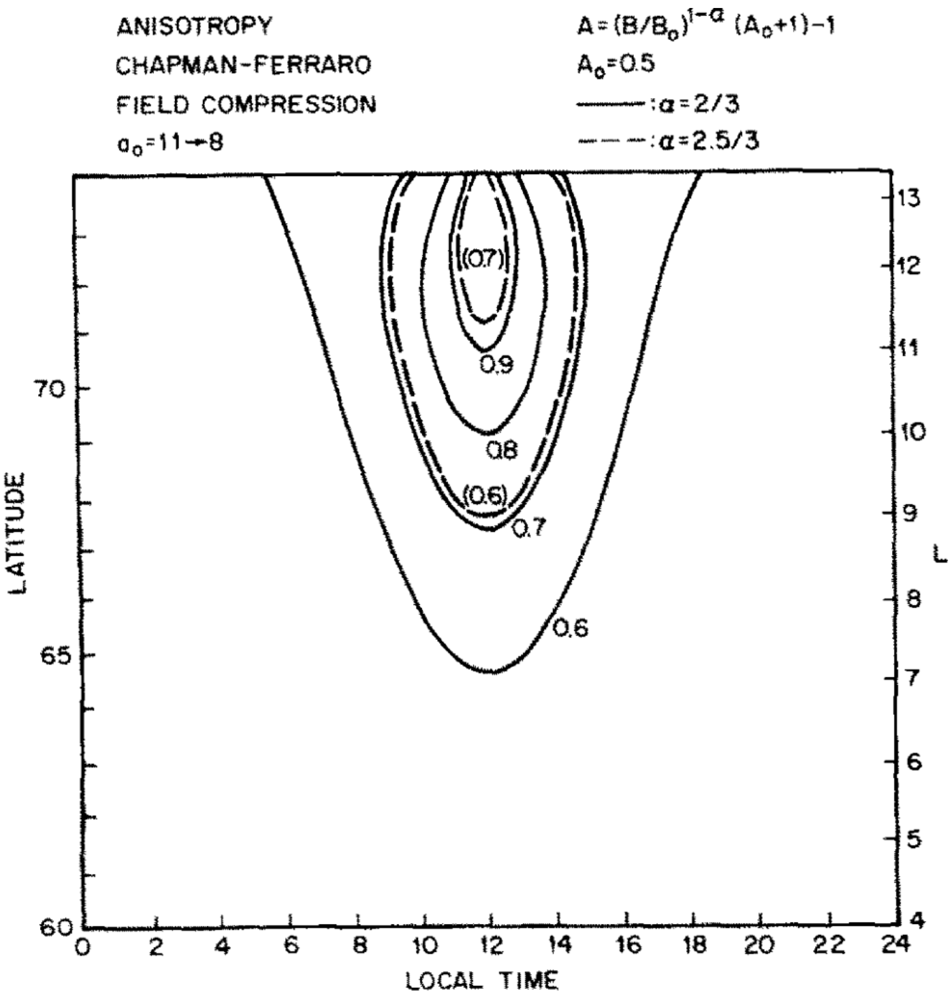
Min et al., 2012

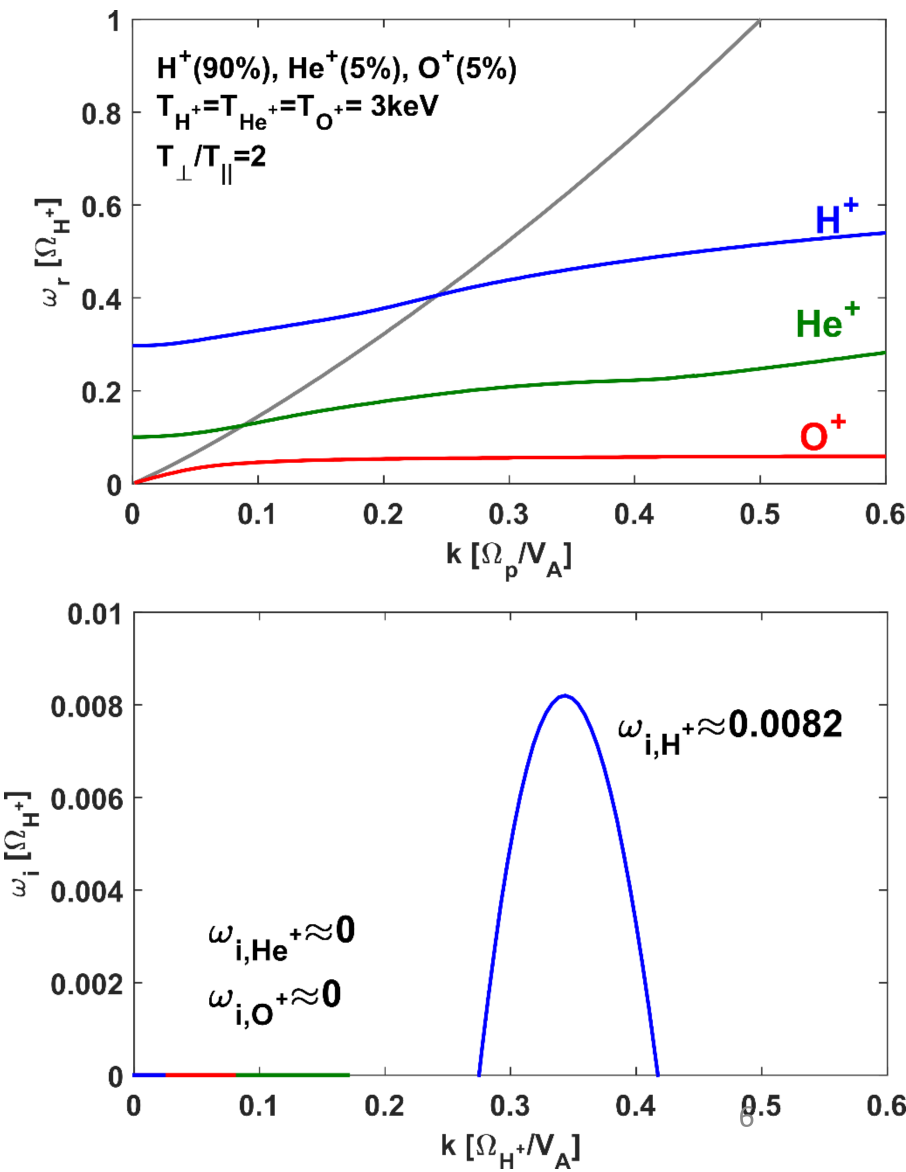
Injection of energetic ions mixed with background ions



Adiabatic compression



Olson and Lee, 1983



(A1) injection of energetic protons

(B) adiabatic compression

→ $\omega_{i,He+} \approx 0$ and $\omega_{i,O+} \approx 0$

(A2) injection of energetic protons, helium and oxygen:

→ $\omega_{i,He+} \approx 0.0035\Omega_{H+}$

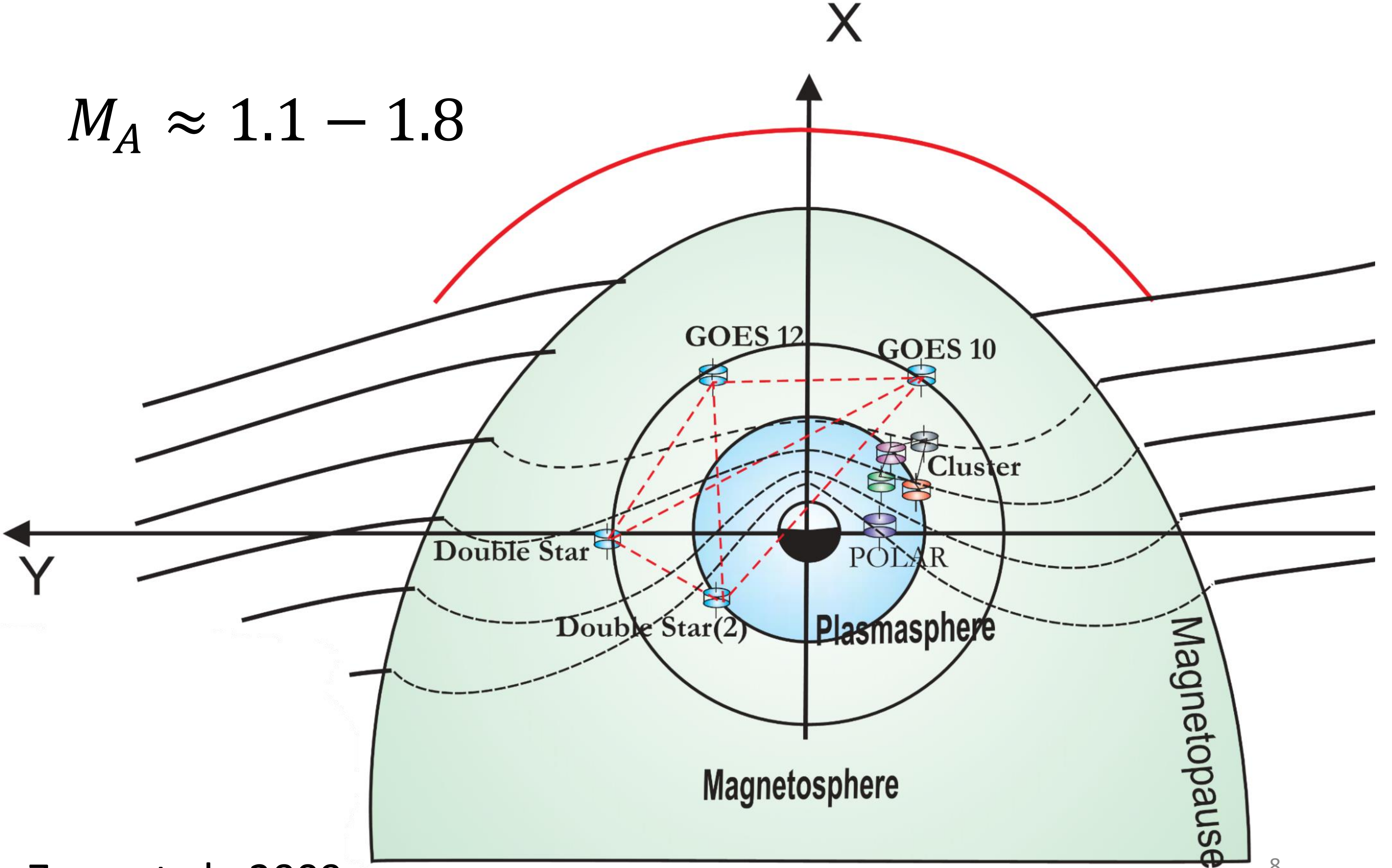
$\omega_{i,O+} \approx 0.0019\Omega_{H+}$

(C) We propose a new generation mechanism for the helium and oxygen EMIC waves by shocks in the magnetosphere.

[K. H. Lee and L. C. Lee, GRL, 2016]

Propagation of shocks

$M_A \approx 1.1 - 1.8$



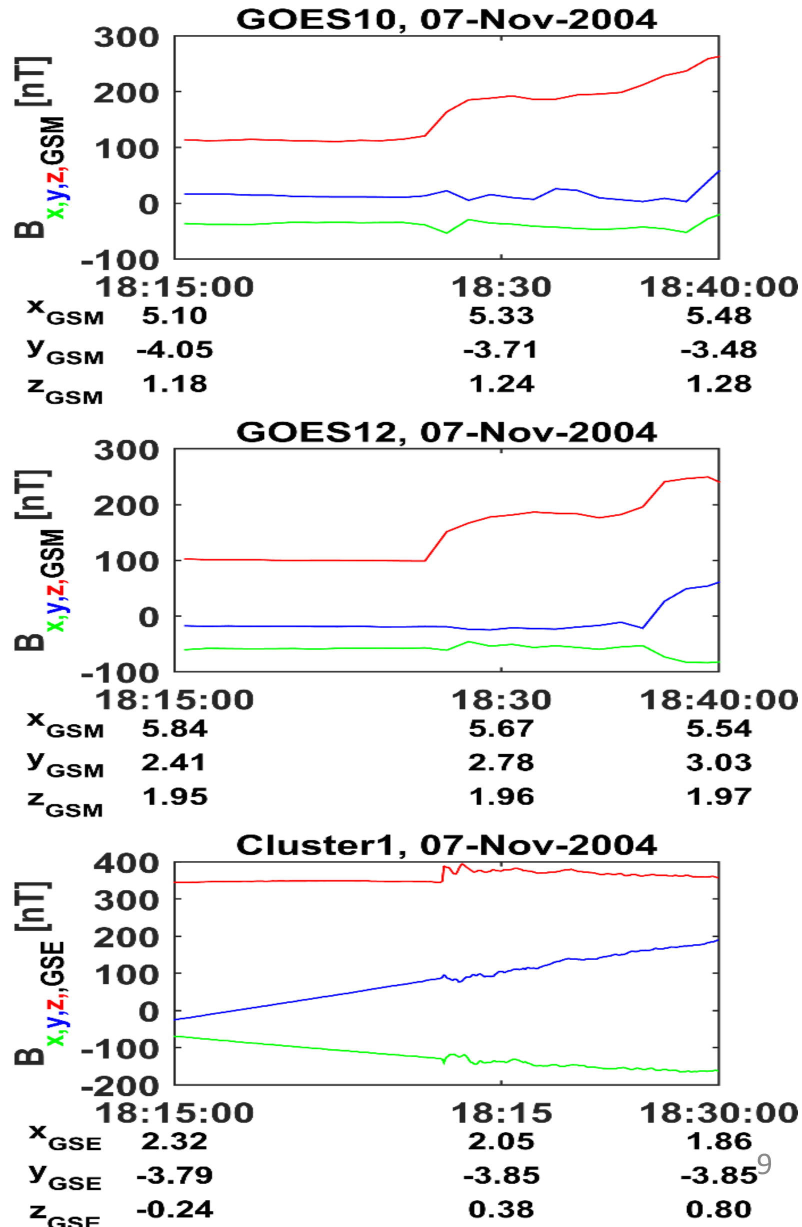
Zong et al., 2009

Observation of shocks in the magnetosphere

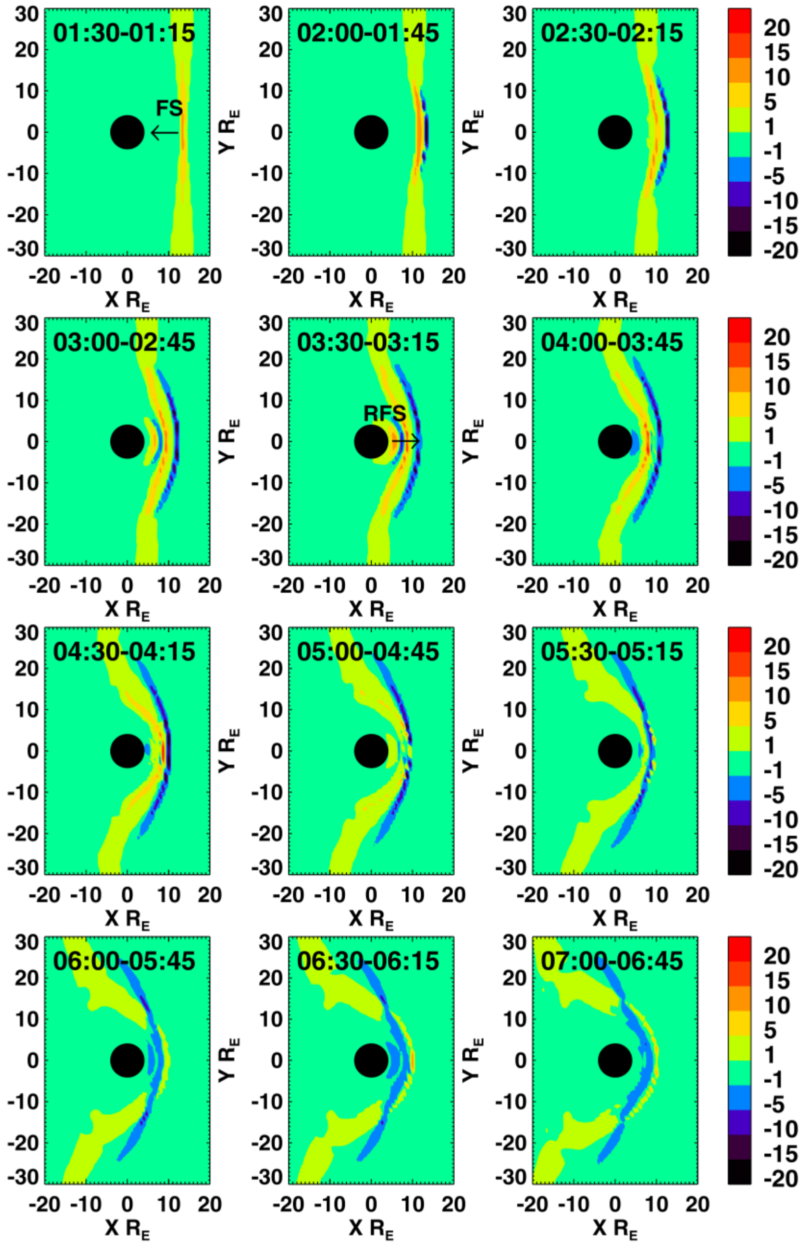
Assume $\beta_1 = 0.1$

GOES 10 & 12:
$M_A = 1.5, \theta_{BN} = 60° - 70°$

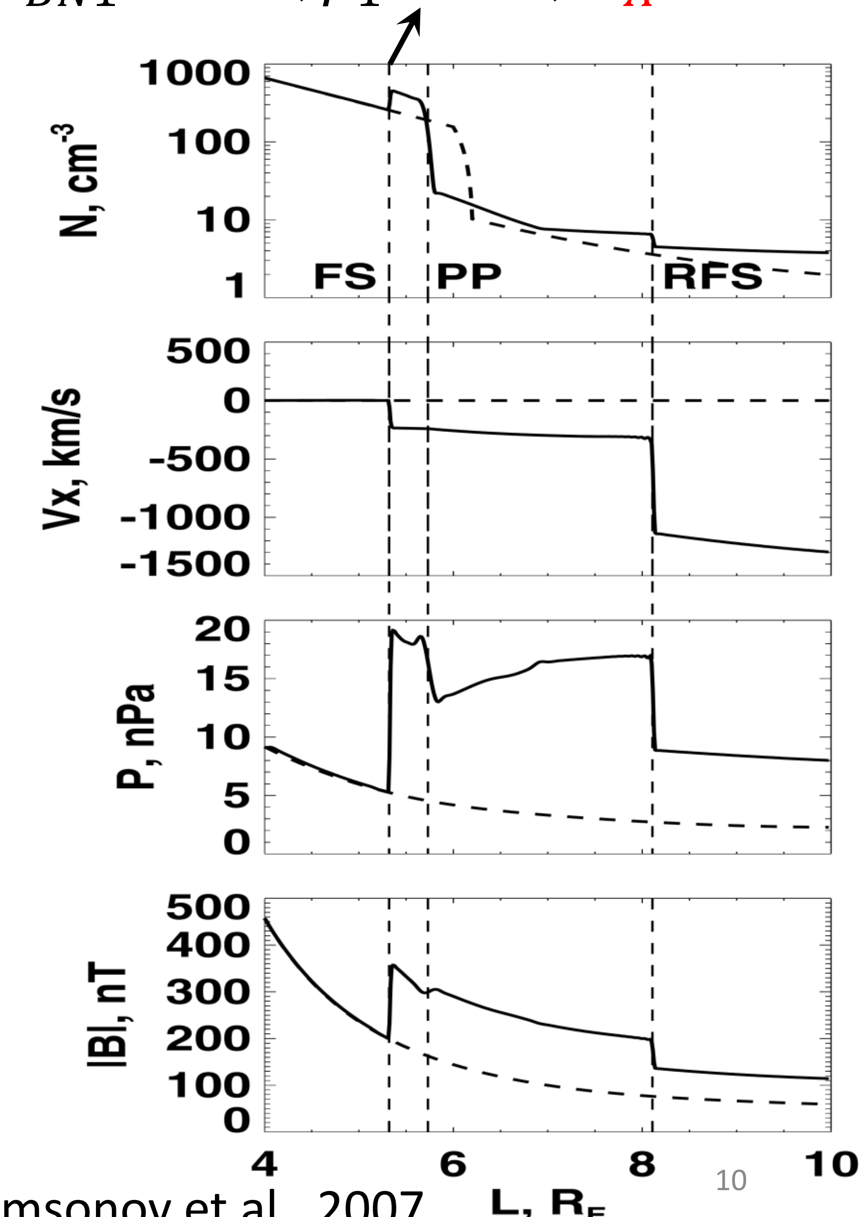
Cluster 1:
$M_A = 1.1, \theta_{BN} = 75°$



MHD simulation of shocks in the magnetosphere



$\theta_{BN1} = 90°, \beta_1 = 0.3, M_A = 1.87$



Samsonov et al., 2007

Coupling of micro-process to macro-process

(1) “Resistivity” for magnetic reconnection in a collisionless plasma

(2) Ion heating in collisionless fast shock

(1) “Resistivity” in a Collisionless Plasma

H.J. Cai and L.C. Lee (1994, 1997)

Force Balance at Neutral Lines for Electrons and Ions

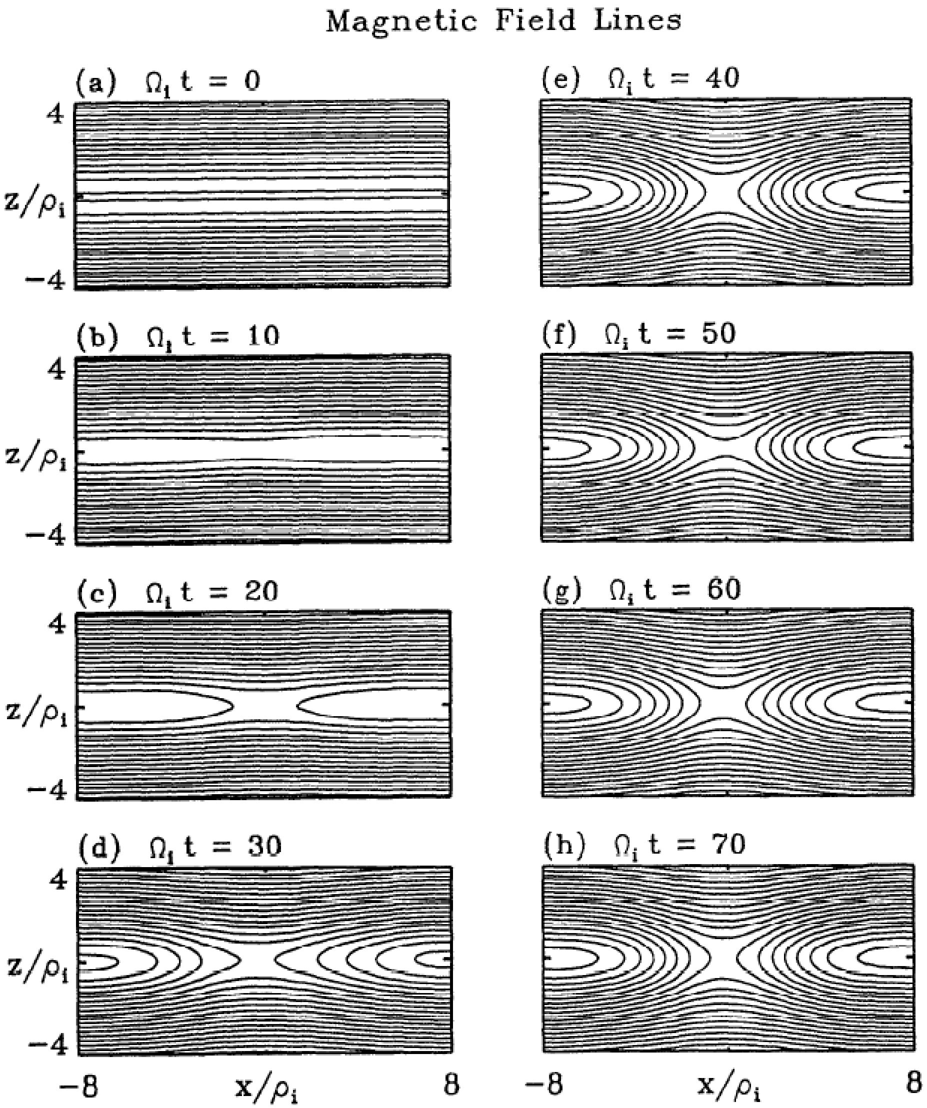
$$-\frac{m_e}{e}\frac{\partial v_y^{(e)}}{\partial t}=E_y+\frac{1}{n_e e}\frac{\partial P_{xy}^{(e)}}{\partial x}+\frac{1}{n_e e}\frac{\partial P_{zy}^{(e)}}{\partial z}$$

$$\frac{m_i}{e}\frac{\partial v_y^{(i)}}{\partial t}=E_y-\frac{1}{n_i e}\frac{\partial P_{xy}^{(i)}}{\partial x}-\frac{1}{n_i e}\frac{\partial P_{zy}^{(i)}}{\partial z}$$

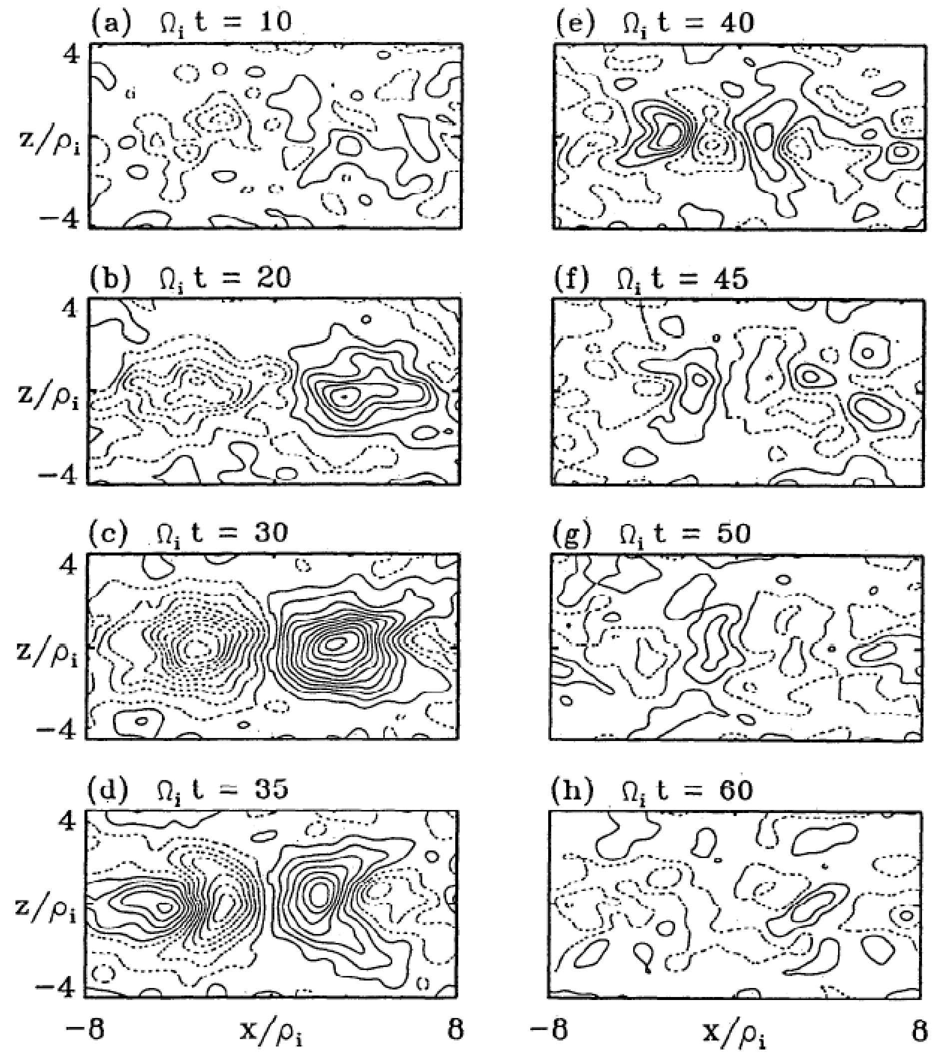
The Generalized Ohm’S Law Near Neutral Line

$$E_y=\frac{m_e}{e^2}\frac{\partial (J_y/n)}{\partial t}+\frac{m_e}{m_i}\frac{1}{ne}\left(\frac{\partial P_{xy}^{(i)}}{\partial x}+\frac{\partial P_{zy}^{(i)}}{\partial z}\right)-\frac{1}{ne}\left(\frac{\partial P_{xy}^{(e)}}{\partial x}+\frac{\partial P_{zy}^{(e)}}{\partial z}\right)$$

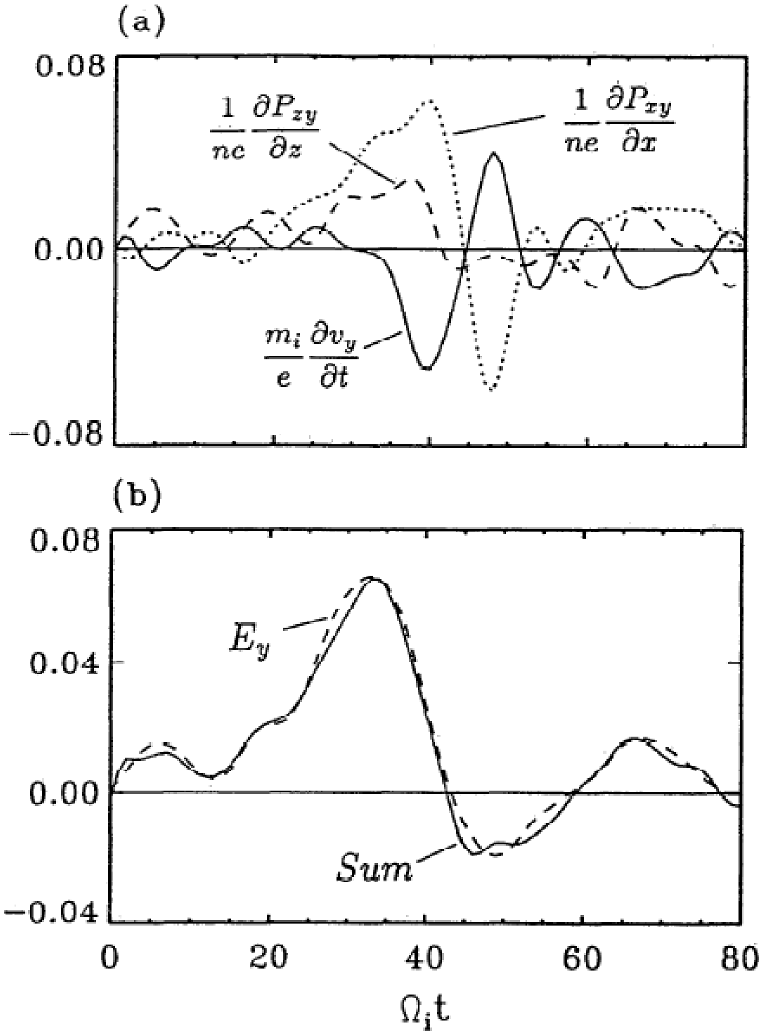
Off-diagonal terms of pressure tensor are the key to the “anomalous” resistivity for collisionless magnetic reconnection



Off-Diagonal Pressure P_{xy}



Force Balance at the X Line



$$\frac{m_i}{e}\frac{\partial v_y^{(i)}}{\partial t} = E_y - \frac{1}{n_i e}\frac{\partial P_{xy}^{(i)}}{\partial x} - \frac{1}{n_i e}\frac{\partial P_{zy}^{(i)}}{\partial z}$$

H.J. Cai and L.C. Lee (1994)

"I think your paper marks the breakthrough", by Jim Dungey

Long Roof
Walberswick

28 March 1995

Dear Dr. Cai

Thank you very much for your paper and the pleasing confirmation of my length scale formula.

I think your paper marks the breakthrough. I am not surprised by the dynamo effect, but you clearly have a simulation, that is capable of answering lots of outstanding questions. You have enough particles to compute the pressure tensor and I would like to see them in detail near the X-line, but the first question is how anisotropic does the pressure tensor get? I think a few per cent would be important.

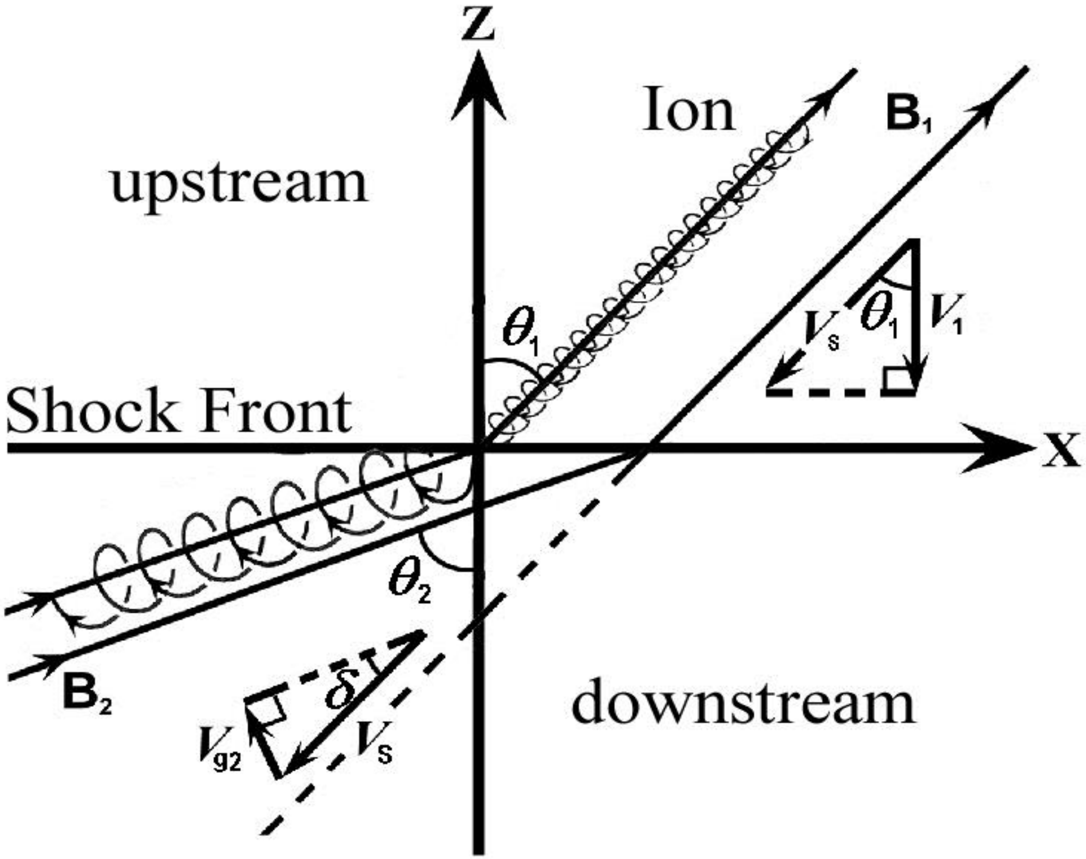
Your mass-ratio scaling is important for the reason you give and I hope this means you are planning to pursue this project. Observations seem to require a variety of scenarios and I expect you haave ideas about varying the initial values.

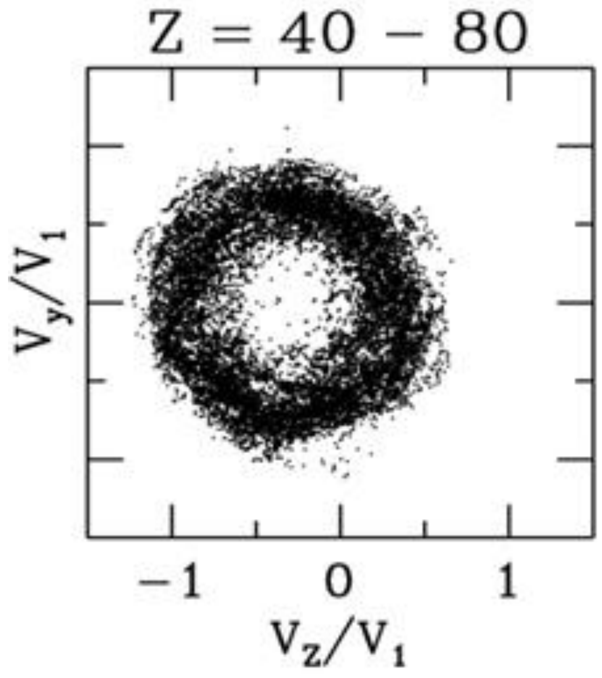
Congratulations on this paper

and keep it up

Jim Dungey

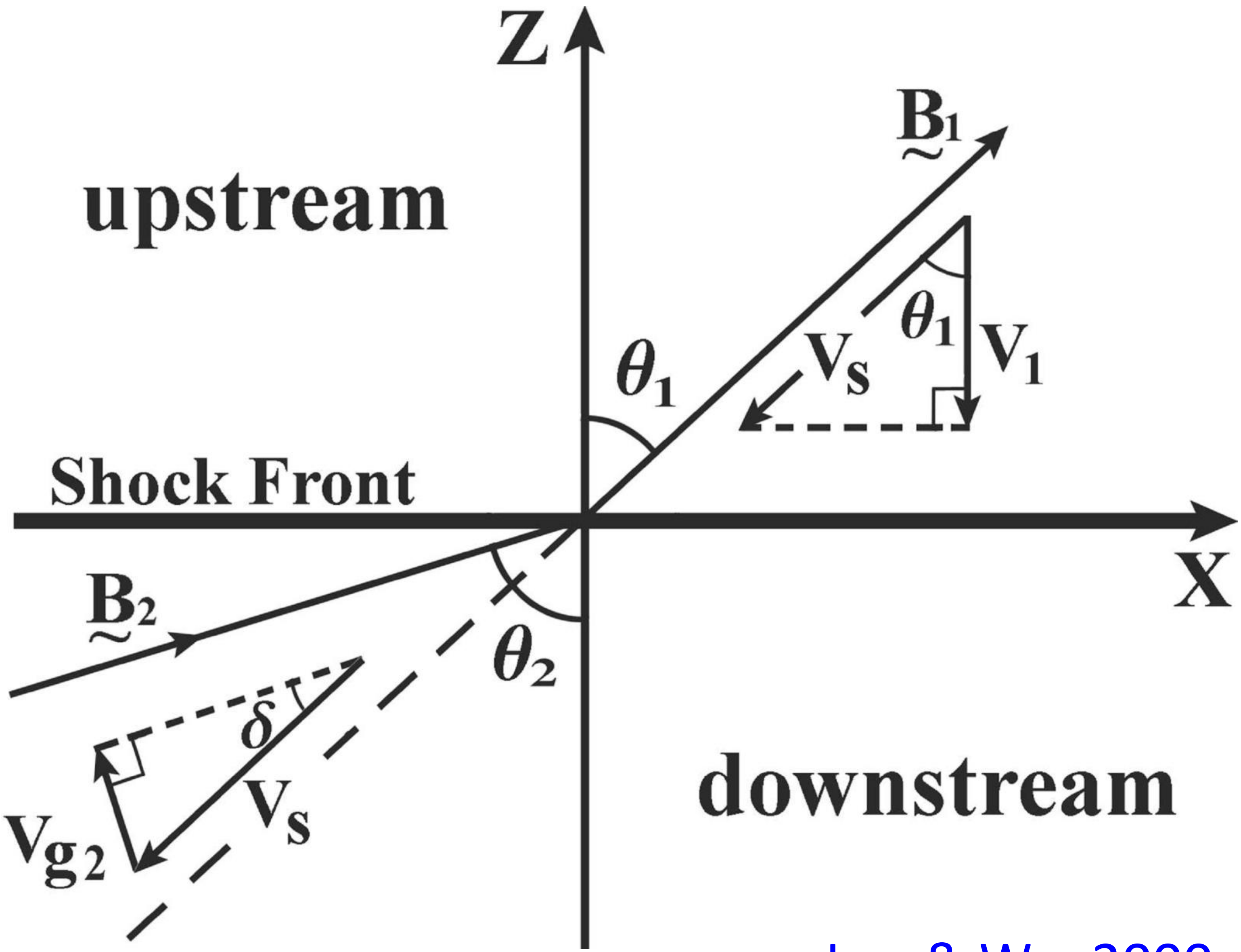
(2) Ion heating in collisionless fast shock





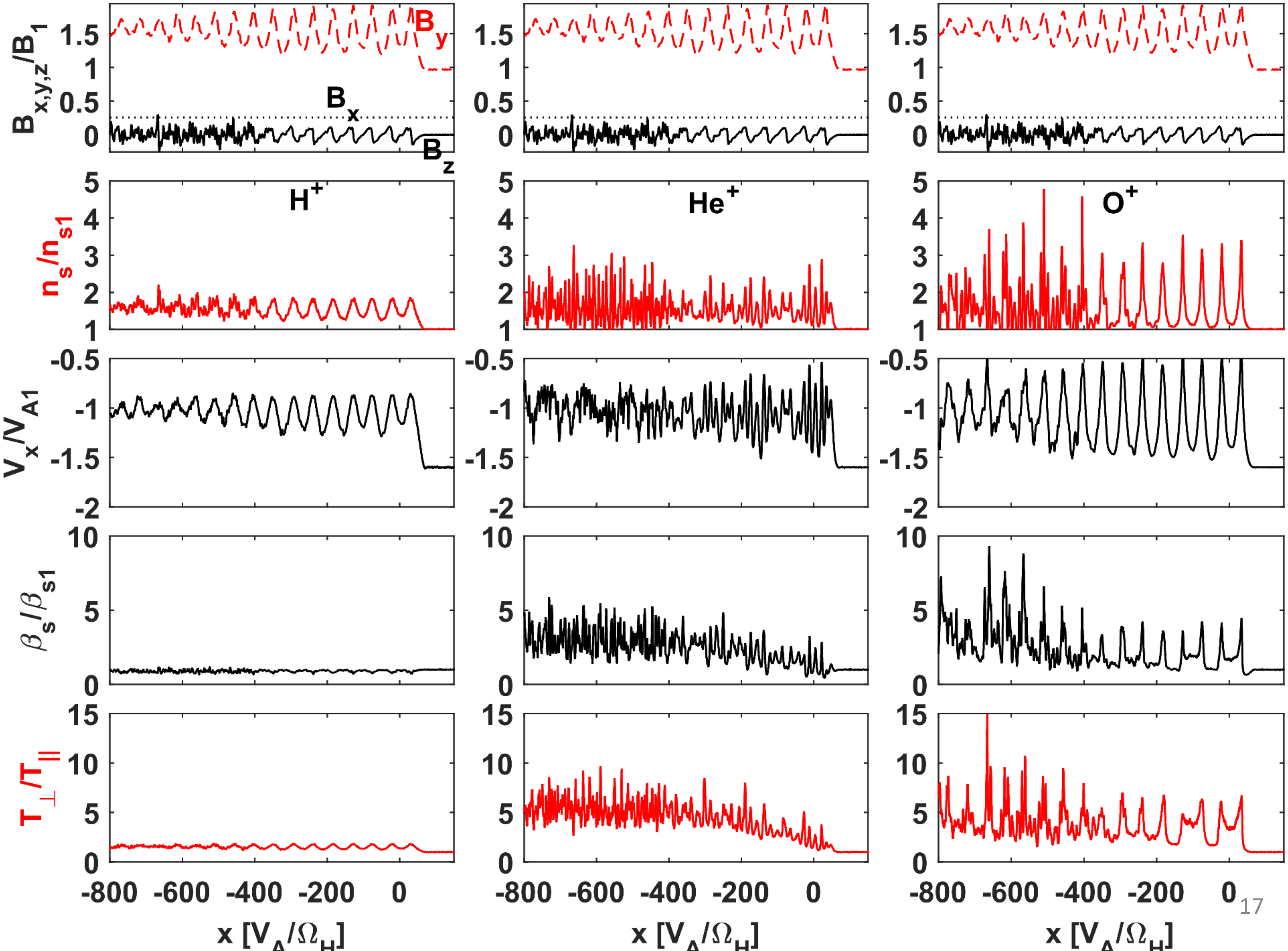
Lee, Wu, and Hu (1986); Lee and Wu (2000); Lee and Lee (2016)

Ion heating by fast shocks

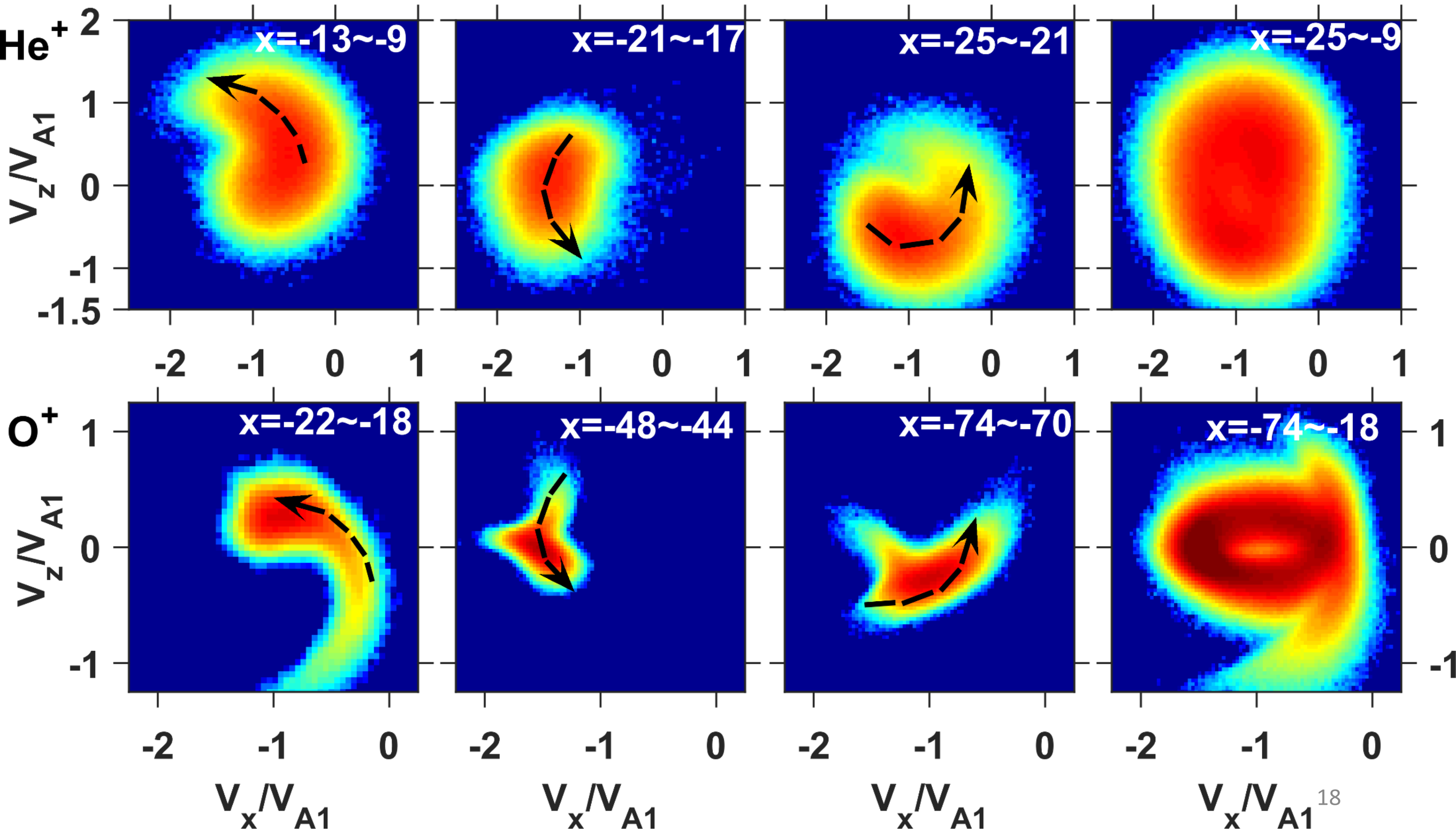


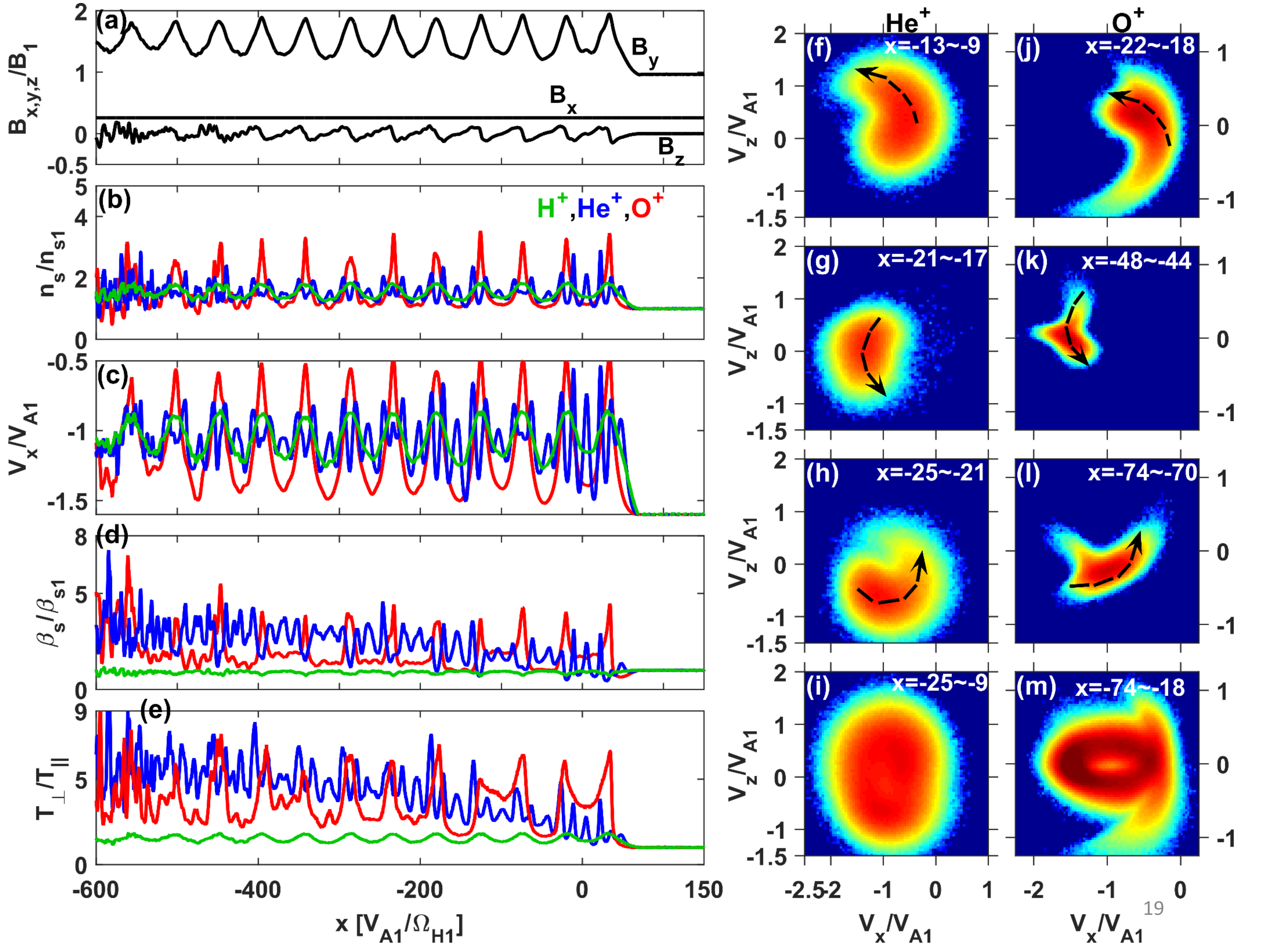
Lee & Wu, 2000

$M_A = 1.6, \beta_1 = 0.1, \theta_{BN} = 75°$
$n_{H+} = 85\%, n_{He+} = 5\%, n_{O+} = 10\%$



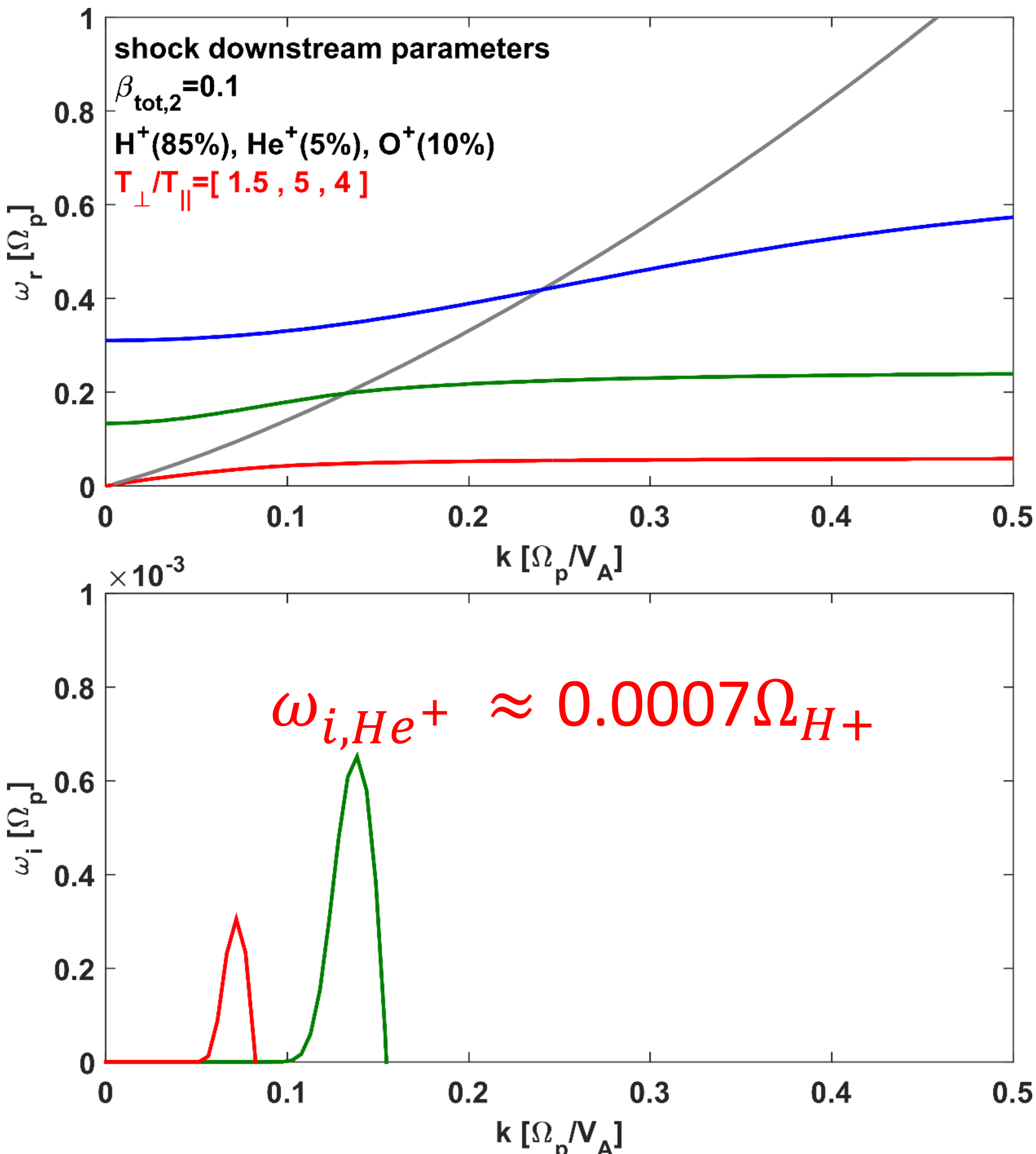
Helium and Oxygen distributions



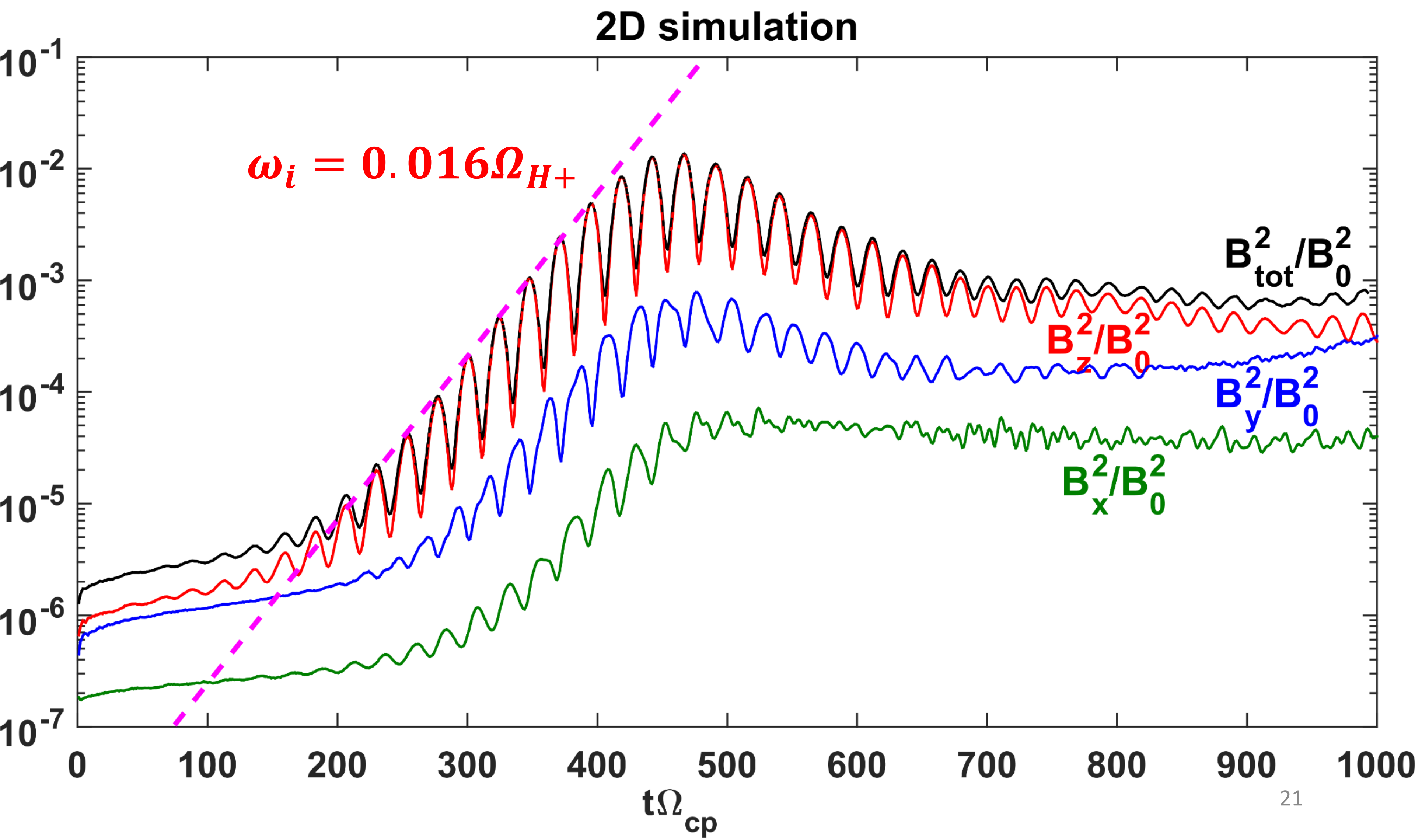


(a)
$B_{x,y,z}/B_1$
B_y
B_x
B_z
(b)
n_s/n_{s1}
H^+,He^+,O^+
(c)
V_x/V_{A1}
(d)
β_s/β_{s1}
(e)
$T_\perp/T_{||}$
x [V_{A1}/Ω_{H1}]
He^+
O^+
(f) x=-13~-9
(g) x=-21~-17
(h) x=-25~-21
(i) x=-25~-9
(j) x=-22~-18
(k) x=-48~-44
(l) x=-74~-70
(m) x=-74~-18
V_z/V_{A1}
V_x/V_{A1}

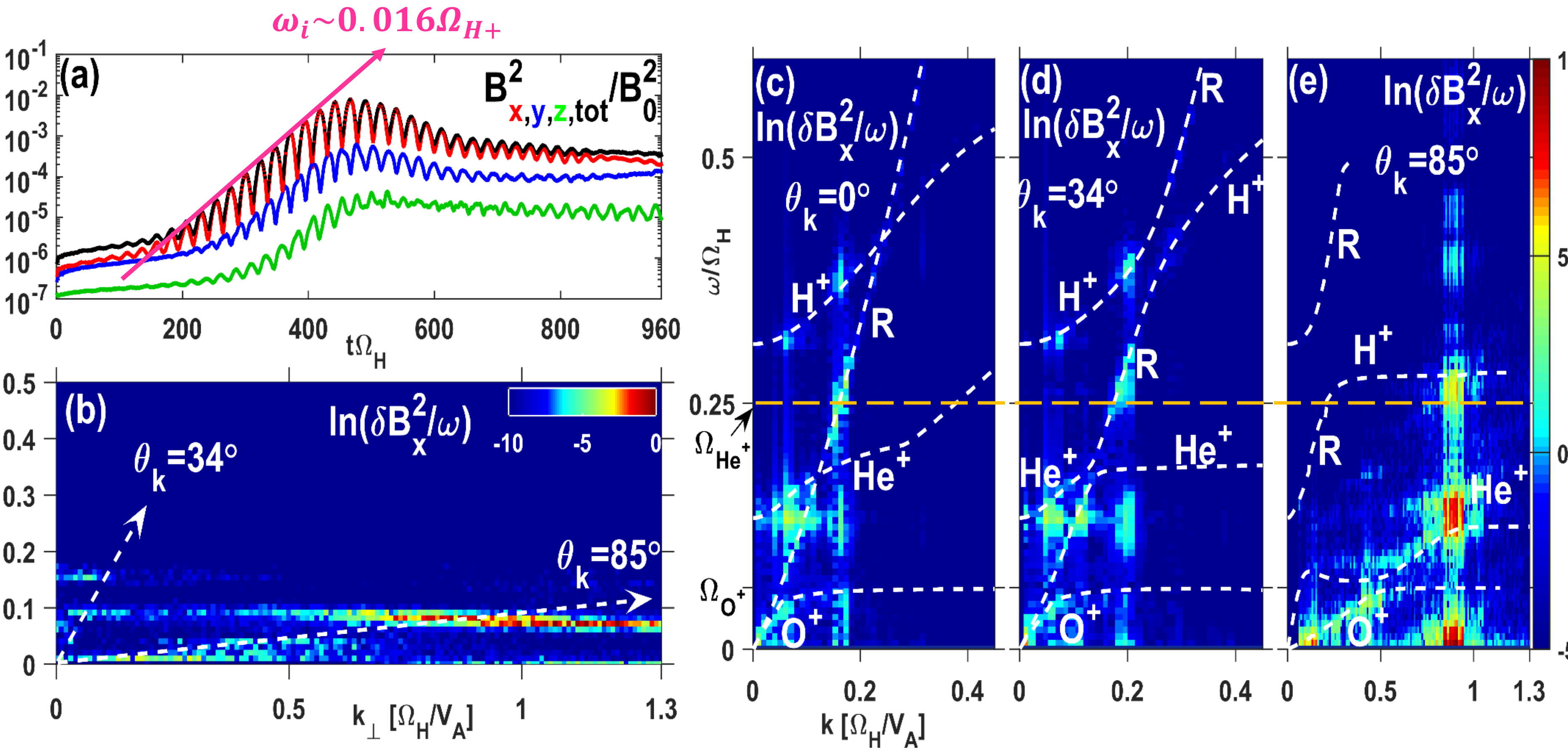
EMIC wave growth rate by anisotropic ions in the downstream of shock

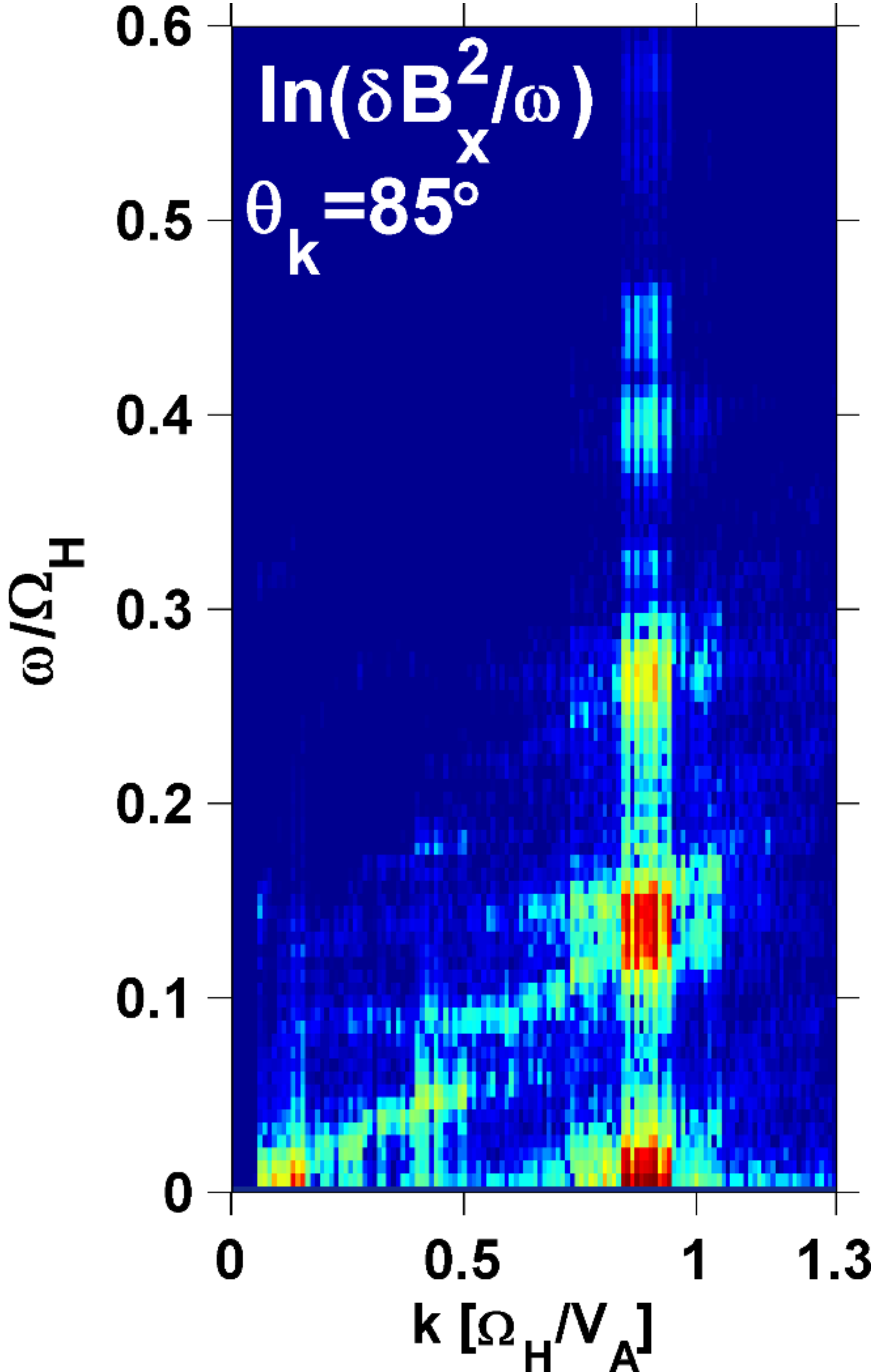


Oxygen bunch distribution in hybrid simulation

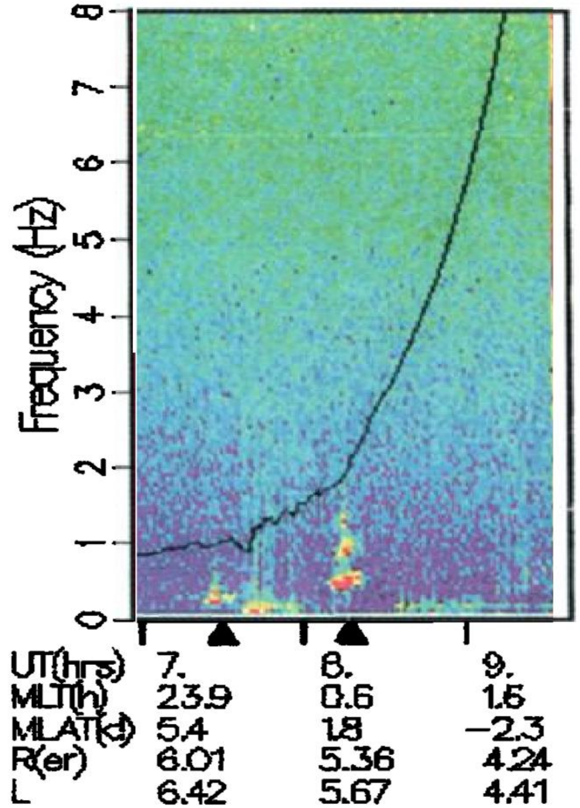


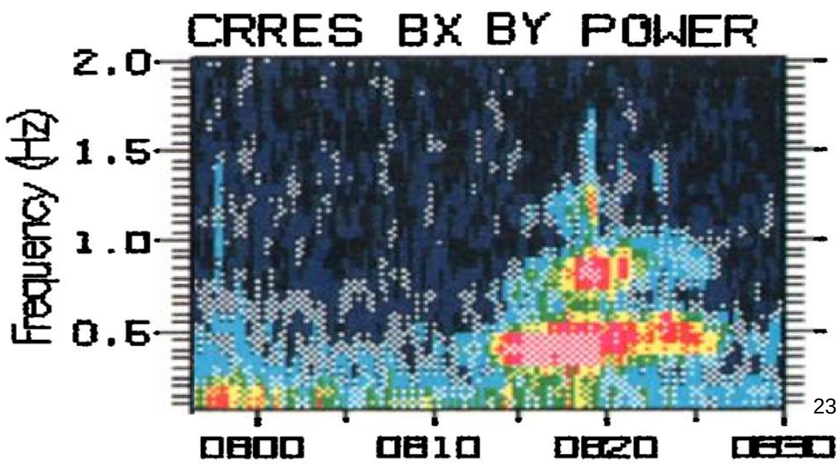
$M_A = 1.6,\ \beta_{i1} = 0.1,\ \theta_{BN1} = 75°$





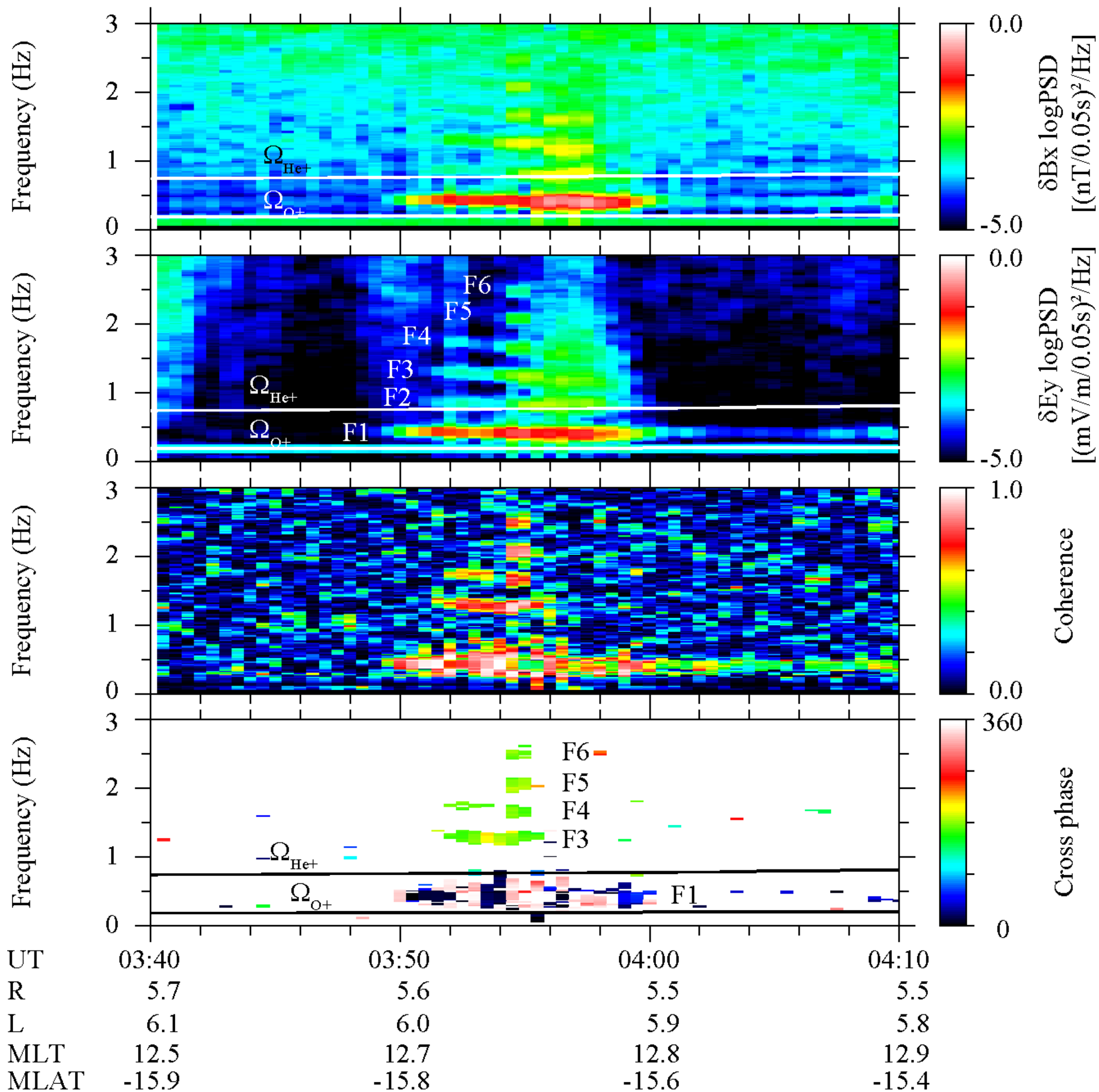
CRRES ICW Wave Spectrogram
Orbit 512 52/91 Feb 21





Fraser et al. 1996

Van Allen Probe-B magnetic and electric field data
25 February (Day 056) 2014

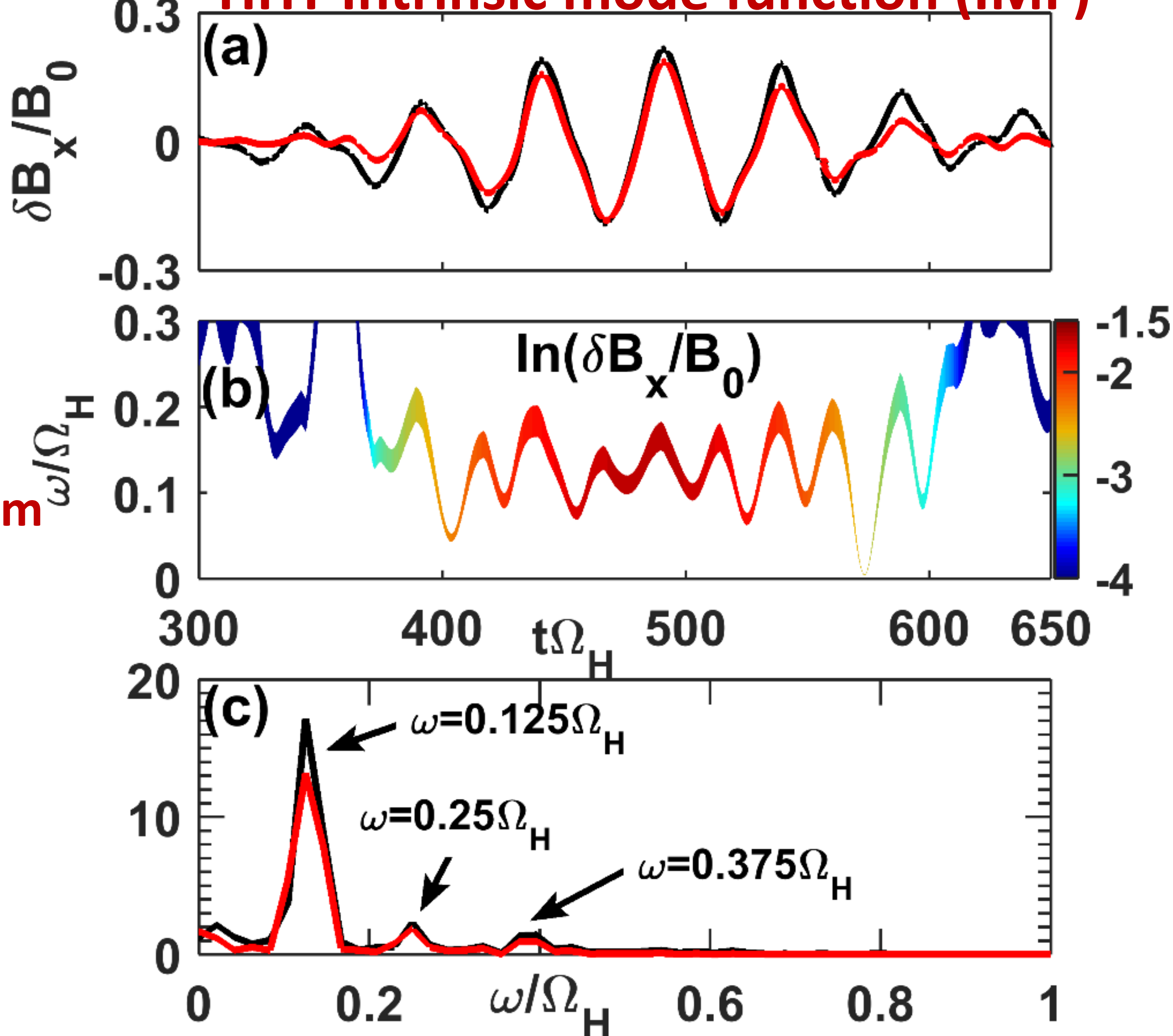


Provided by Dr. Bruce Tsurutani (2016)

Harmonics caused by frequency modulation

HHT Intrinsic mode function (IMF)

HHT Hilbert Transform



	H^+	He^+	O^+
ω_i/Ω_H in Case A (injection)	0.02	0.0025	0.001
ω_i/Ω_H in Case B (compression)	0.008	~0	~0
ω_i/Ω_H in Case C (shock, $T_\perp/T_\parallel > 1$)	~0	0.0007	0.0003
ω_i/Ω_H in Case D (shock, O^+ bunch)	---	0.016	---
(relative intensity)	(0.047)	(1)	(0.048)

Case A (injection):

Background: 76% H^+, 9% He^+, 9% O^+ with $T_{bg} = 300\text{eV}$

Energetic: 4% H^+, 1% He^+, 1% O^+ with $T_{inj\perp}/T_{inj\parallel} = 5$ and $T_{inj} = 6\,\text{keV}$

Case B (compression):

90% H^+, 5% He^+ and 5% O^+ with $T = 3\,\text{keV}$, $T_\perp/T_\parallel = 2$

Summary

- Anisotropy of protons, helium and oxygen caused by (A) injection of energetic ions from tail and by (B) adiabatic compression is not sufficient to generate He^+ and O^+ EMIC waves observed in the magnetosphere.
- **Fast shocks** in the magnetosphere can lead to a large anisotropic distribution for He^+ and **bunch** distribution for $\boldsymbol{O^+}$.
- The O^+ bunch distribution can excite $\boldsymbol{He^+}$ and $\boldsymbol{He^+}$ **harmonics** (dominant), O^+ and H^+ EMIC waves.
- Helium EMIC waves and harmonics can also scatter radiation belt electrons into loss cone.

Thank You

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