

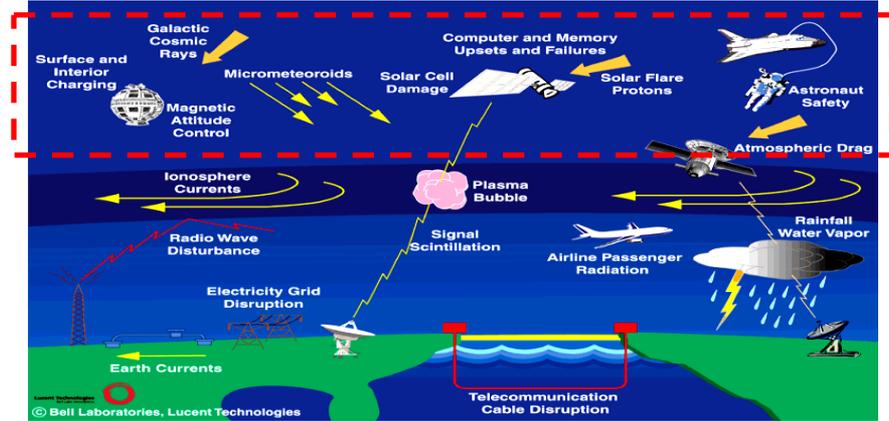
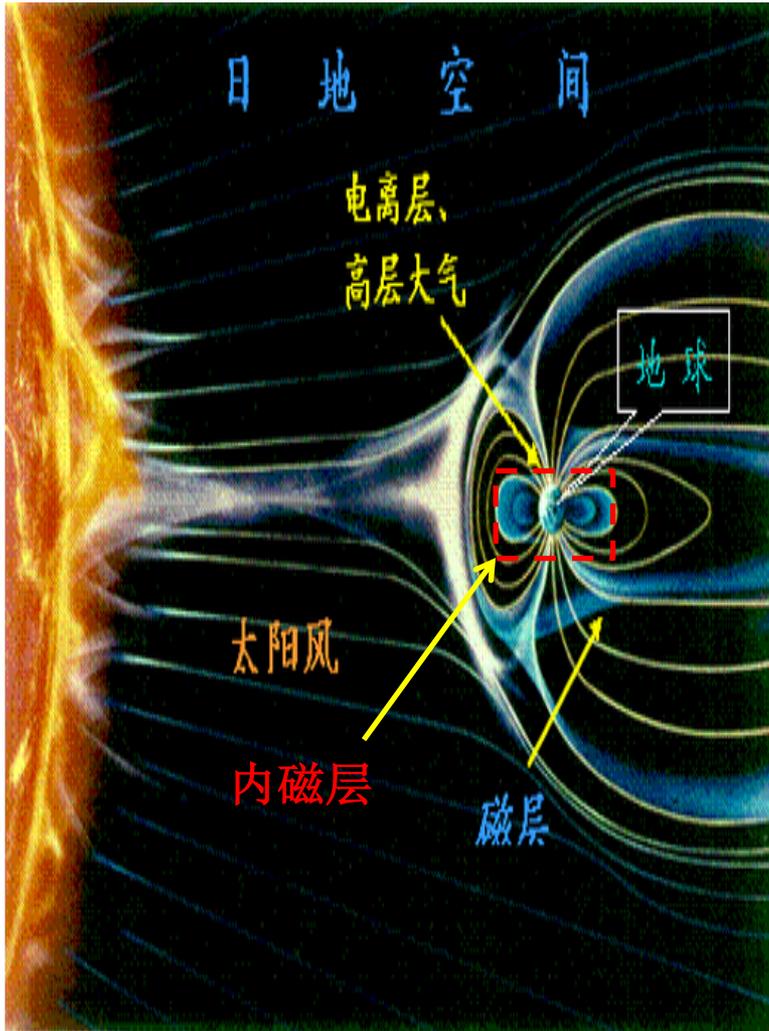
内磁层磁声波研究进展

袁志刚

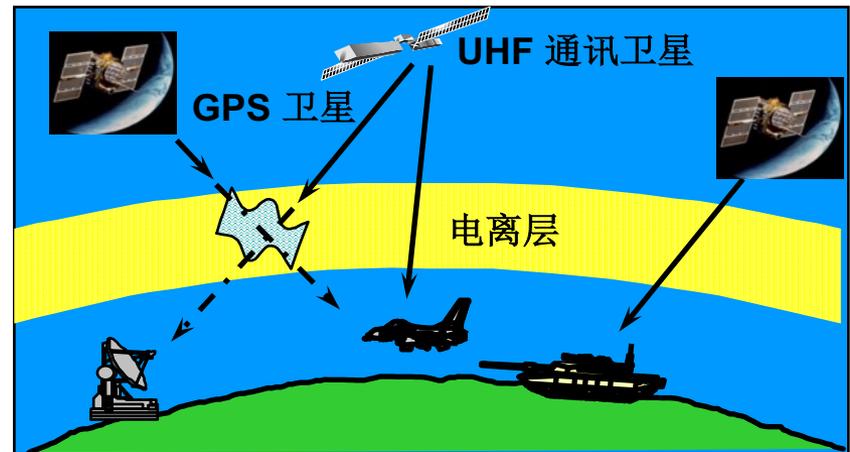
武汉大学电子信息学院

内磁层与电离层

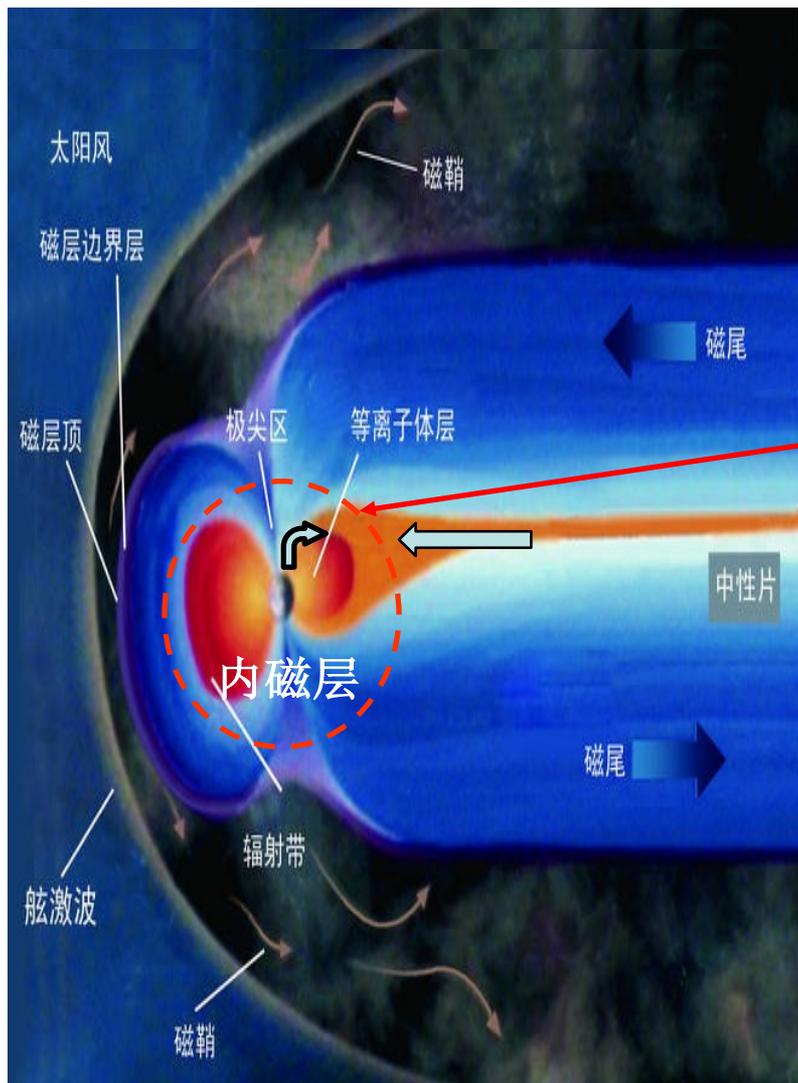
内磁层：卫星及航天飞机的空间环境



电离层：无线电波传播的空间环境

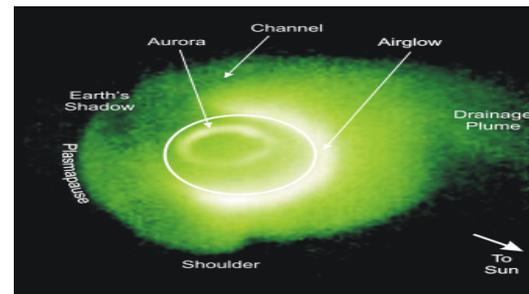


内磁层粒子 (H^+ , He^+ , O^+)



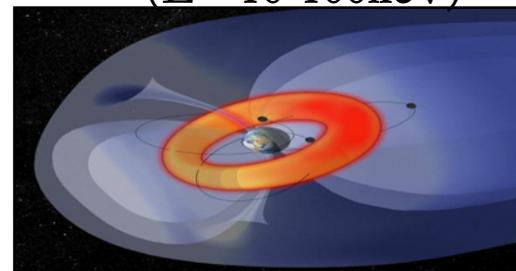
内磁层

等离子体层 ($E \sim 1 \text{ eV}$)



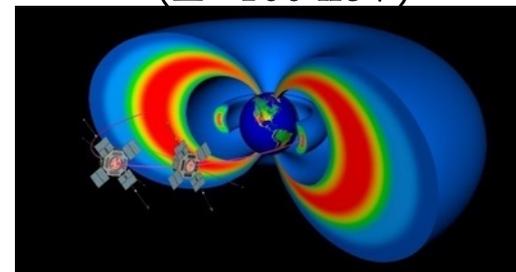
环电流

($E \sim 10-100 \text{ keV}$)

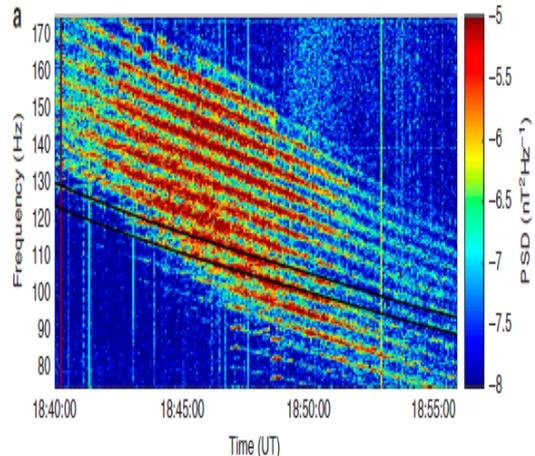


辐射带

($E > 100 \text{ keV}$)

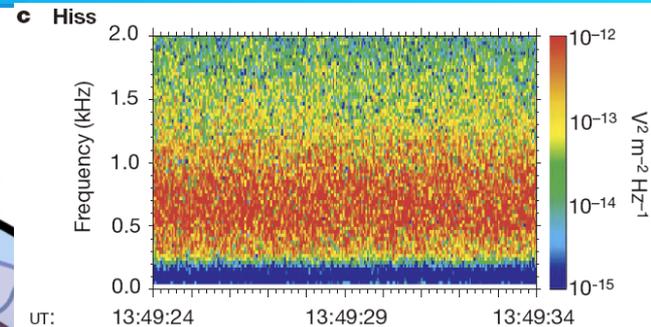
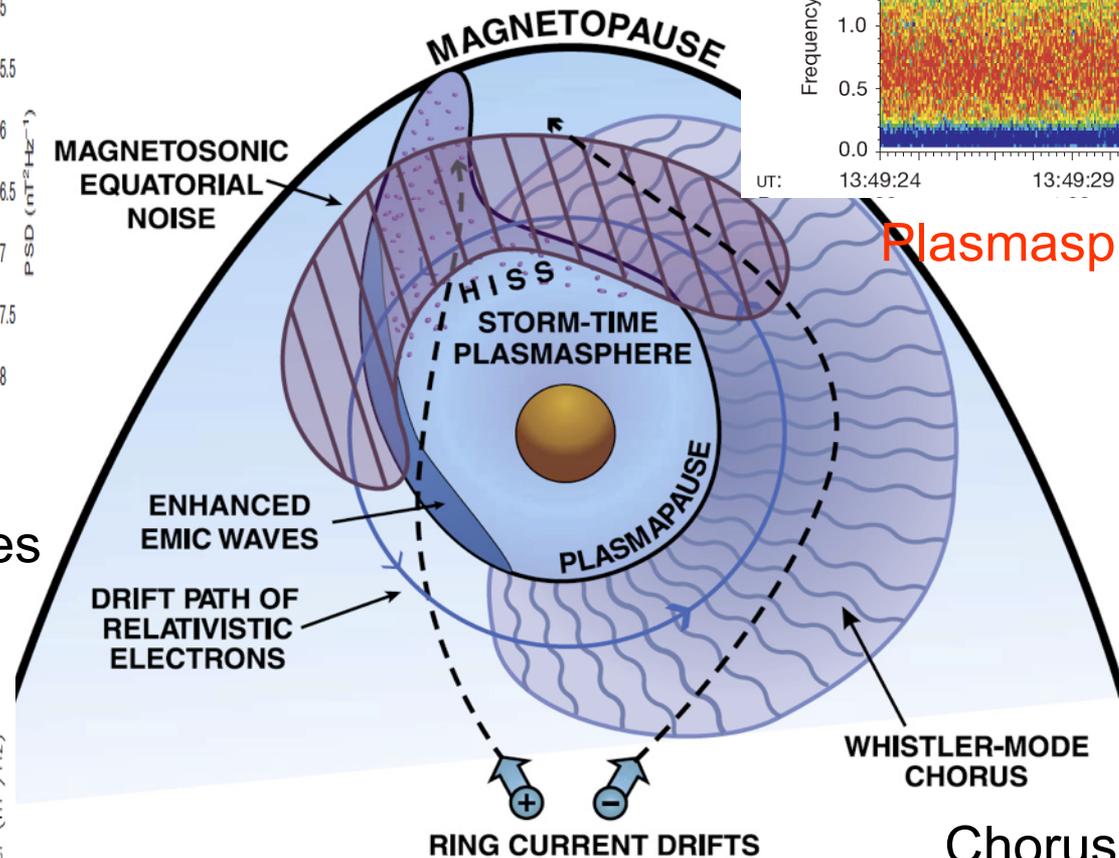
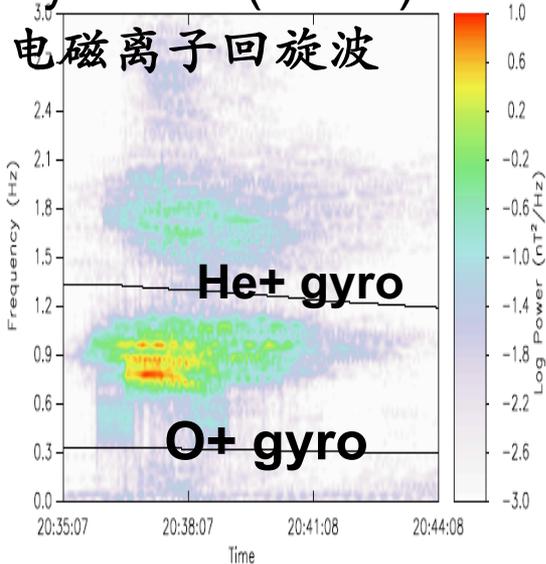


Magnetosonic waves (磁声波)



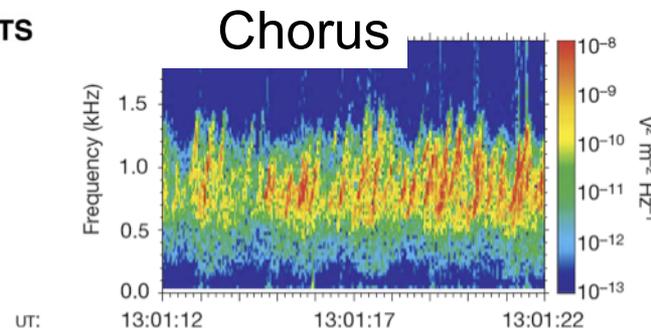
Electromagnetic Ion Cyclotron (EMIC) waves

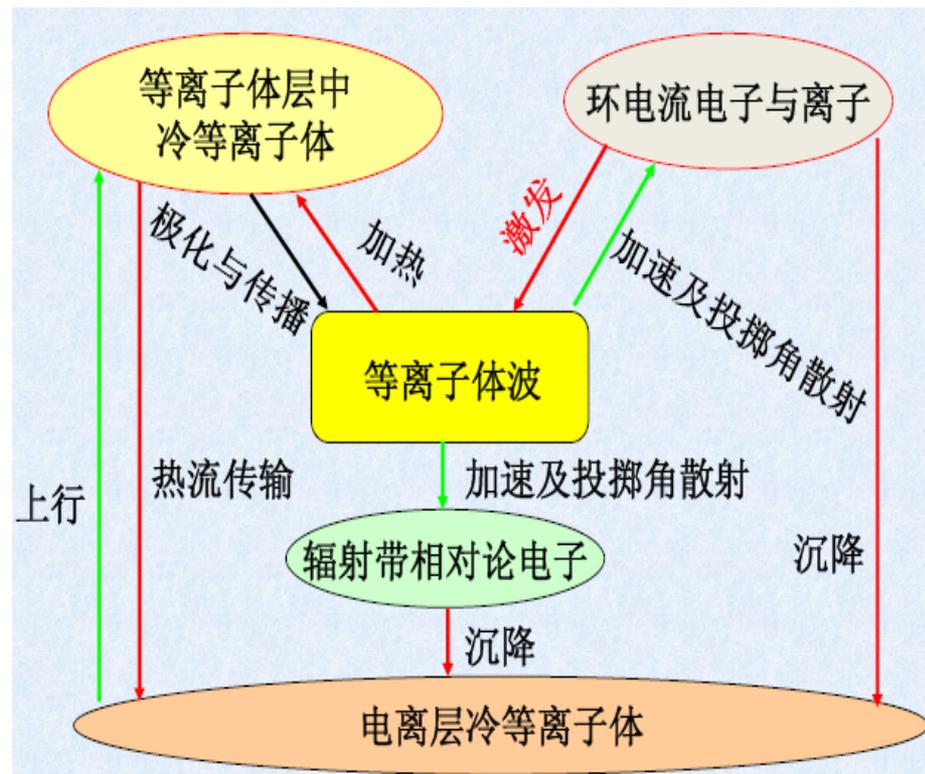
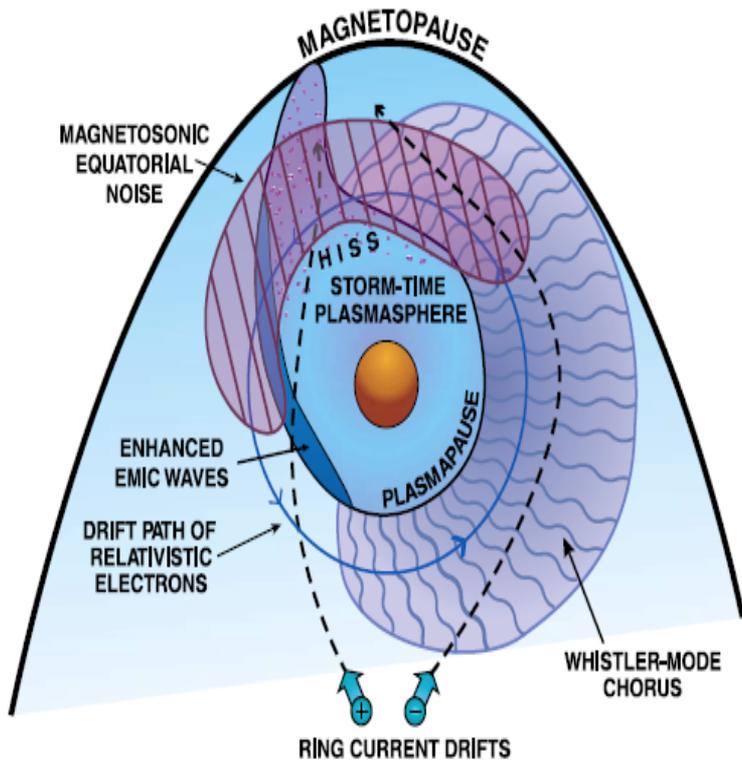
电磁离子回旋波



Plasmaspheric Hiss

Thorne, GRL, 2010





Wave-Particle interaction:

EMIC: RC ions Relativistic electrons

Hiss: RC electron Relativistic electrons

Chorus: RC electron Relativistic electrons

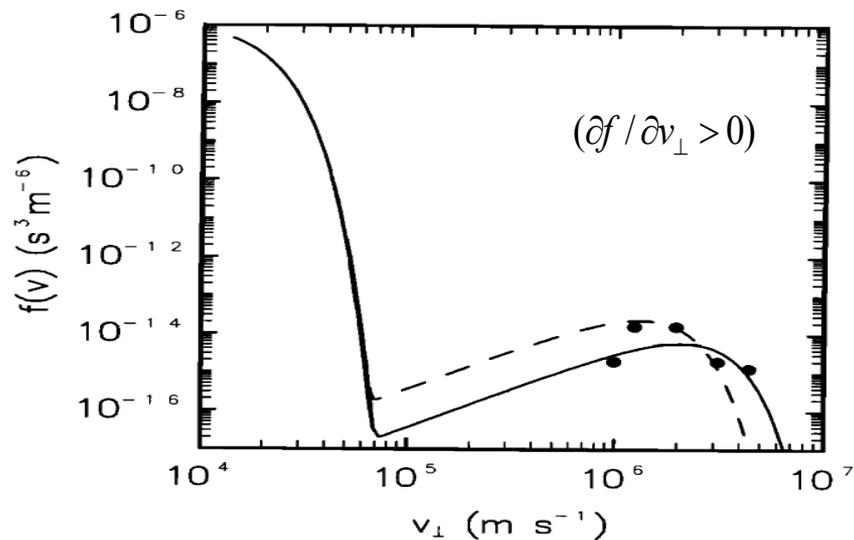
Ms: RC ions Relativistic electrons

内磁层-电离层物质耦合系统

磁声波的激发

磁声波的传播

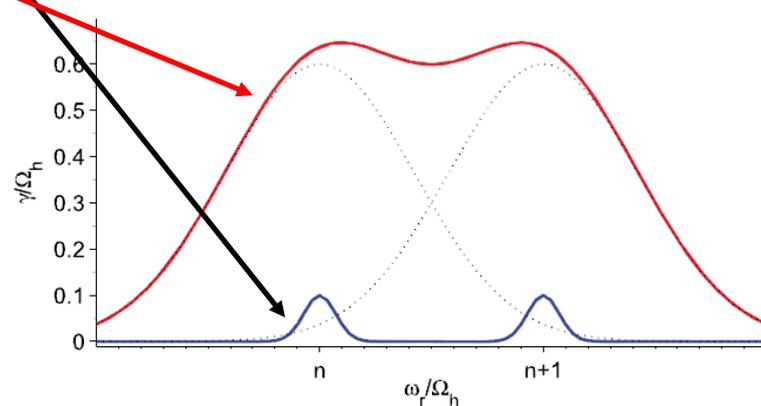
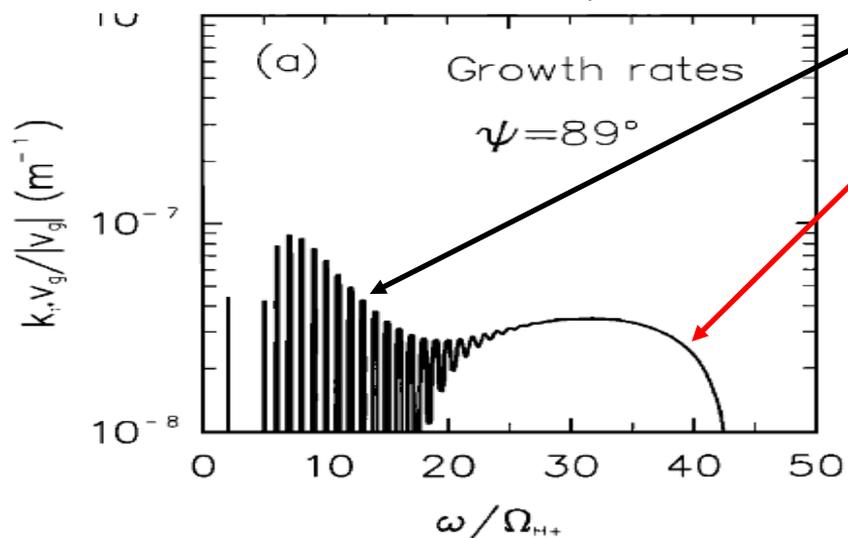
磁声波的波粒相互作用



高斜传播的磁声
(Magnetosonic MS)波由
环分布的能量质子激发。

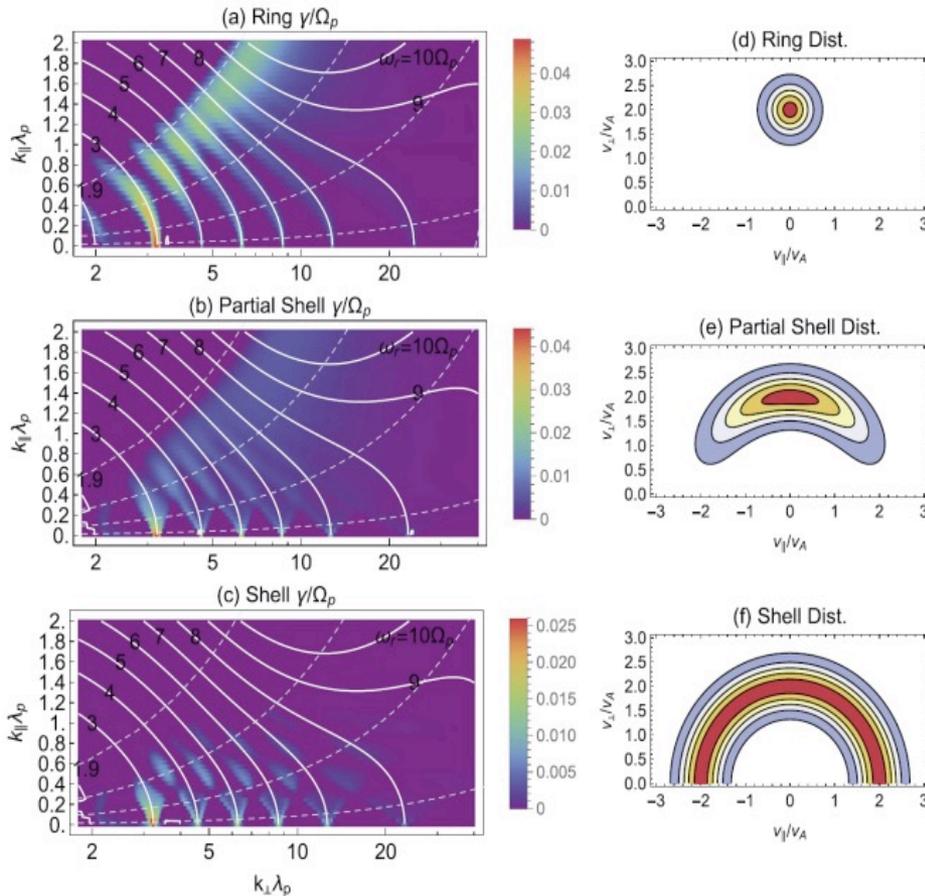
$$(\partial f / \partial v_{\perp} > 0)$$

频谱特征：
质子回旋频率与低混杂频率之间
低频谐波：离散谱
高频部分：连续谱



动理学色散关系的求解-磁声波激发

磁声波激发源的分布



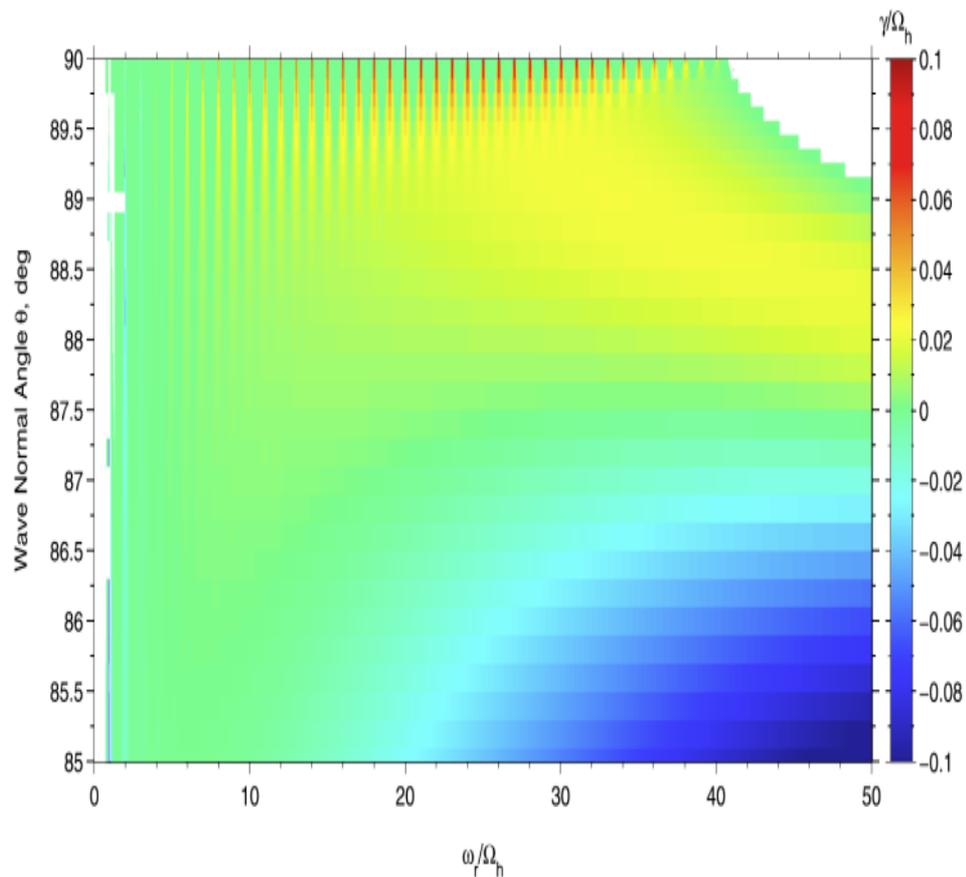
$$f_r = \frac{n_r}{\pi^{3/2} \theta_{\parallel r} \theta_{\perp r}^2 C_r} e^{-v_{\parallel}^2/\theta_{\parallel r}^2} e^{-(v_{\perp} - v_r)^2/\theta_{\perp r}^2},$$

$$C_r = e^{-v_r^2/\theta_{\perp r}^2} + \sqrt{\pi} \left(\frac{v_r}{\theta_{\perp r}} \right) \operatorname{erfc} \left(-\frac{v_r}{\theta_{\perp r}} \right),$$

$$f_s = \frac{n_s}{\pi^{3/2} \theta_s^3 C_s} e^{-(v-v_s)^2/\theta_s^2} \sin^{\sigma_s} \alpha,$$

$$C_s = \left[\frac{v_s}{\theta_s} e^{-v_s^2/\theta_s^2} + \sqrt{\pi} \left(\frac{1}{2} + \frac{v_s^2}{\theta_s^2} \right) \operatorname{erfc} \left(-\frac{v_s}{\theta_s} \right) \right] \frac{\Gamma(1 + \sigma_s/2)}{\Gamma(1.5 + \sigma_s/2)},$$

动理学色散关系的求解-磁声波激发

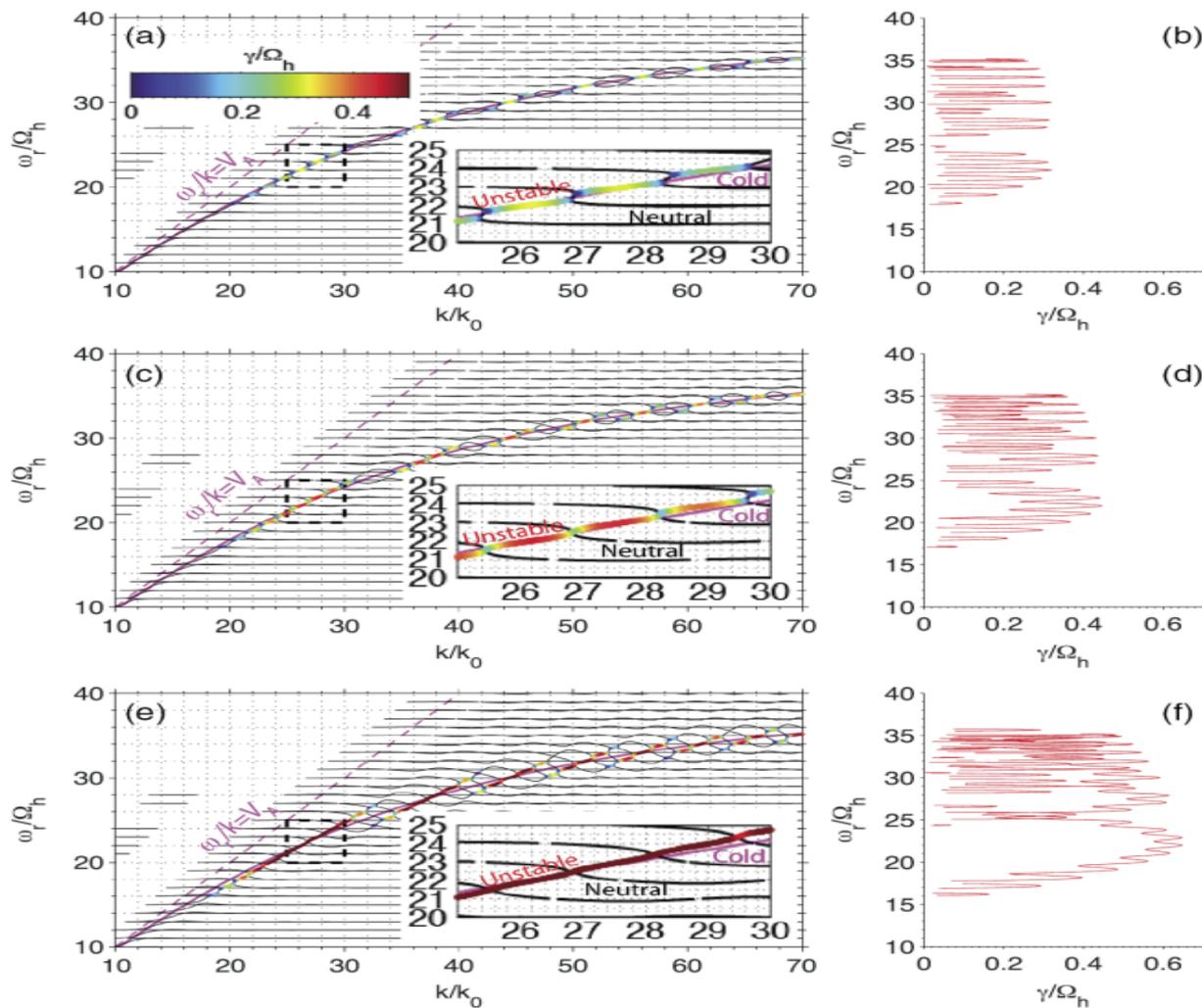


环分布的源离子

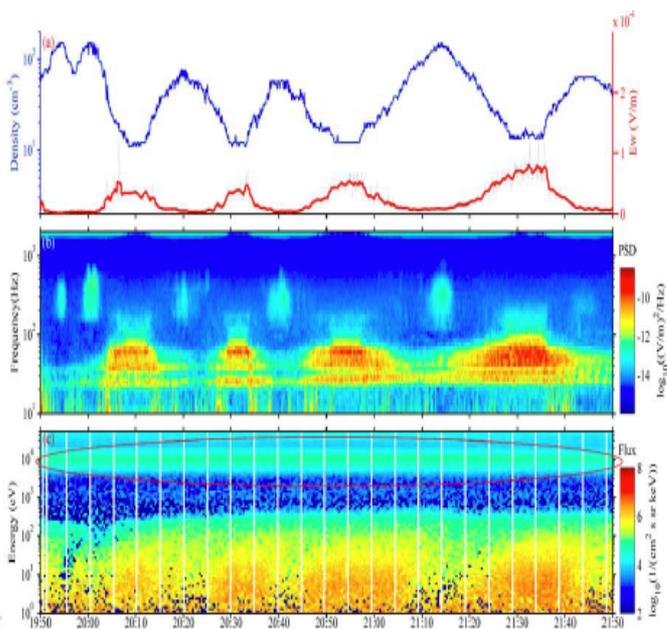
$$f_r = \frac{n_r}{\pi^{3/2} \theta_{\parallel r} \theta_{\perp r}^2 C_r} e^{-v_{\parallel}^2 / \theta_{\parallel r}^2} e^{-(v_{\perp} - v_r)^2 / \theta_{\perp r}^2},$$

$$C_r = e^{-v_r^2 / \theta_{\perp r}^2} + \sqrt{\pi} \left(\frac{v_r}{\theta_{\perp r}} \right) \operatorname{erfc} \left(-\frac{v_r}{\theta_{\perp r}} \right),$$

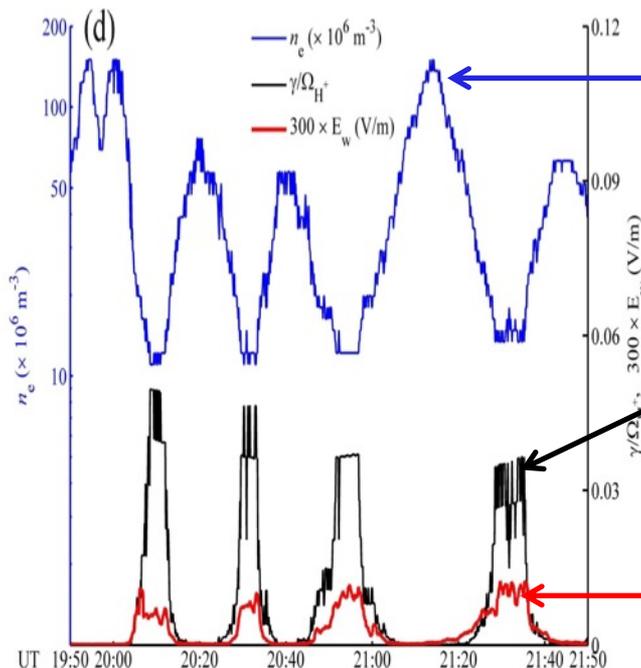
磁声波的色散曲线



RBSP卫星观测



波与背景参数的对比



等离子体密度

控制

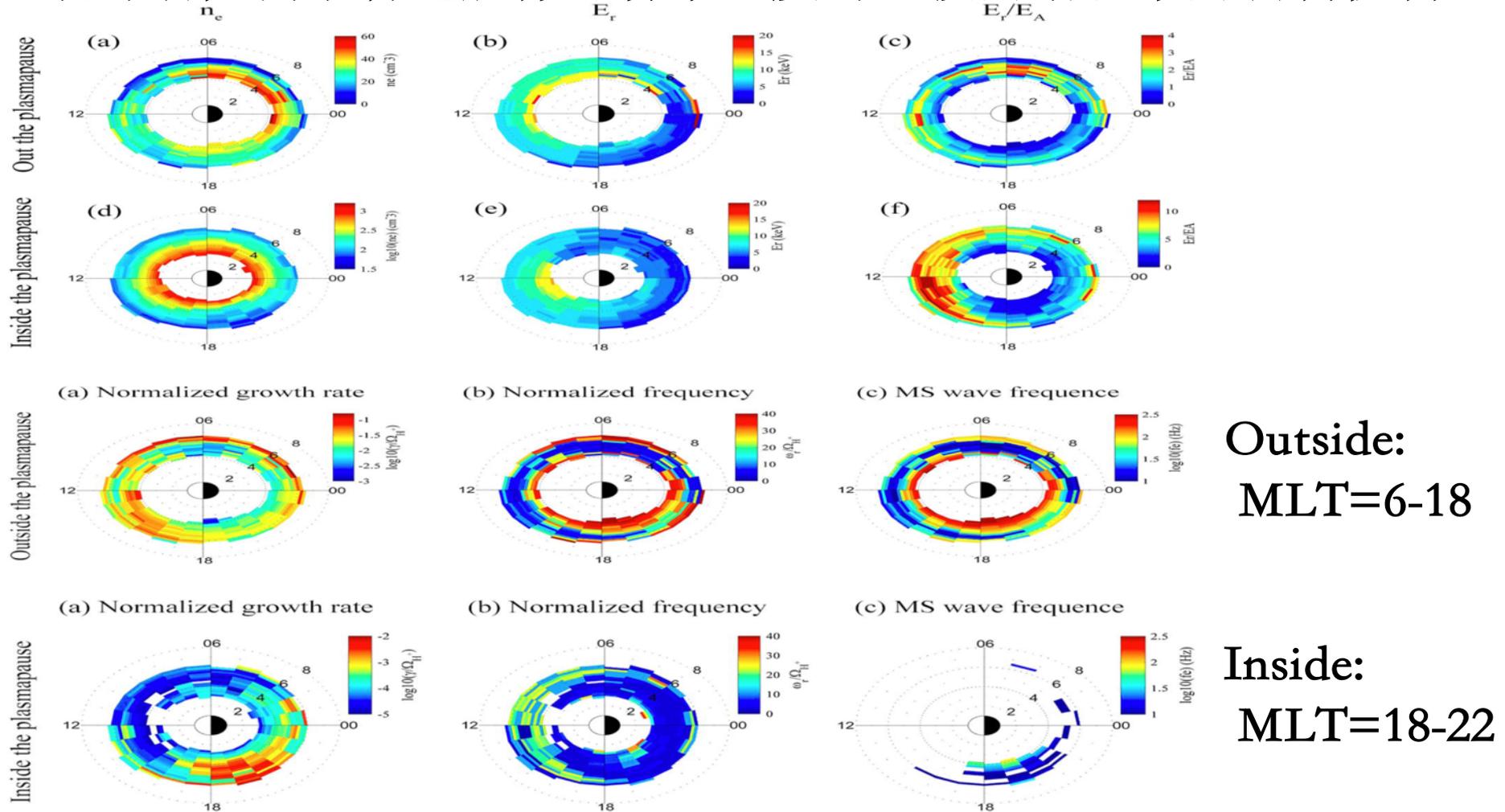
线性增长率

调制

磁声波幅度

意义：提供了背景电子密度对磁声波幅度调制的实地观测证据，揭示了背景电子密度对磁声波幅度调制的物理机制。

统计研究揭示普适规律：背景密度对MS波的增长率的调制机制



RBSP观测

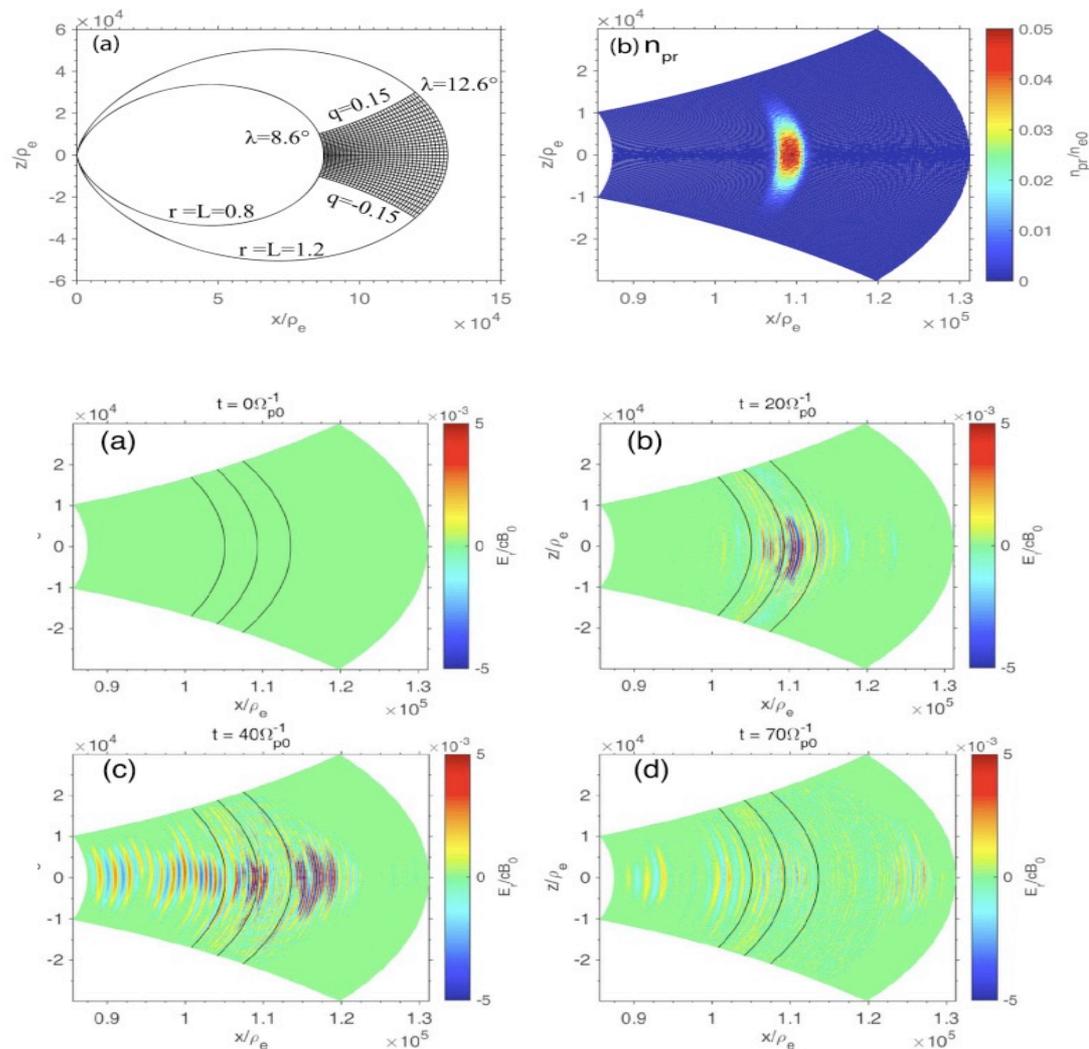
Yuan et al., 2018 GRL

磁声波的激发

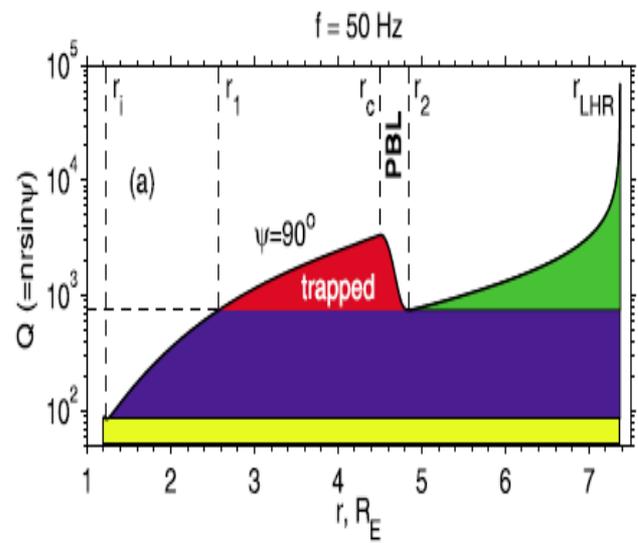
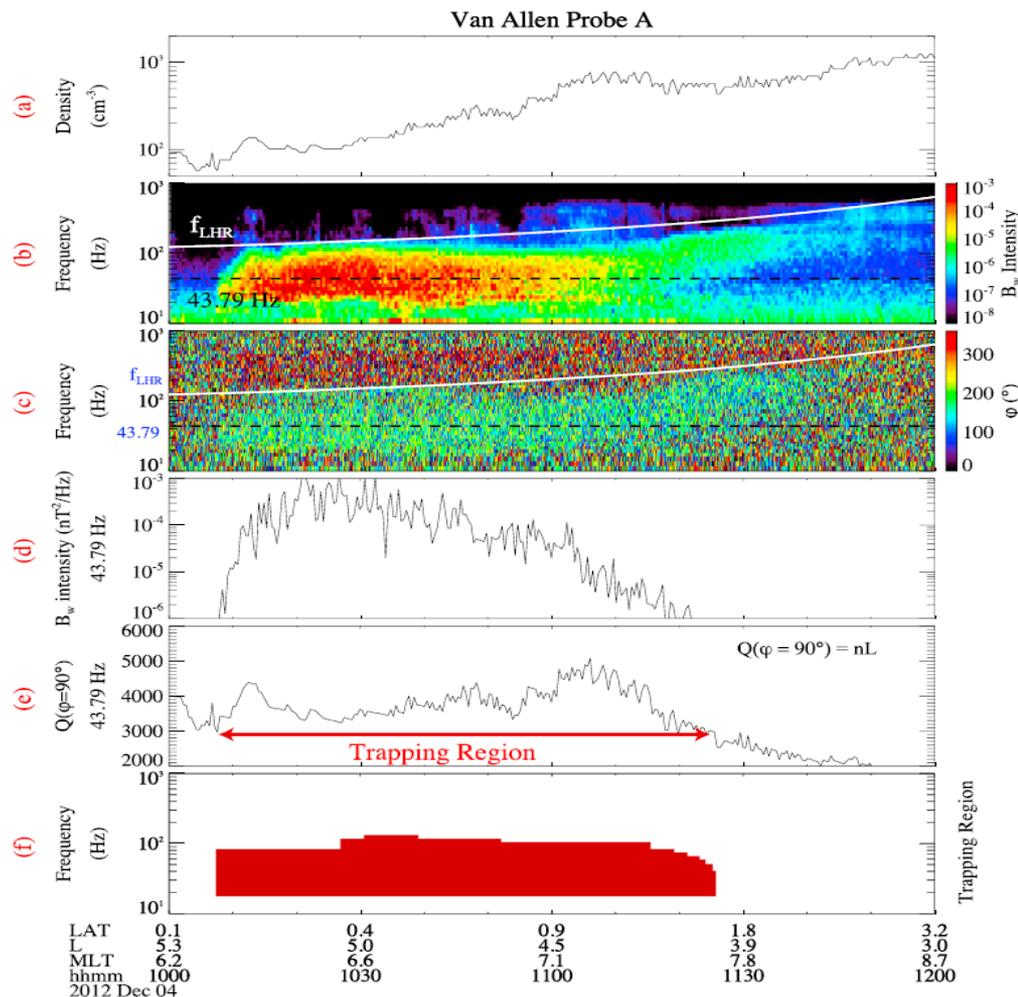
磁声波的传播

磁声波的波粒相互作用

PIC模拟磁声波的传播



背景电子密度对磁声波传播的调制



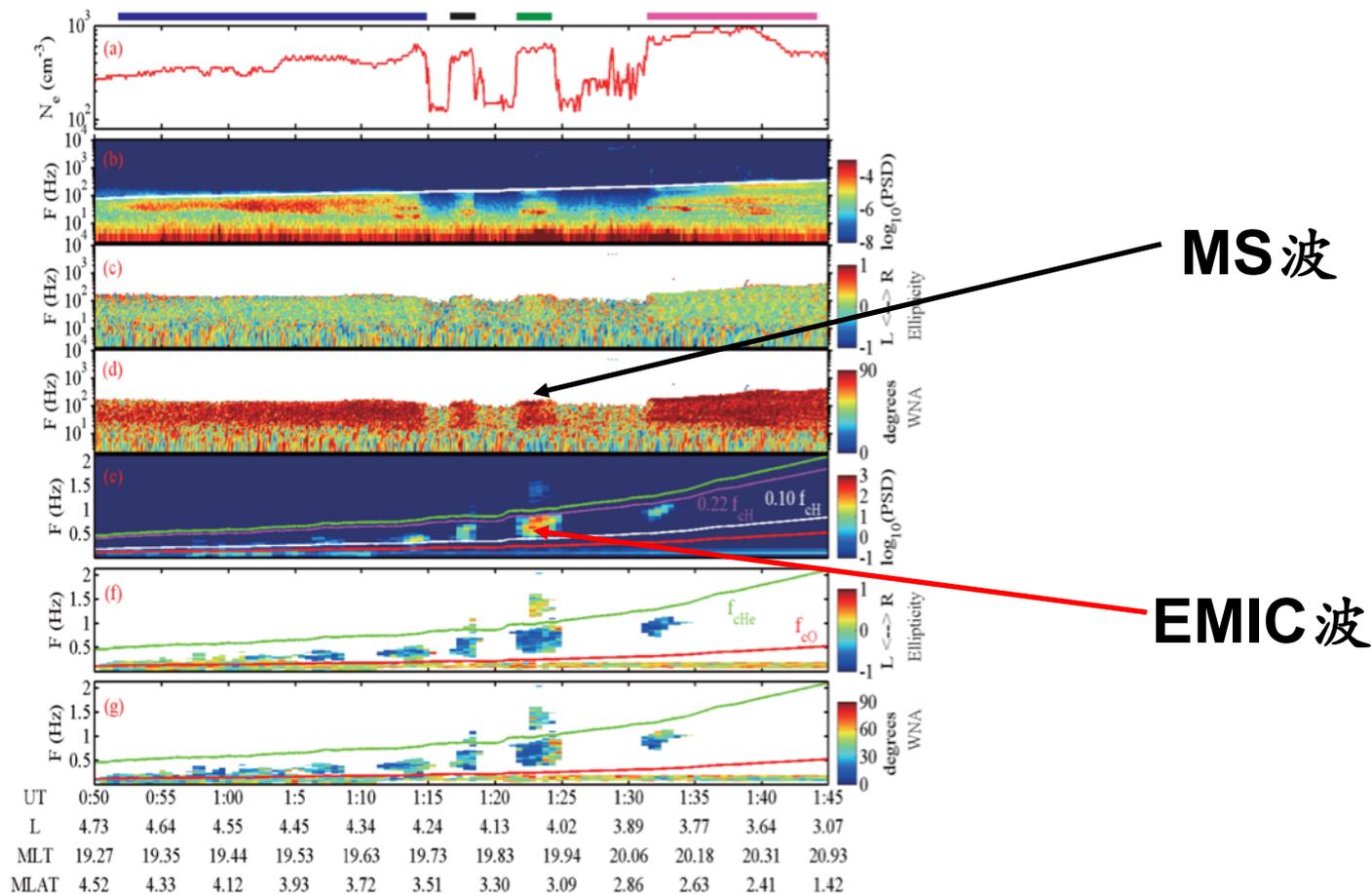
Chen and Thorne
2012 GRL

背景密度调制
传播因子Q

$$Q = nrsin\psi$$

Ma et al., 2014 GRL

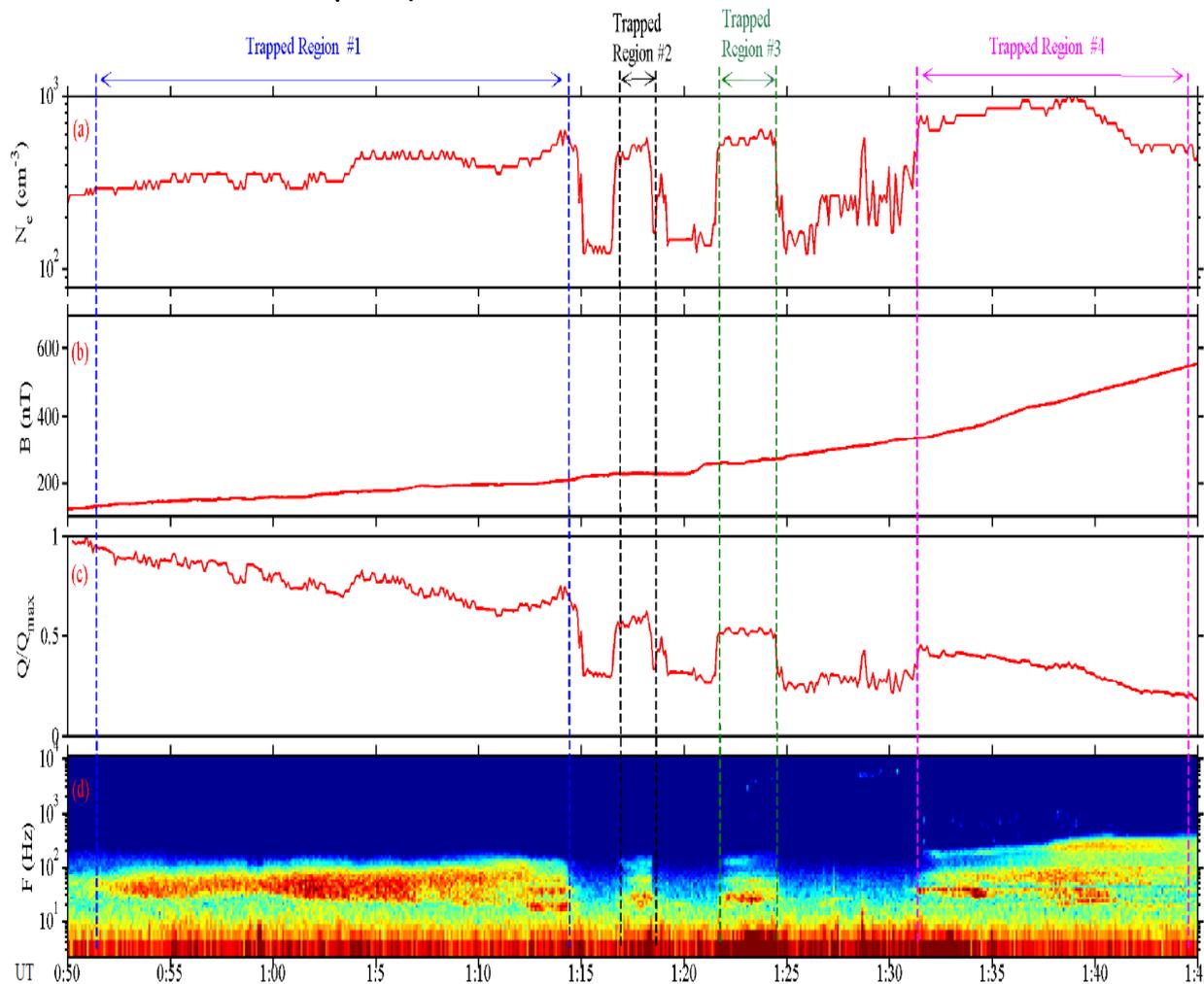
EMIC波及MS波的同时束缚观测



RBSP观测

Yuan et al., 2019 JGR

MS波的束缚

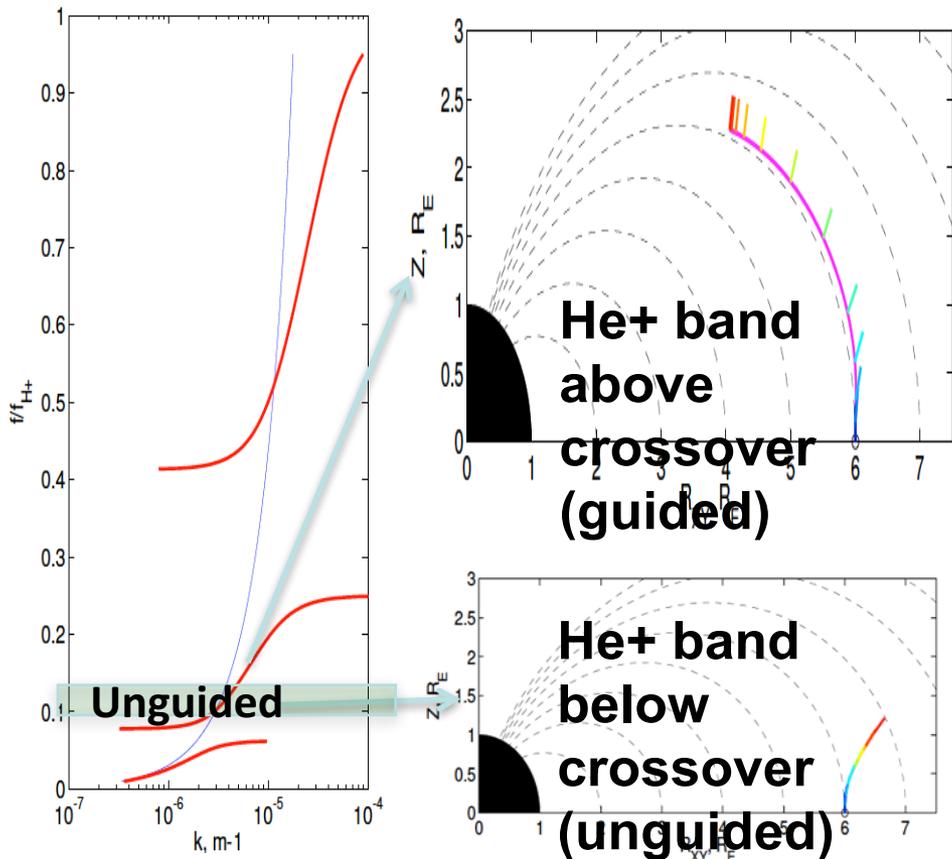
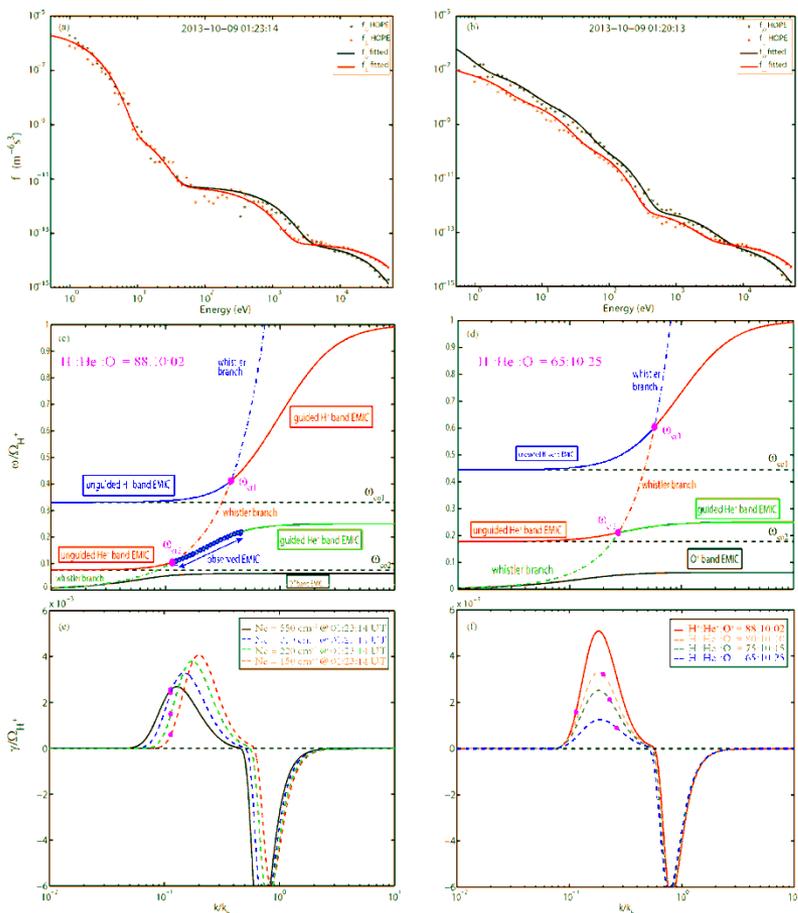


背景密度调制
传播因子Q
Snell 定理

$$Q = n r \sin \psi$$

$f=30$ Hz

揭示了背景等离子体结构同时束缚磁声波和EMIC波的物理机制。开拓了等离子体层边界的波粒相互作用的新思路。

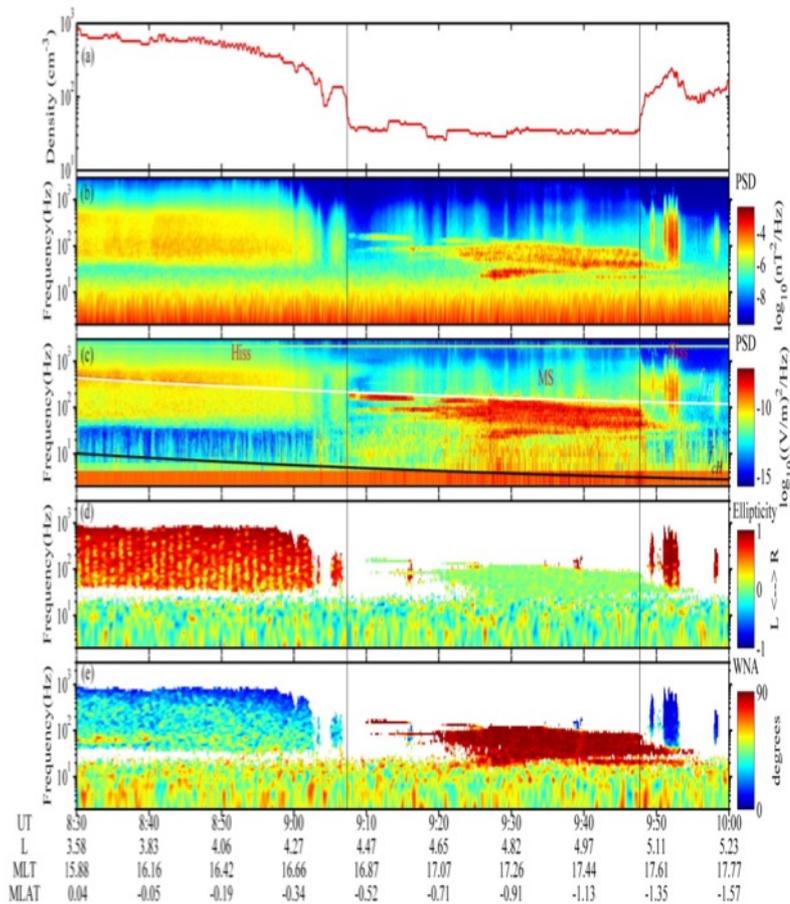


右旋波模
左旋波模

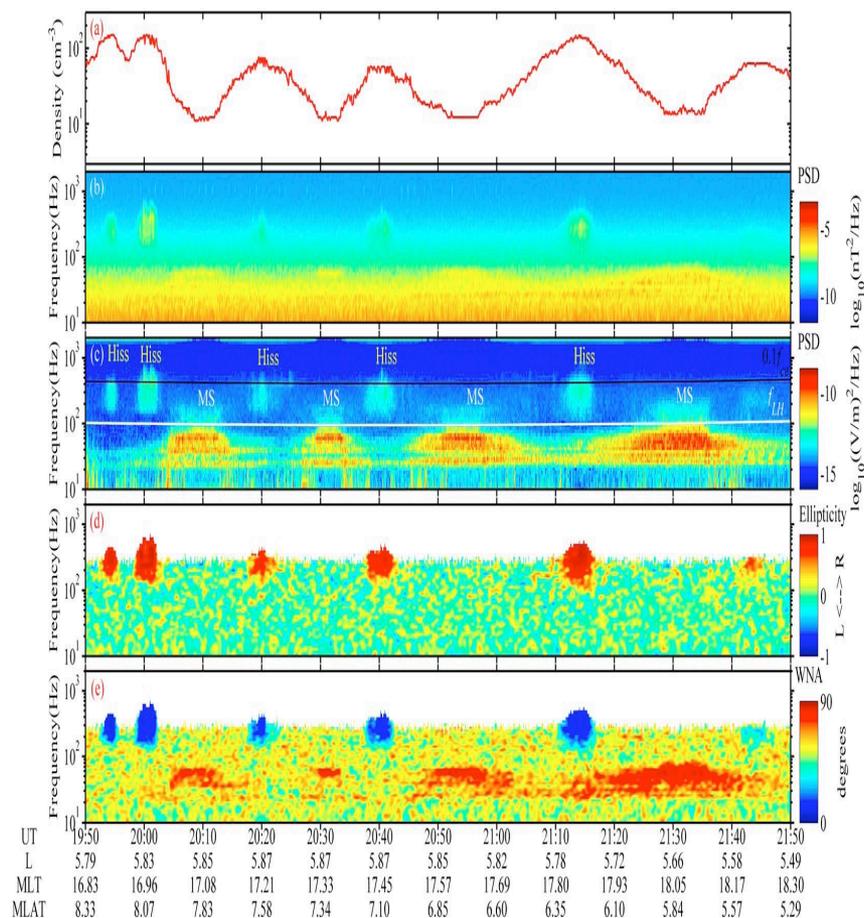
背景离子成分调制 ω_{cr2}

EMIC波的束缚

电磁型磁声波（经典型）

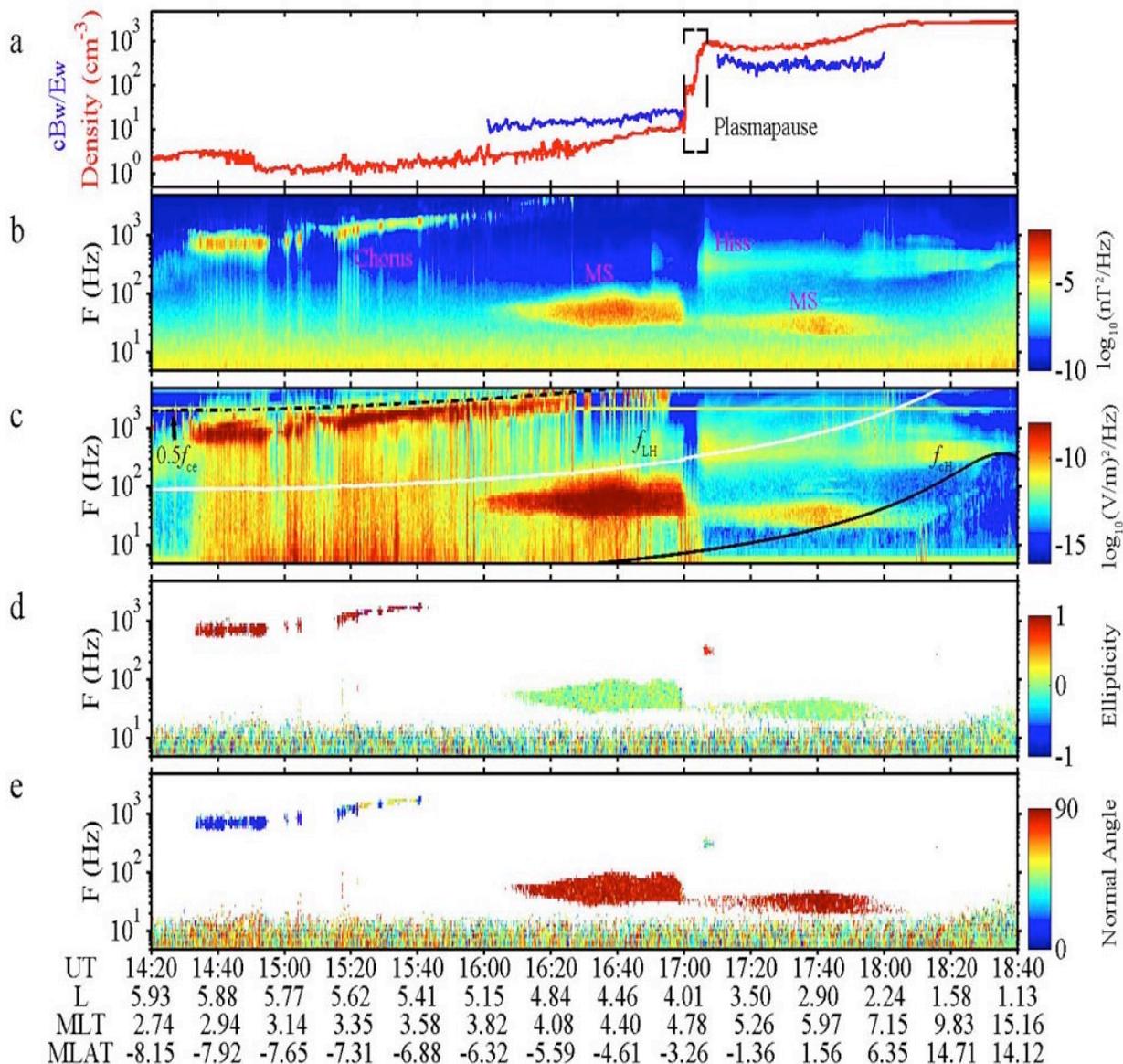


静电型磁声波（新型）



关键问题： 决定磁声波的电磁特性的**关键因数**是什么？内磁层中两种类型磁声波的相对比例是多少？

背景等离子体密度对磁声波的调制



$$\nabla \times \delta E = -\frac{\partial B}{\partial t}$$

$$k \times \delta E = \omega \delta B$$

$$\delta E_{k//} \Rightarrow \delta B = 0$$

$$\frac{c \delta B}{n \delta E_{\perp}} = 1$$

$$\frac{c \delta B}{n \delta E} \ll 1$$

静电型

$$\frac{\delta E_{\perp}}{\delta E_{//}} \ll 1$$

$$\frac{c \delta B}{n \delta E} \approx 1$$

电磁型

$$\frac{\delta E_{\perp}}{\delta E_{//}} \gg 1$$

电磁型

静电型



$$c\Delta B/\Delta E$$

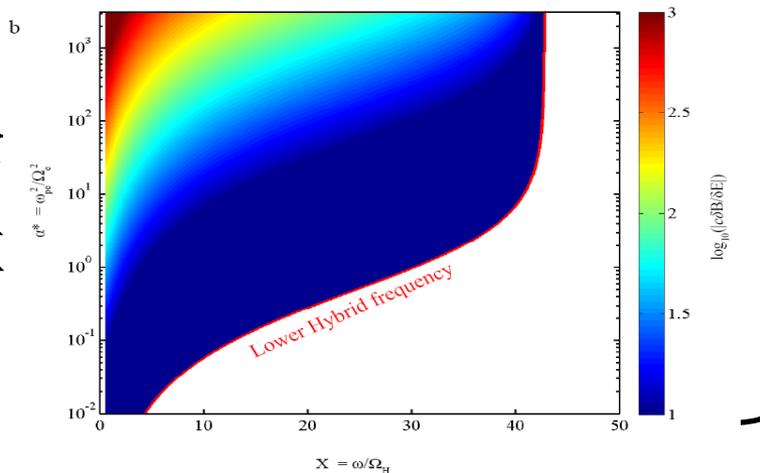
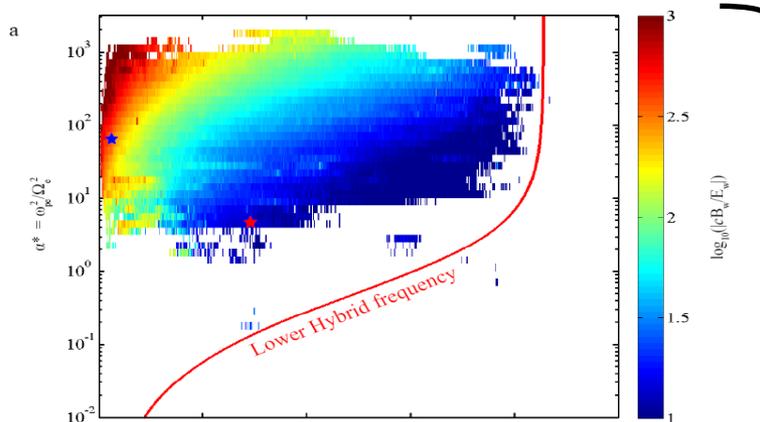
电磁型

静电型



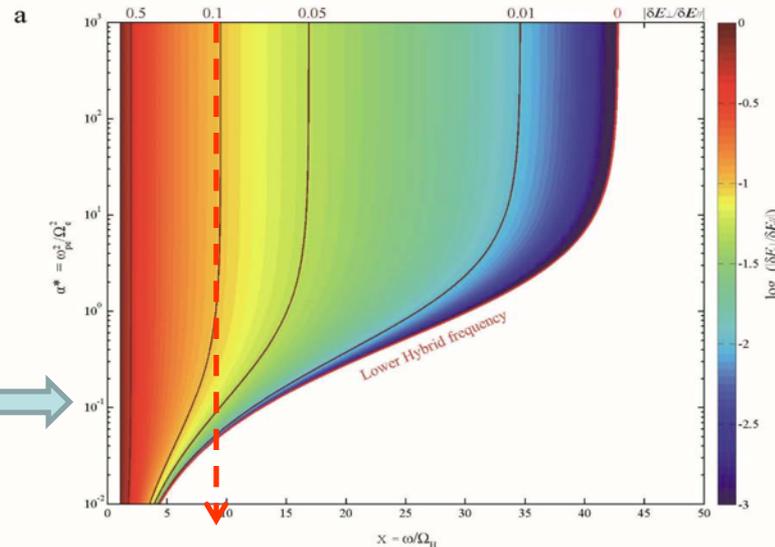
$$\Delta E_{\text{电磁}}/\Delta E_{\text{静电}}$$

卫星
观测



理论
计算

冷等离子体近似

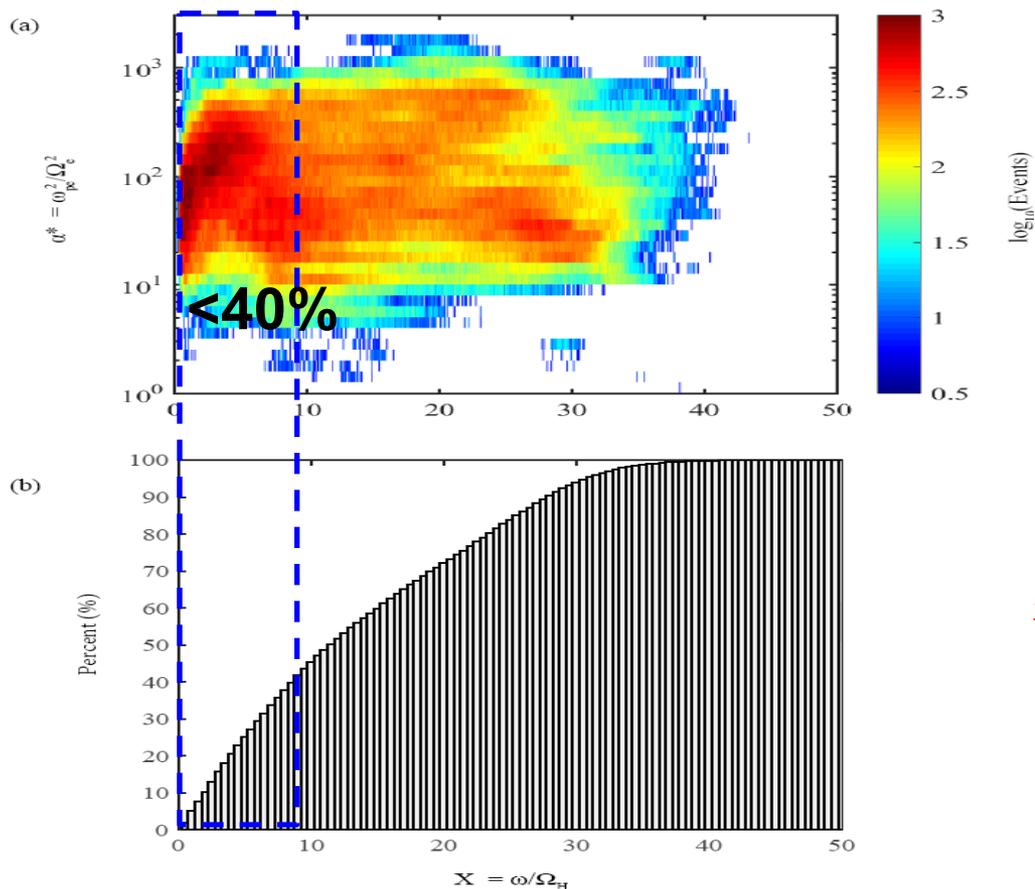


判断标准: $\Delta E_{\text{电磁}}/\Delta E_{\text{静电}}=0.1$

电磁型: 谐波阶数 $X < 8$

静电型: 谐波阶数 $X > 8$

RBSP卫星观测磁声波事件的分布



结论

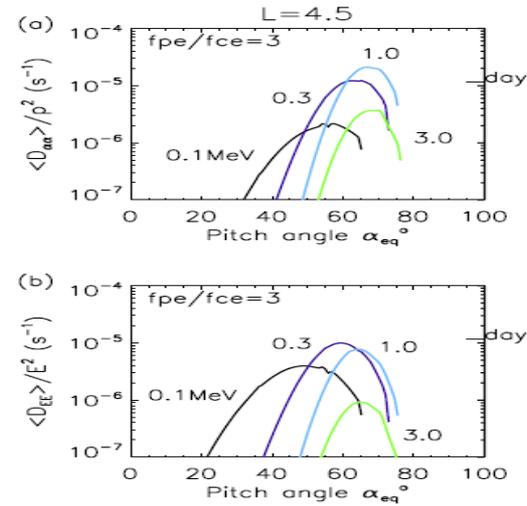
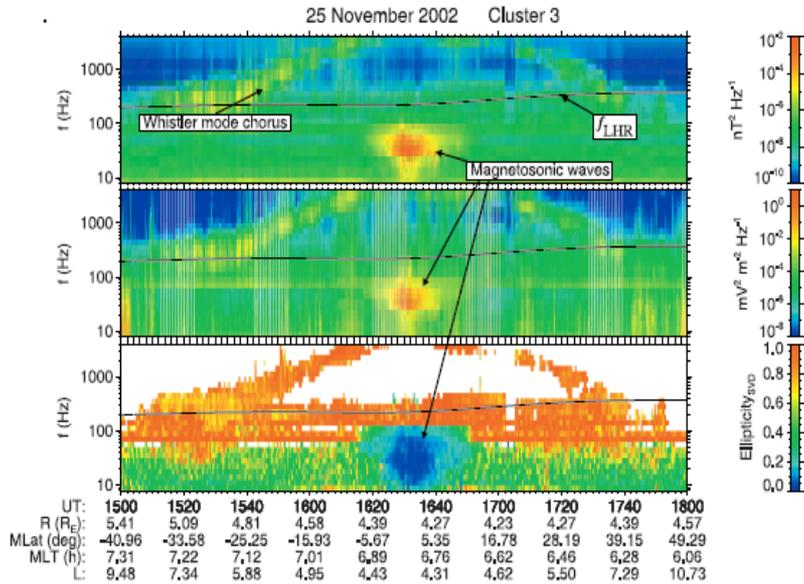
内磁层磁声波以静电型为主导。

静电分量亟待重点考虑。

磁声波的激发

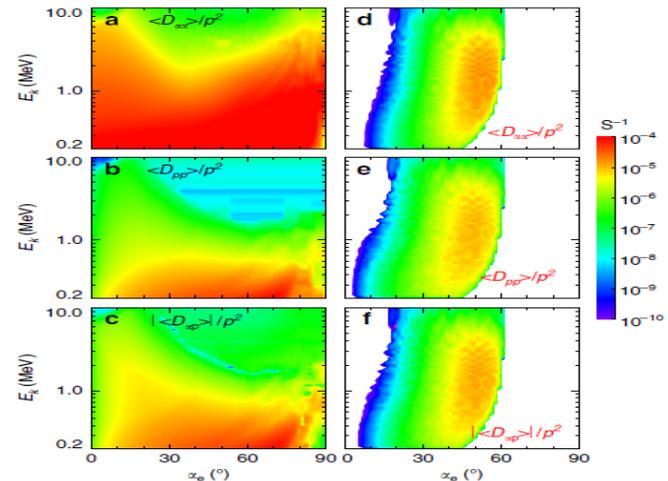
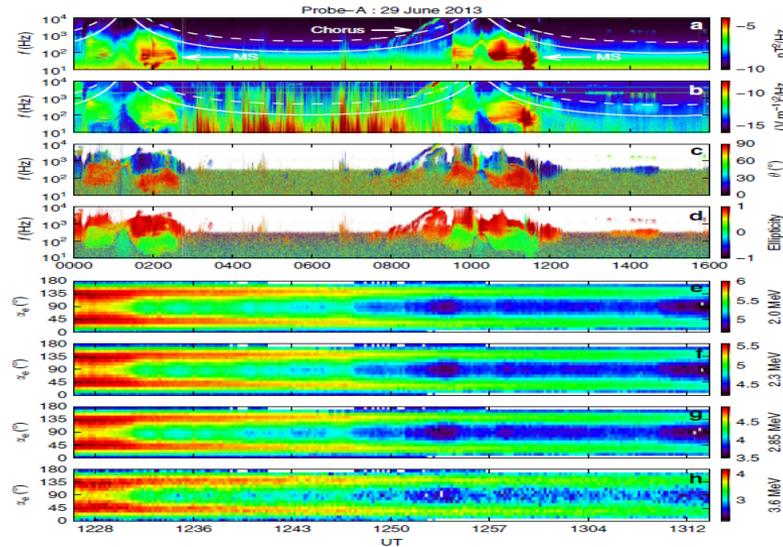
磁声波的传播

磁声波的波粒相互作用



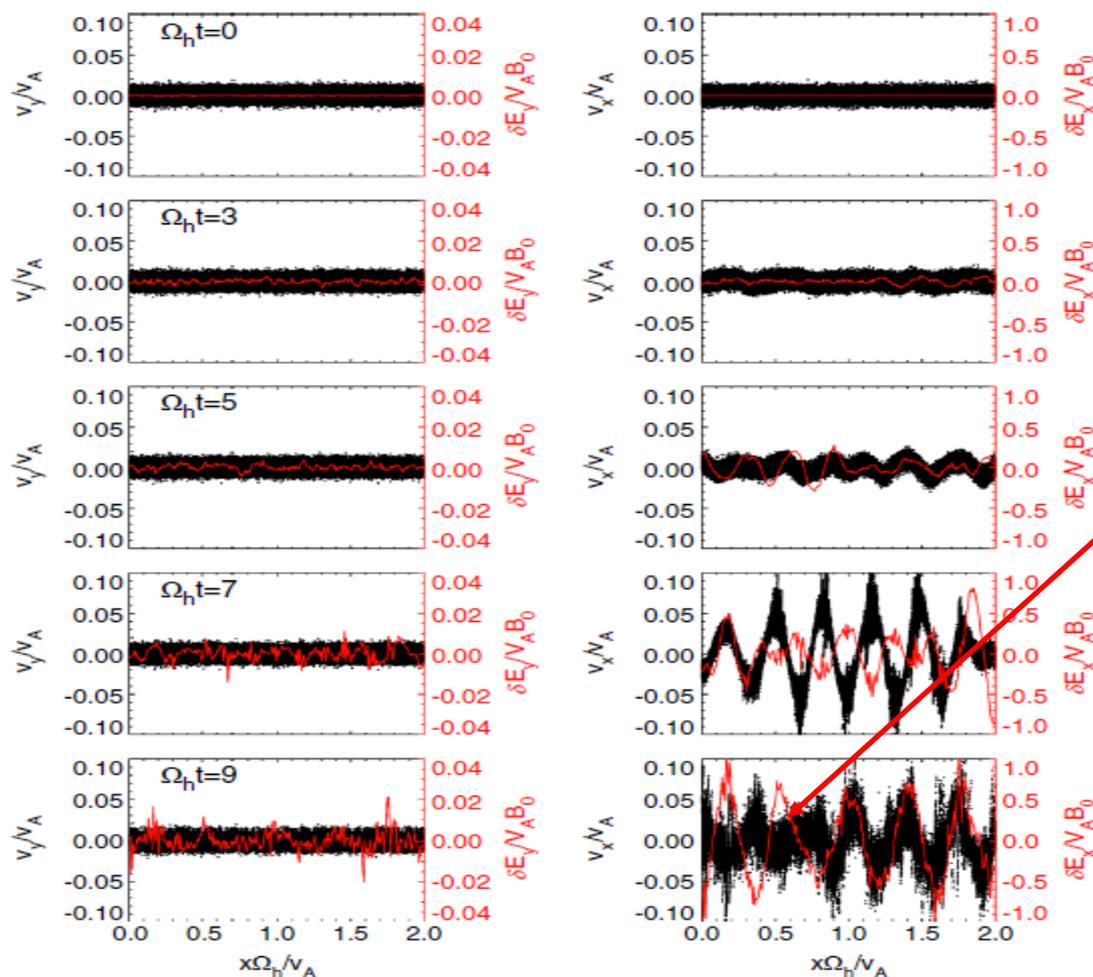
Horne, GRL, 2007

加能RC电子



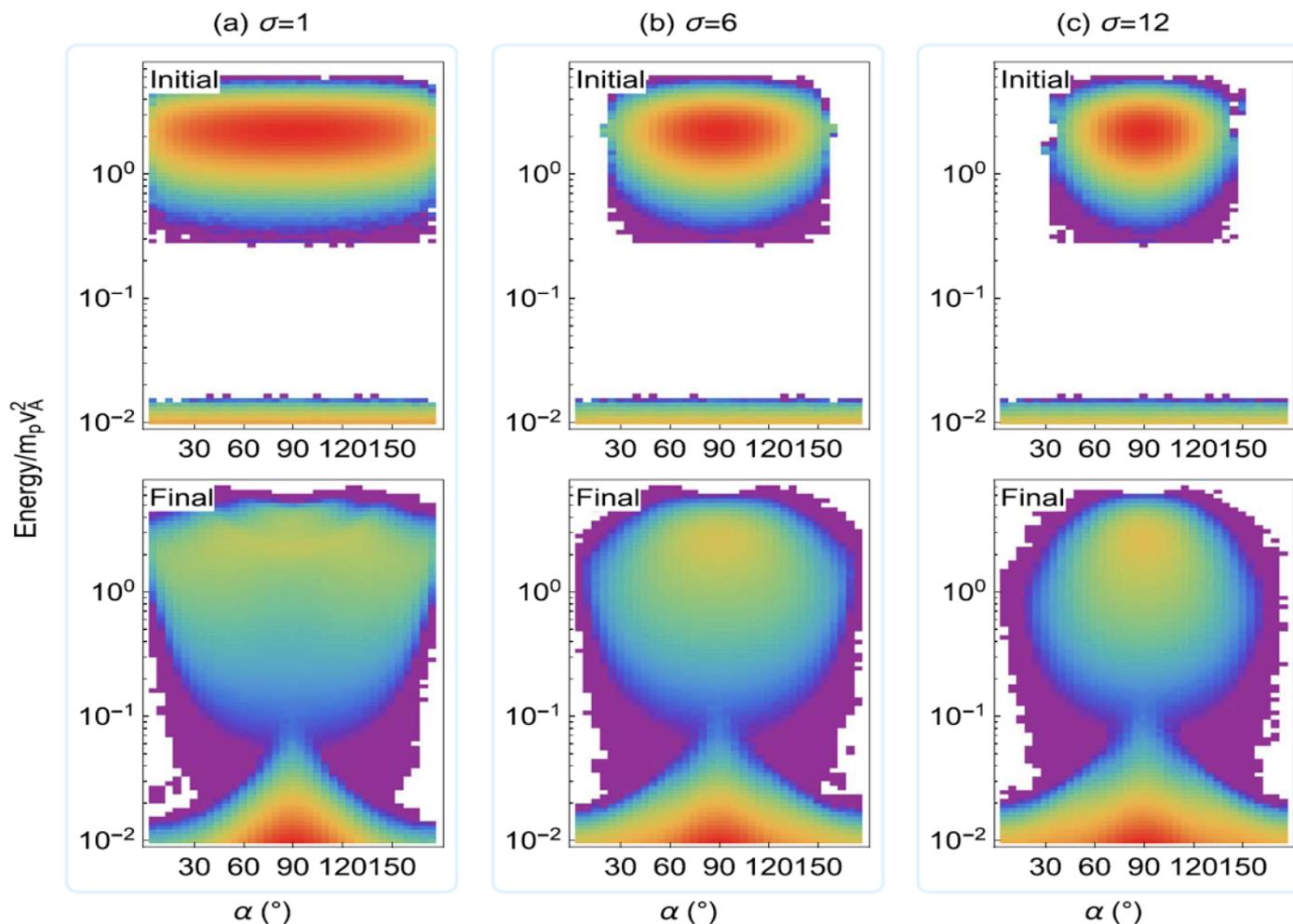
Xiao, NC, 2015

磁声波对等离子体层离子的加热

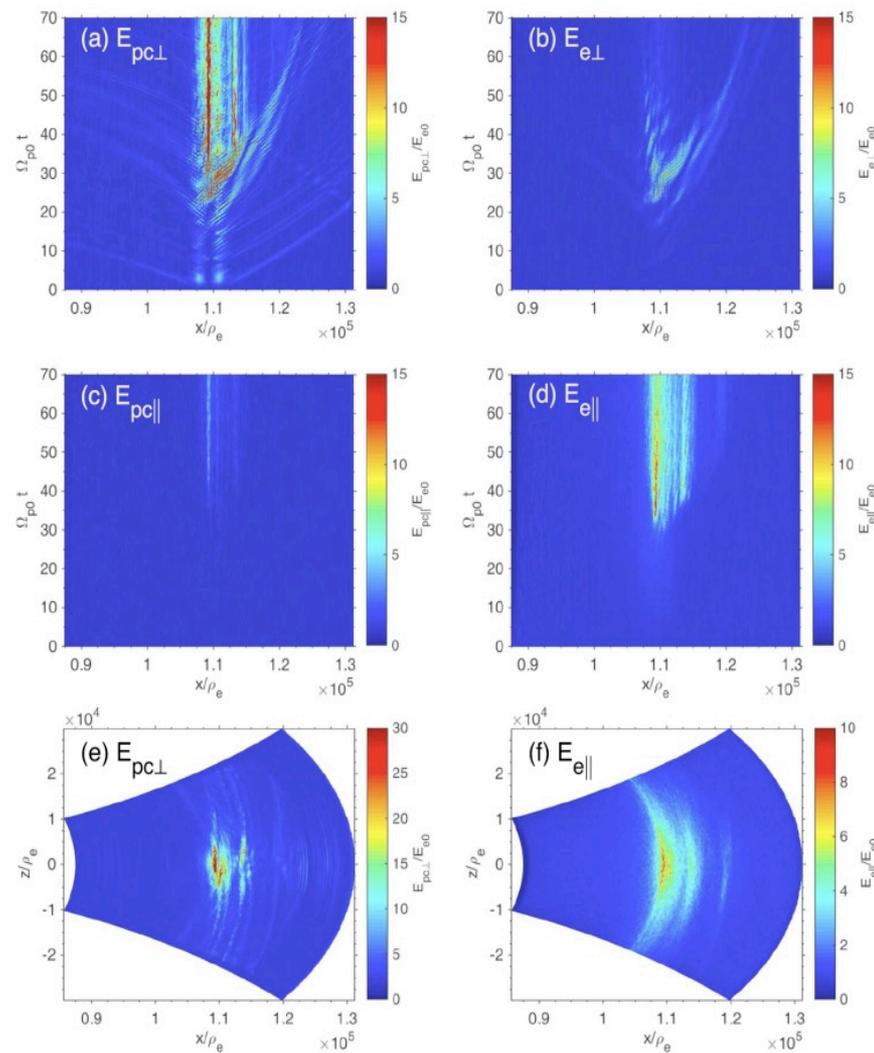
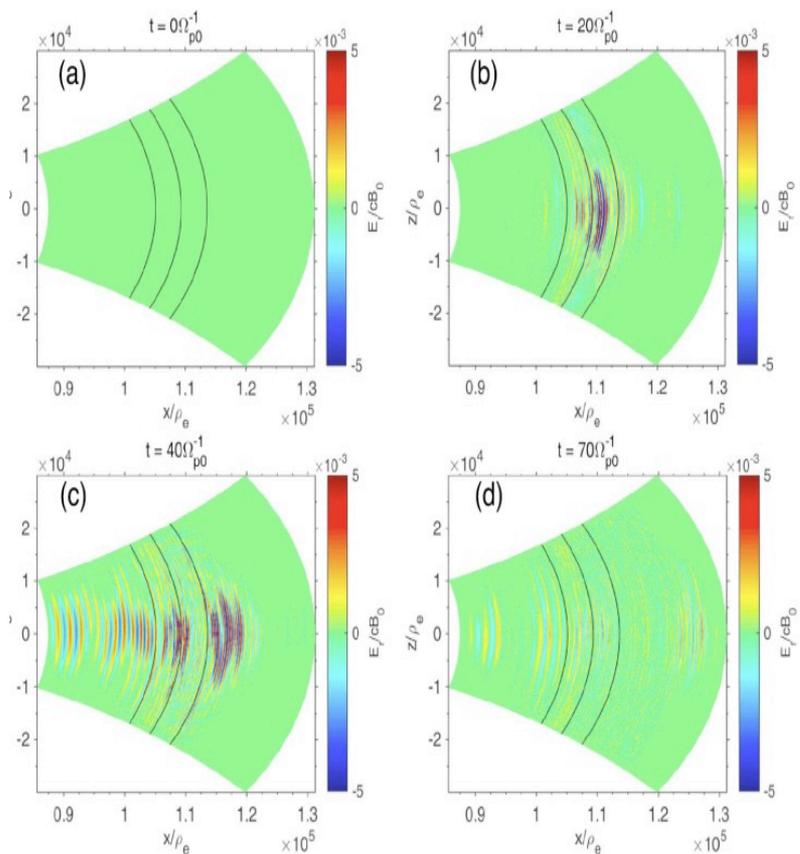


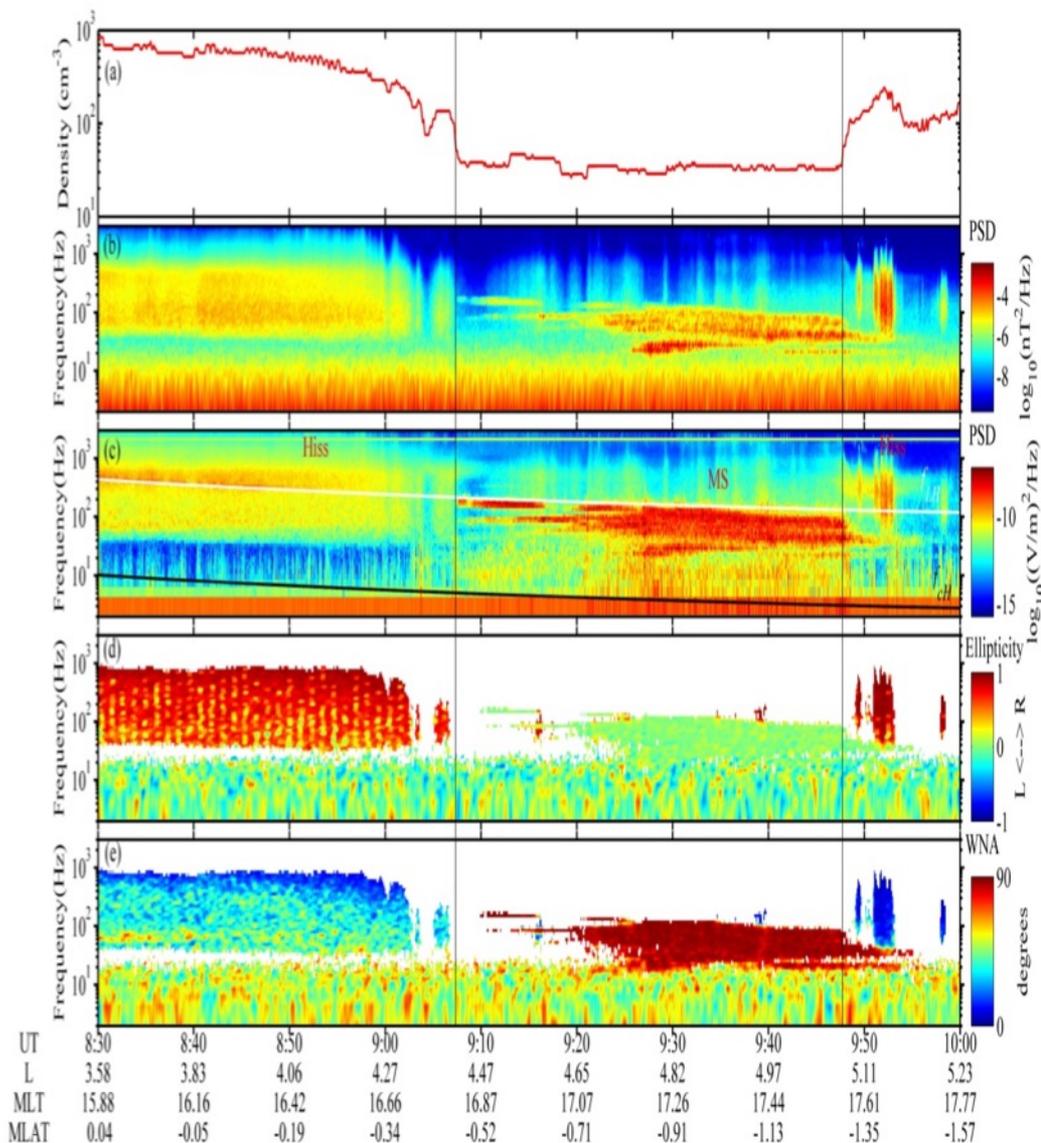
粒子模拟研究
表明：磁声波
能够垂直加热
等离子体层冷
离子

PIC 磁声波与离子的相互作用



PIC 磁声波冷等离子体的相互作用





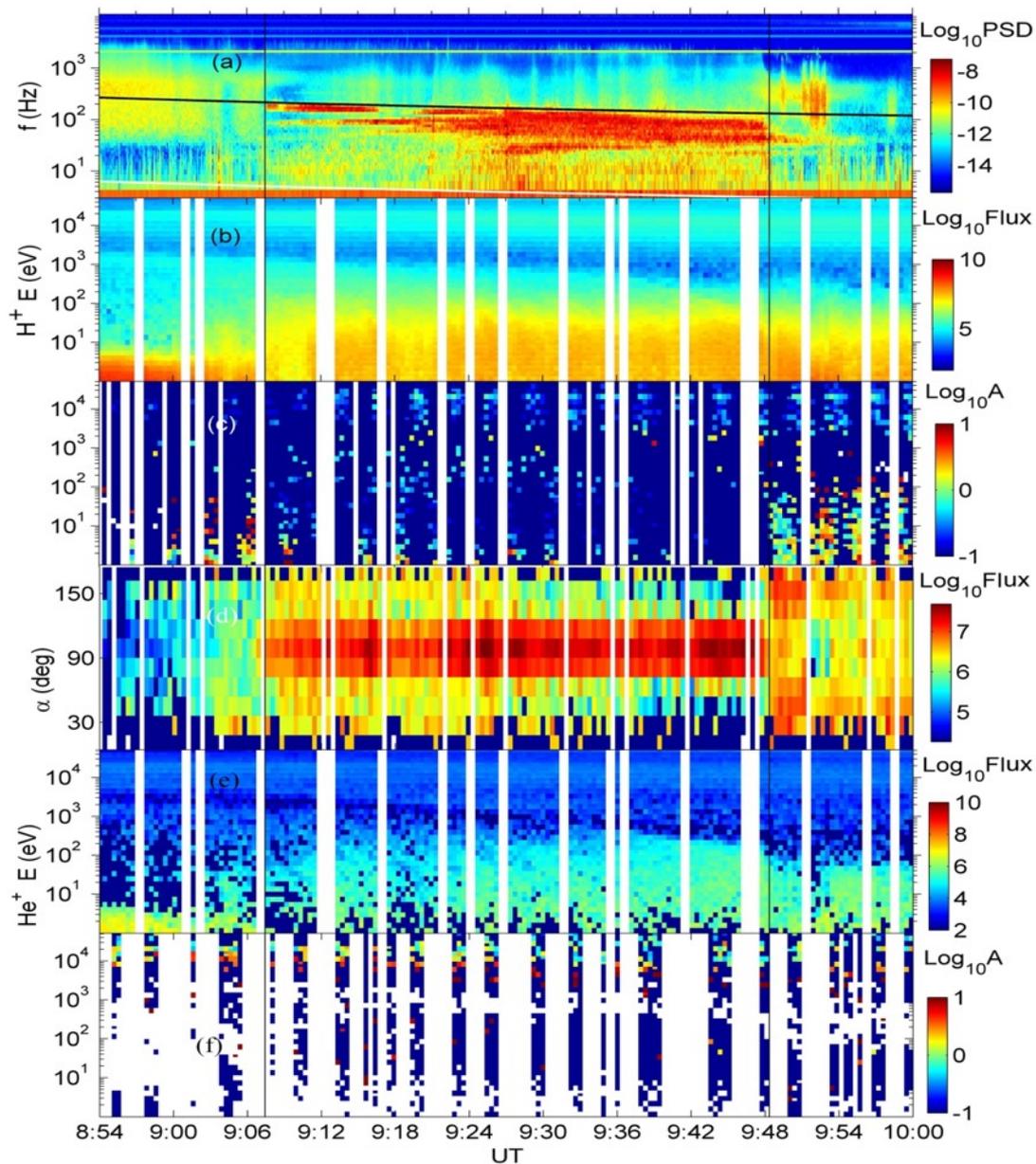
背景等离子体密度

磁场功率谱密度

电场功率谱密度

线性极化
 $|\epsilon| \sim 0$

高斜传播角 (~ 90 deg)



电场功率谱密度

H⁺ 通量

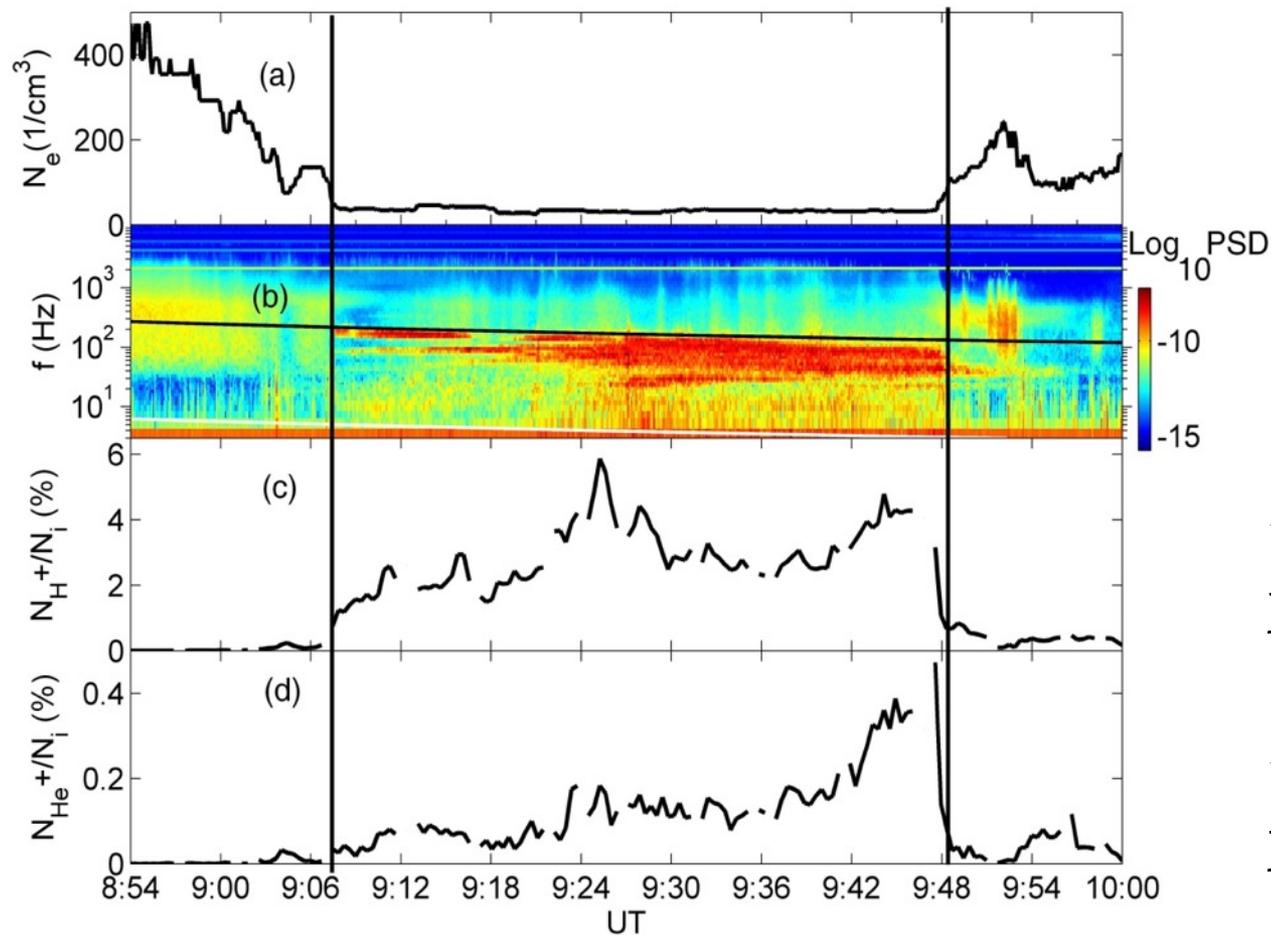
H⁺ 各向异性

73 eV H⁺

He⁺ 通量

He⁺ 各向异性

$$\omega - k_{\parallel} v_{\parallel} = m \omega_i$$

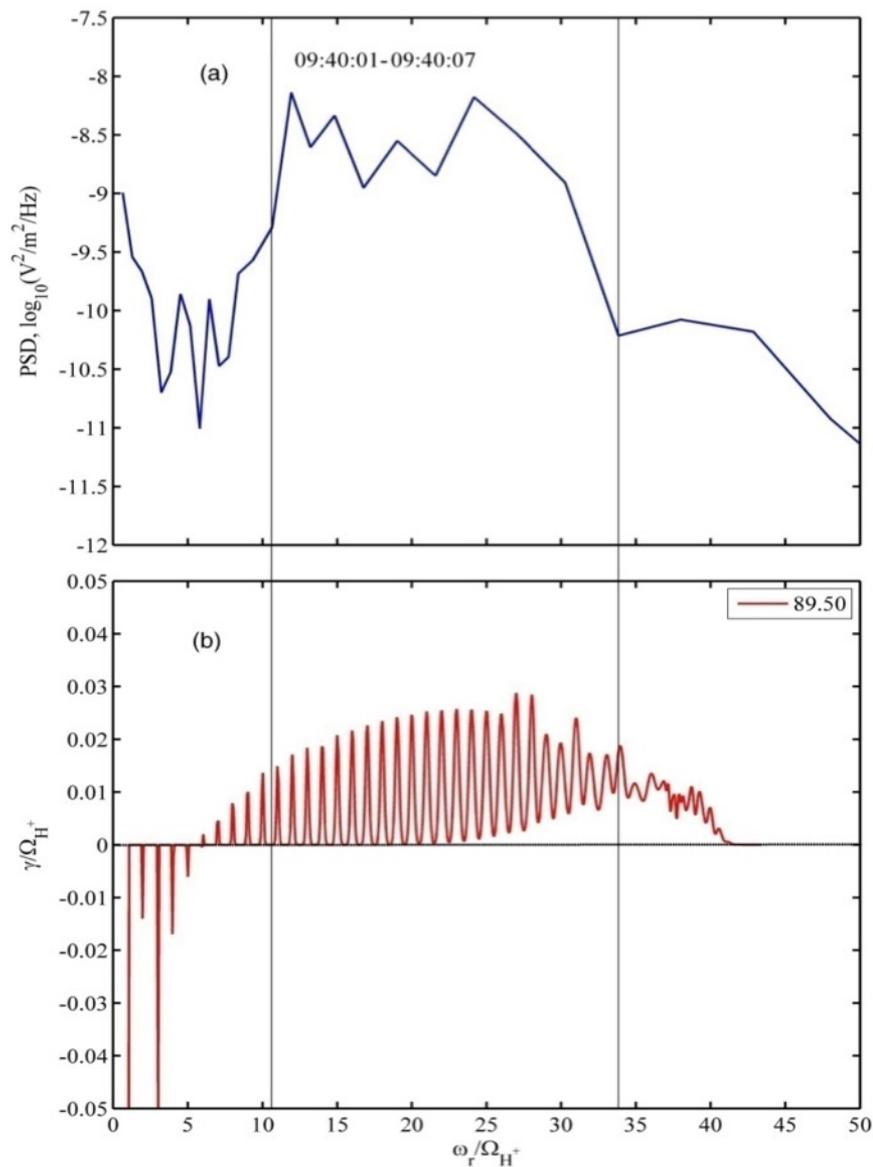


等离子体内槽

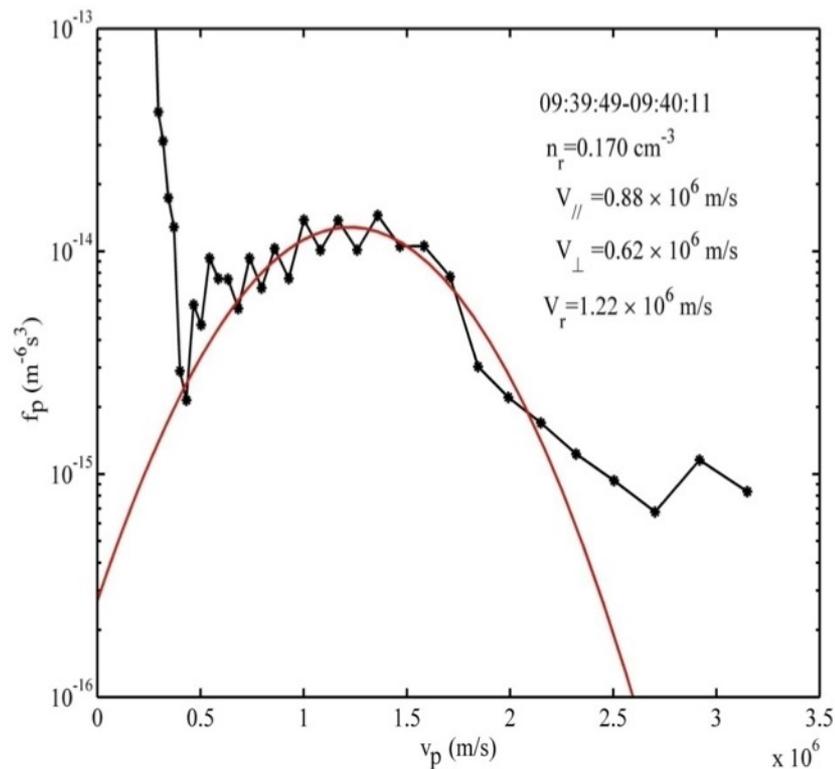
磁声波的功率谱

10-100 eV加热的
 H^+ 的比例增加

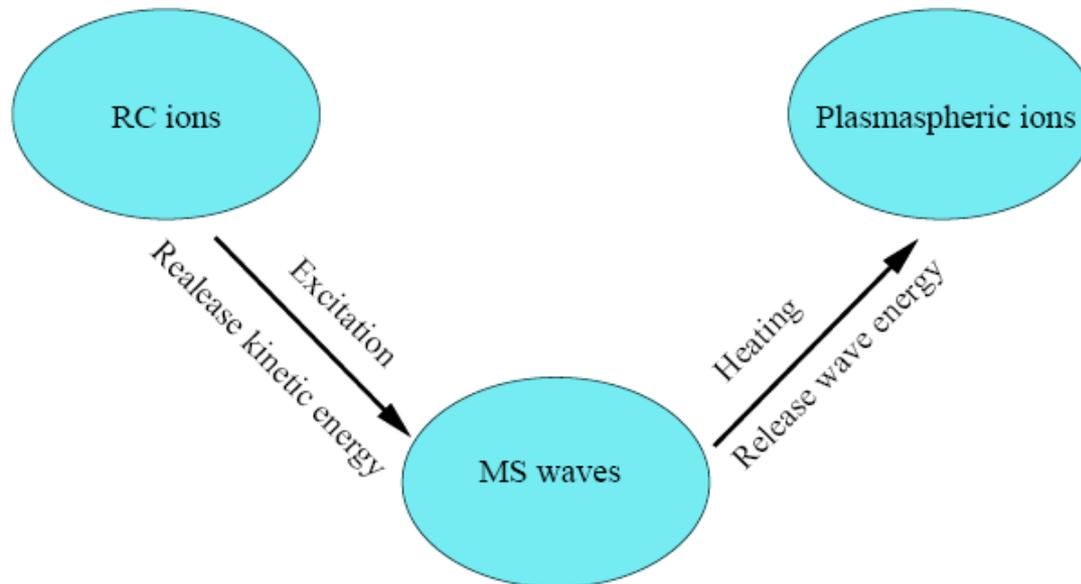
10-100 eV加热的
 He^+ 的比例增加



磁声波可以当地激发

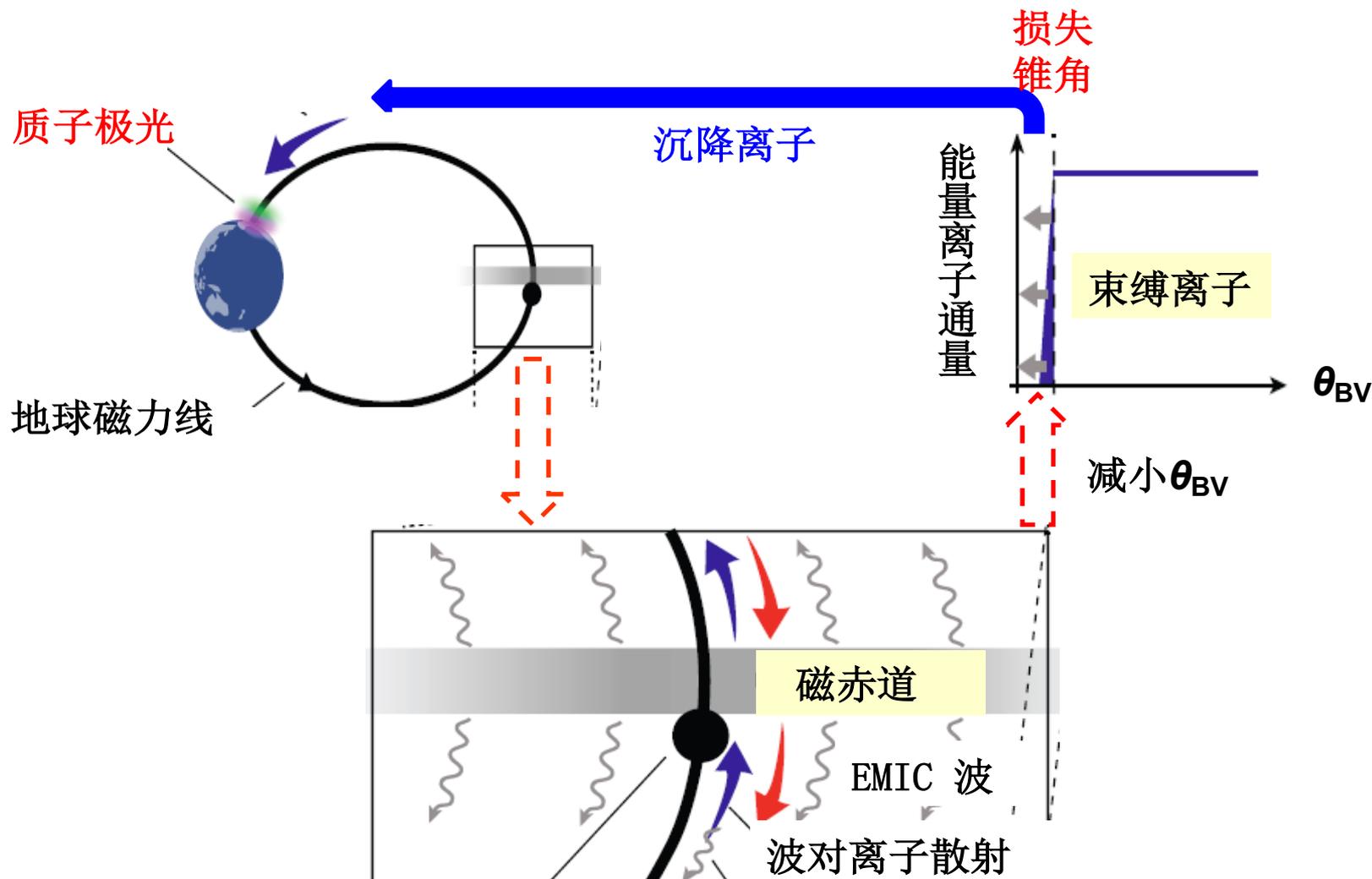


发现磁声波对冷离子加热的观测证据，证实了磁声波对等离子体层离子高谐共振加热的物理机制。提出了环电流与等离子体层能量转换的新机制。

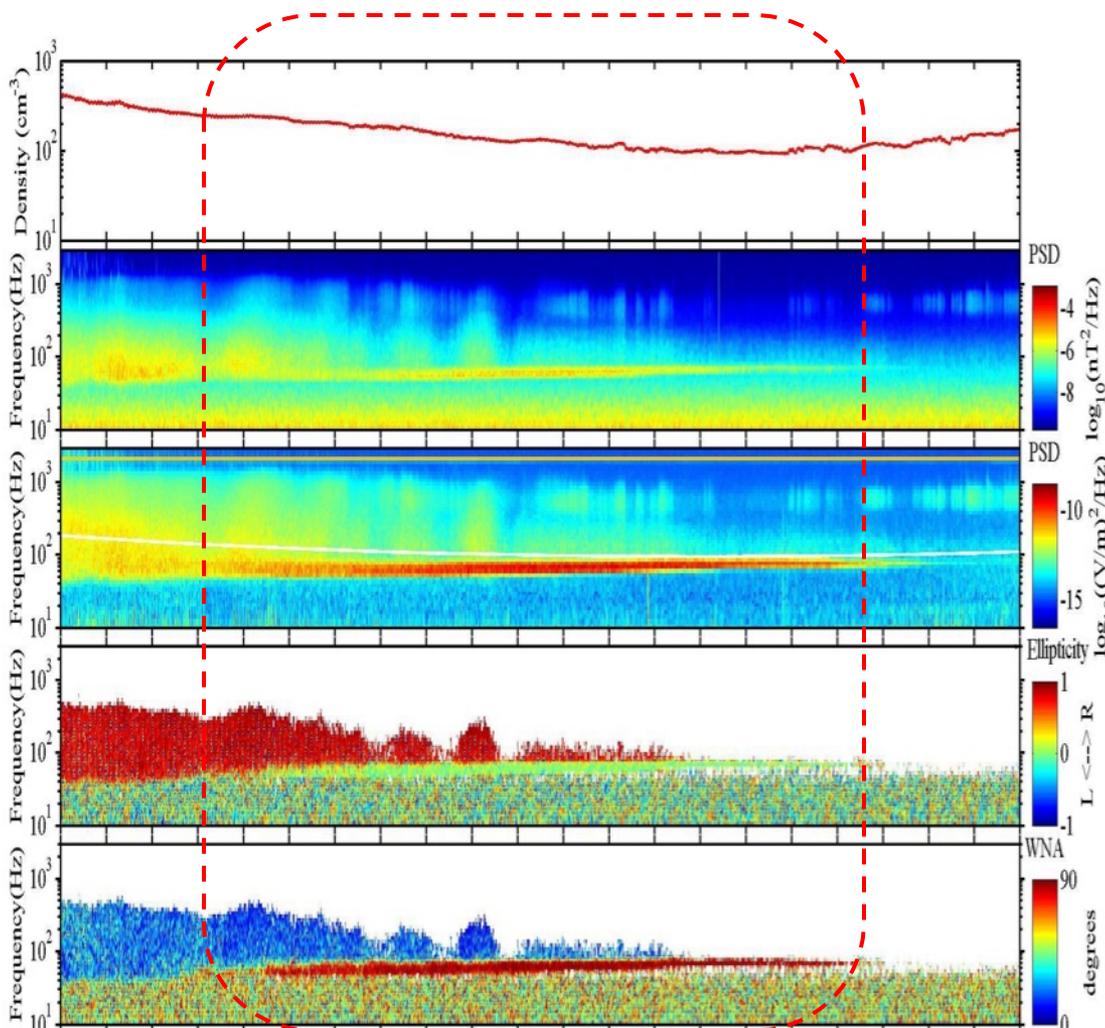


Yuan et al., 2018 JGR

电磁离子回旋波 (EMIC) 导致能量离子沉降



磁声波对质子的散射



背景等离子体密度

磁场功率谱密度

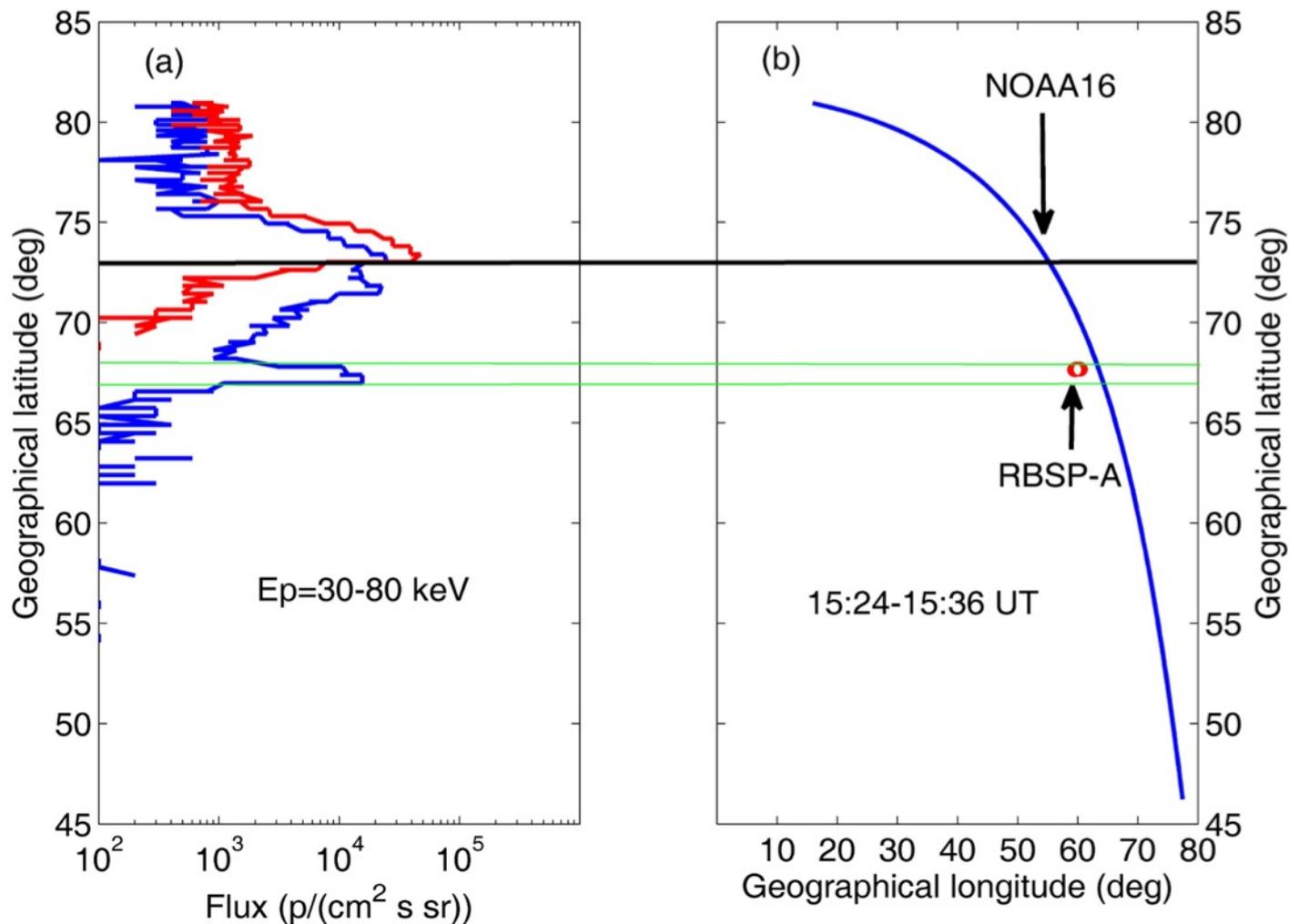
电场功率谱密度

线性极化
 $|\epsilon| \sim 0$

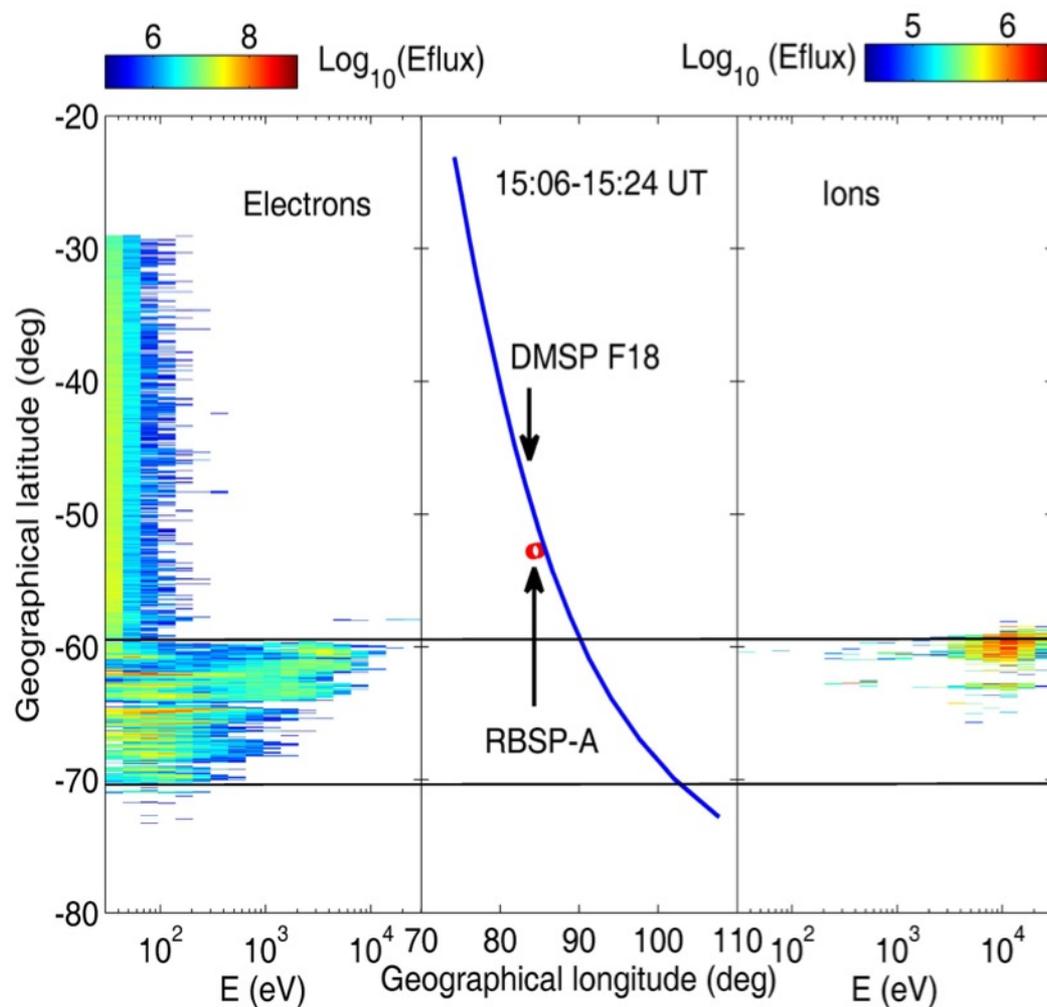
高斜传播角 (~ 90 deg)

UT	13:00	13:10	13:20	13:30	13:40	13:50	14:00	14:10	14:20	14:30	14:40	14:50	15:00	15:10	15:20	15:30	15:40	15:50	16:00	16:10	16:20	16:30	
L	4.70	4.86	5.01	5.14	5.26	5.37	5.46	5.54	5.61	5.67	5.72	5.75	5.78	5.79	5.78	5.76	5.72	5.68	5.62	5.55	5.47		
MLT	17.47	17.65	17.82	17.99	18.15	18.30	18.45	18.59	18.73	18.87	19.00	19.14	19.27	19.40	19.53	19.67	19.80	19.93	20.07	20.21	20.35	20.49	
MLAT	1.47	1.33	1.19	1.06	0.94	0.82	0.70	0.59	0.48	0.38	0.27	0.16	0.05	-0.06	-0.17	-0.30	-0.43	-0.56	-0.71	-0.87	-1.05	-1.24	

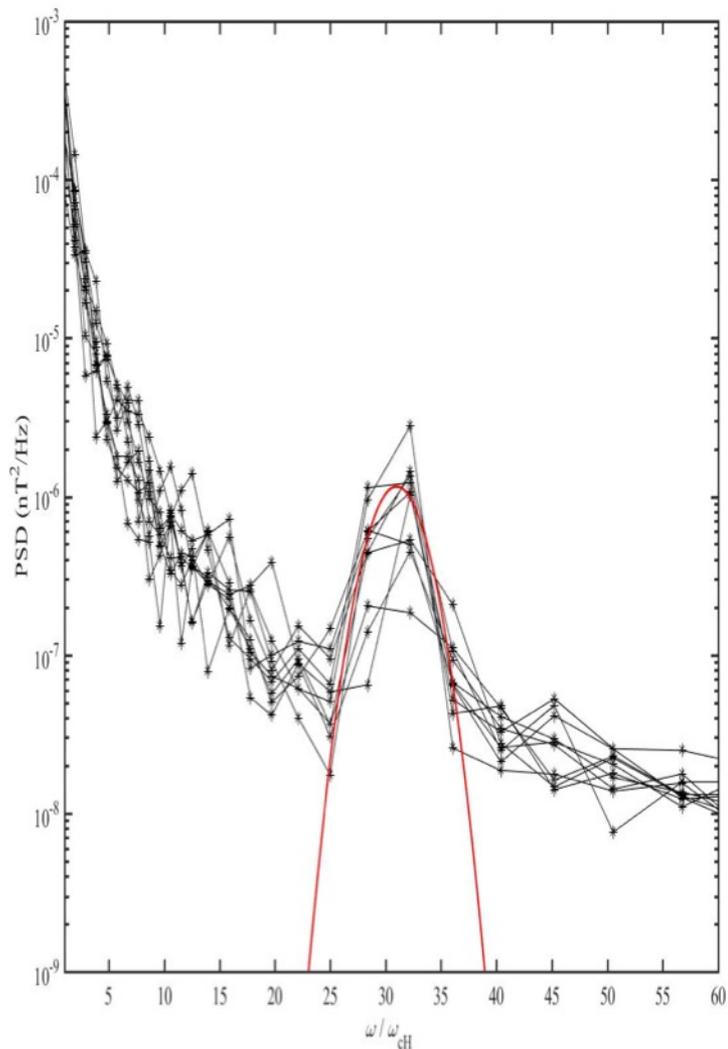
磁声波对质子扩散的联合观测



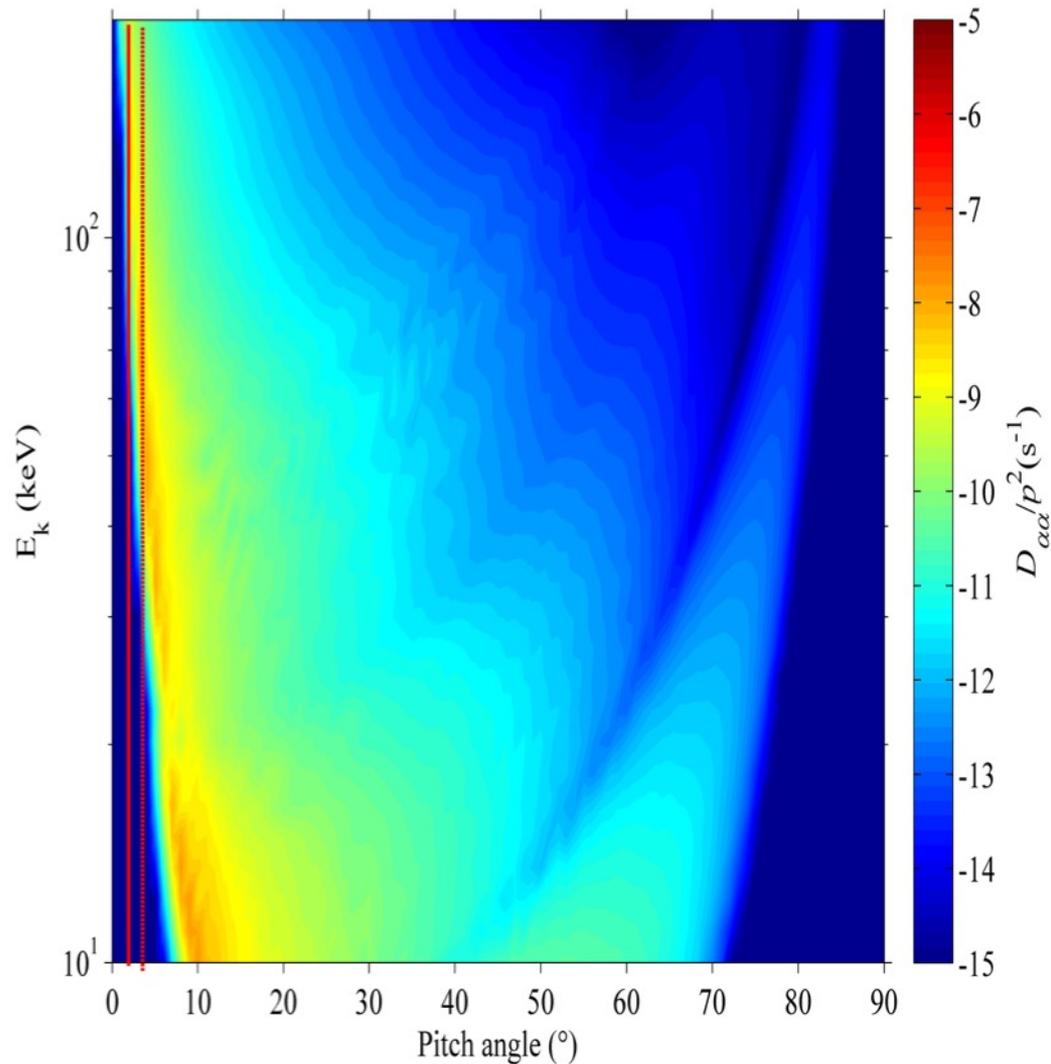
磁声波对质子扩散的联合观测



观测的磁声波频谱



磁声波对质子扩散系数



谢谢!

敬请批评指正!

