Electromagnetic ion cyclotron (EMIC) waves in warm plasmas

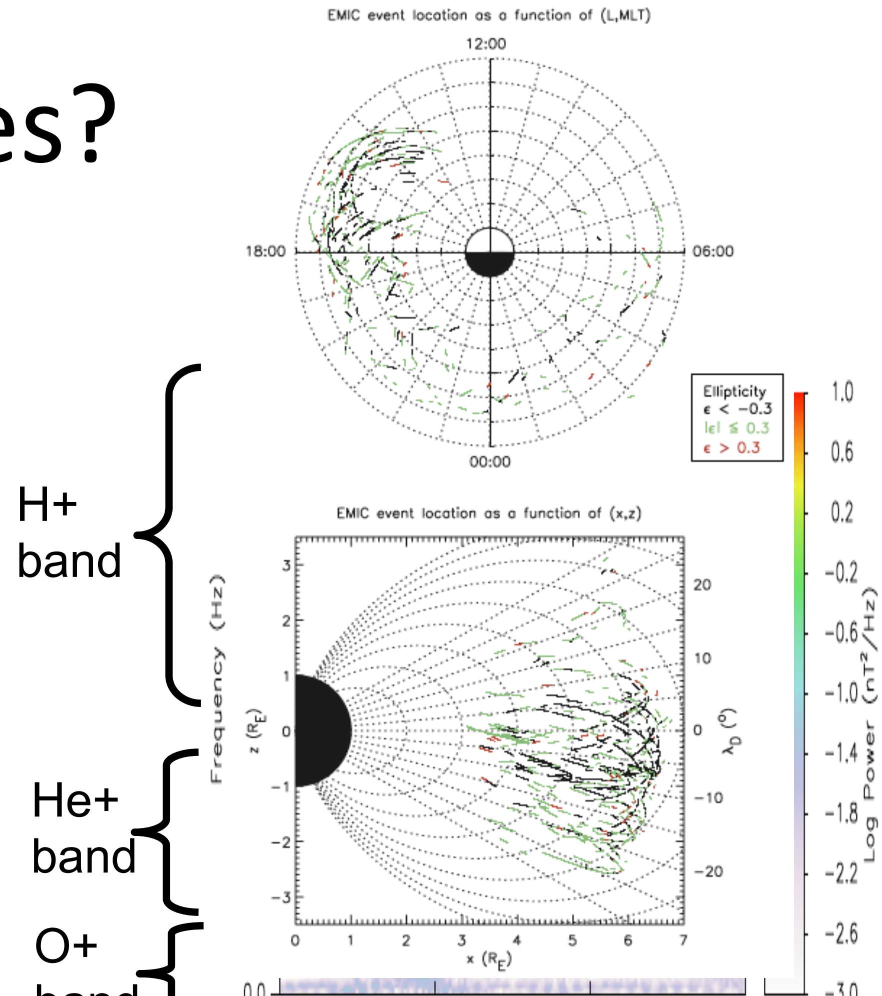
Lunjin Chen, Richard Thorne, and Jacob Bortnik

Oct, 7th, 2011, AOS 296G Group meeting

What are EMIC waves?

- ➢Left-handed polarization
- ➢Below ion gyro-frequency (~ Hz)
- ➢Multiple-band structure
- ➢Stronger emission in He+ band

[*Meredith et al.,* 2003, *Fraser et al*., 2010]



EMIC event locations from CRRES observations (July 1990-Oct 1991)

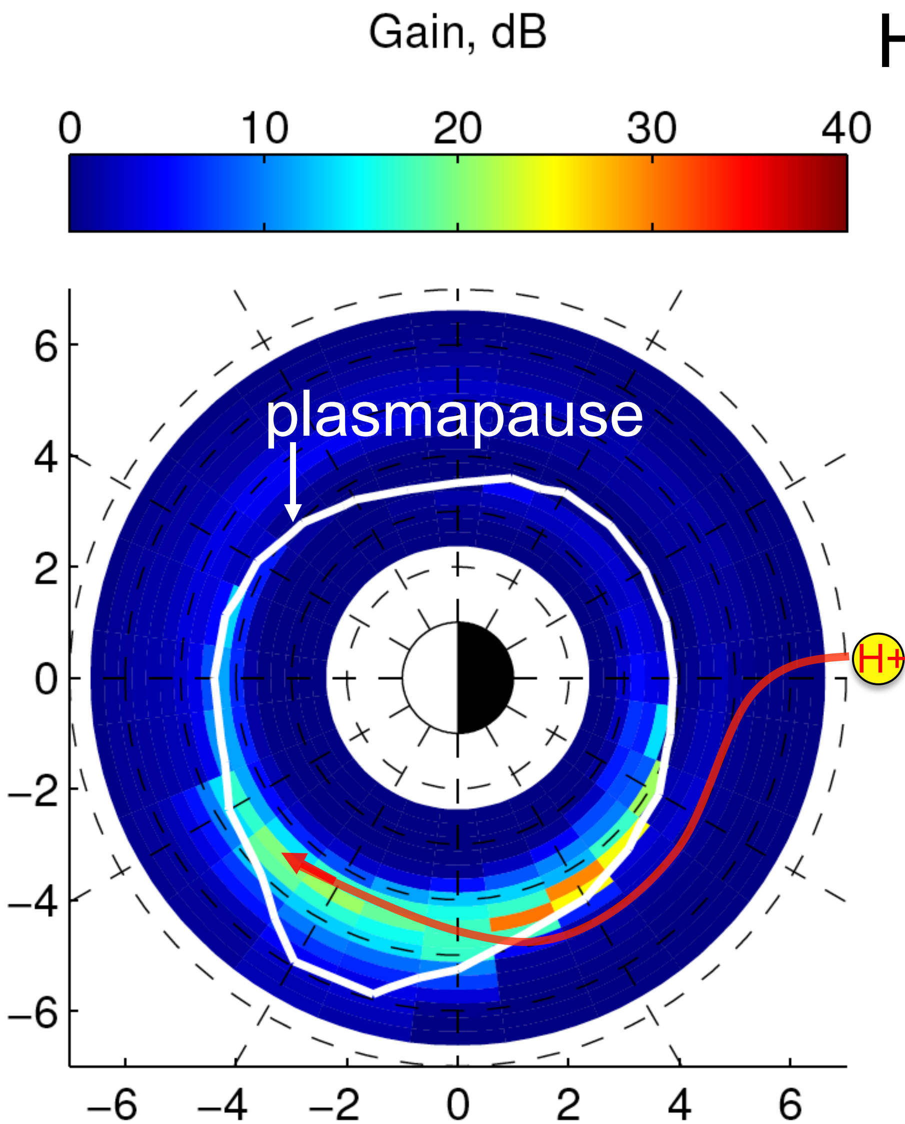
[*Meredith et al.,* 2003]

Where and when?

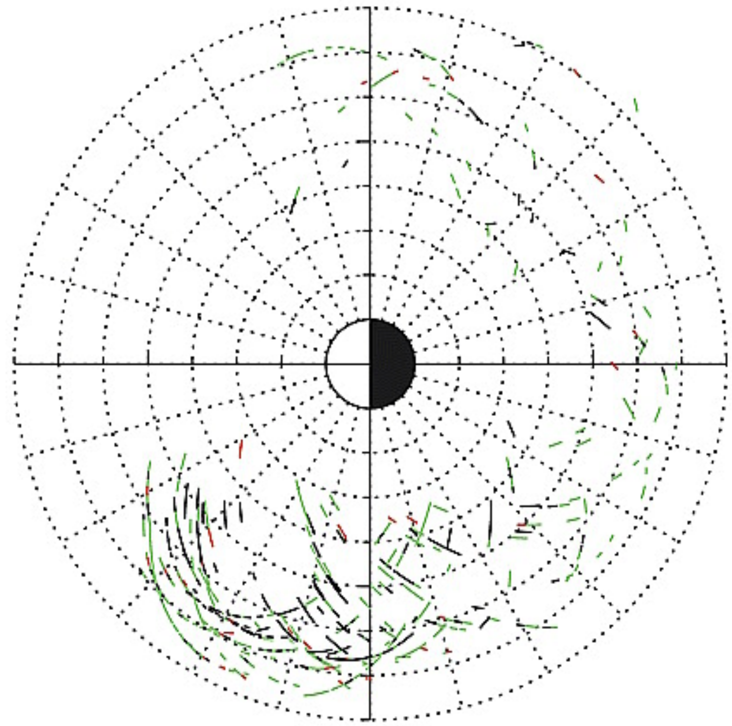
- ➢Source region within +/- 11° of the equator
- ➢82% observed in 1300-2000 MLT, L>3
- ➢Occurrence rate 5 times higher during storm times than quiet time

[*Loto'aniu et al.,* 2005, *Fraser and Nguyen,* 2001, *Erlandson and Ukhorskiy*, 2001]

How to generate EMIC waves?



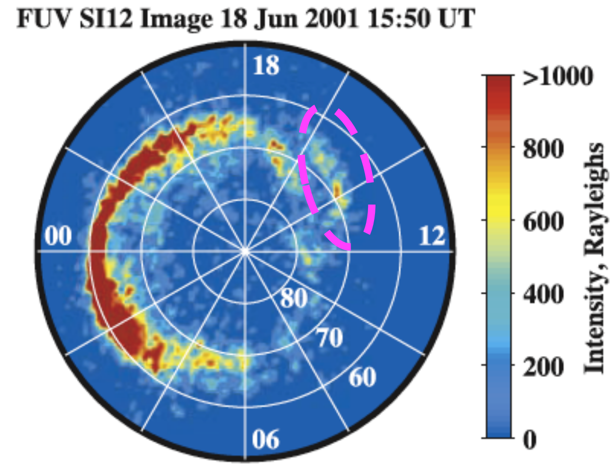
Chen et al., 2010



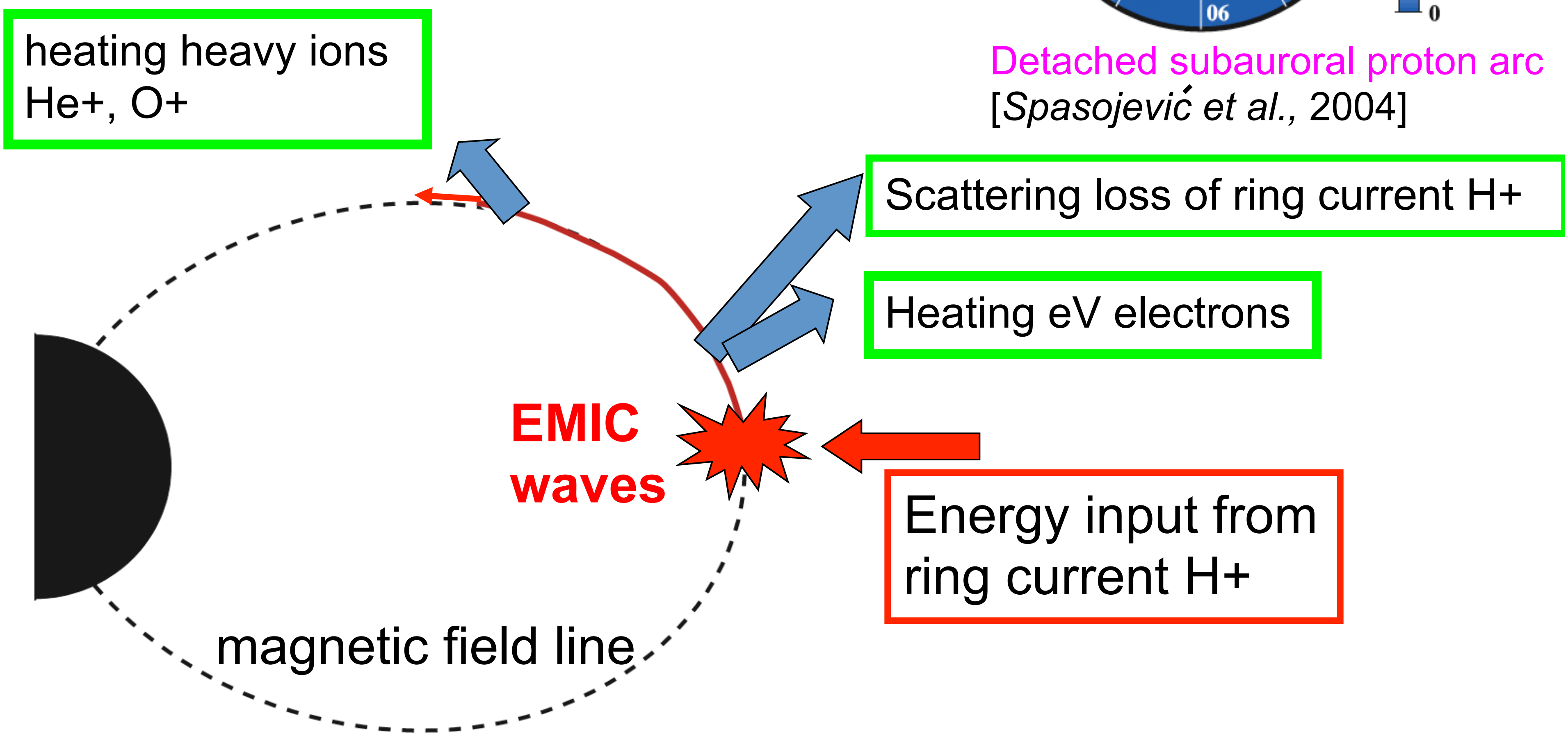
EMIC waves are generated in the duskside plume and nightside plasmapause, where ring current anisotropic H+ (Tp>Tz) overlaps high plasma density.

EMIC waves are agents for energy and momentum exchange between different groups of particles.

[*Thorne et al.*, 2006 Review]

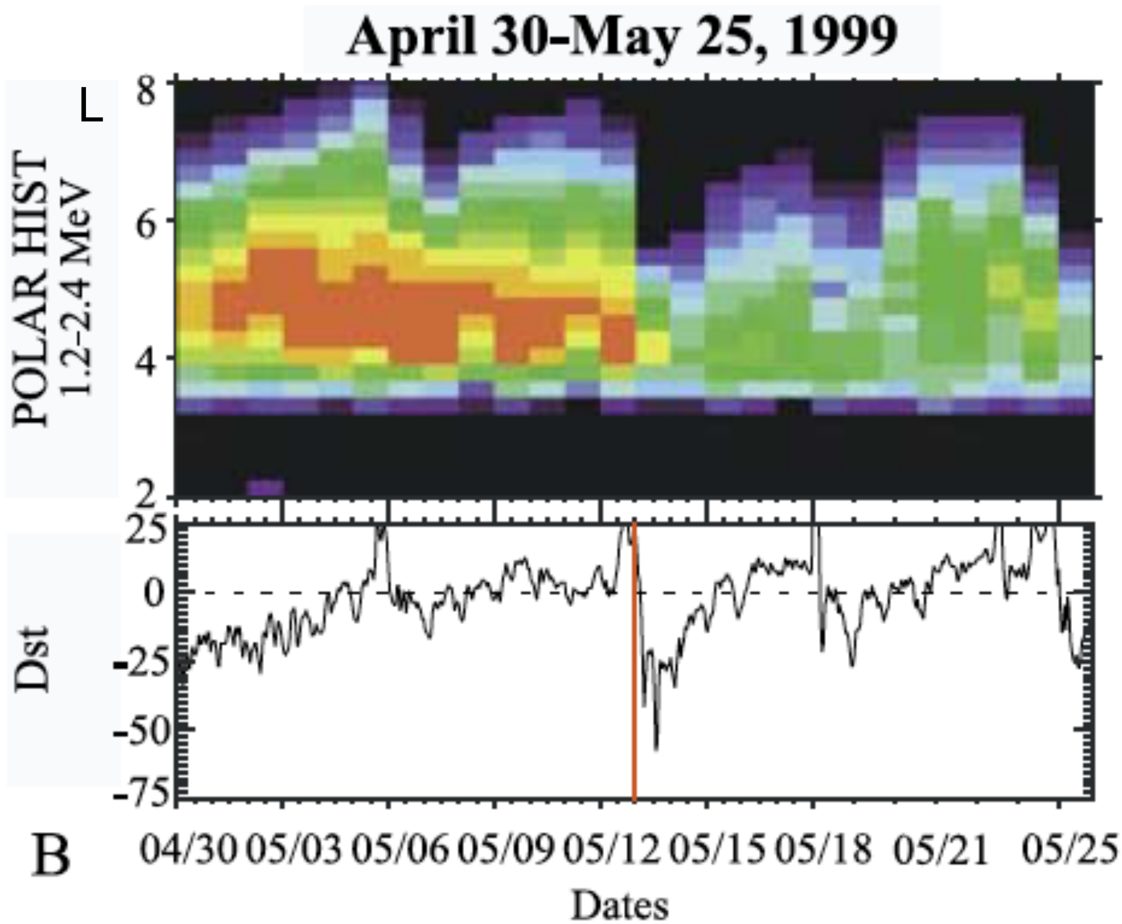


Detached subauroral proton arc
[*Spasojević et al.*, 2004]



EMIC waves are also proposed to cause dramatic loss of MeV electrons over a time scale of hours during main phase of geomagnetic storms. [*Thorne and Kennel* 1971]

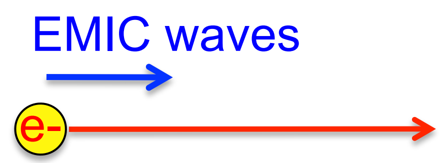
Relativistic electron flux dropout during main phase



[*Reeves et al.,* 2003]

Condition for Resonant Interaction between EMIC waves and electrons

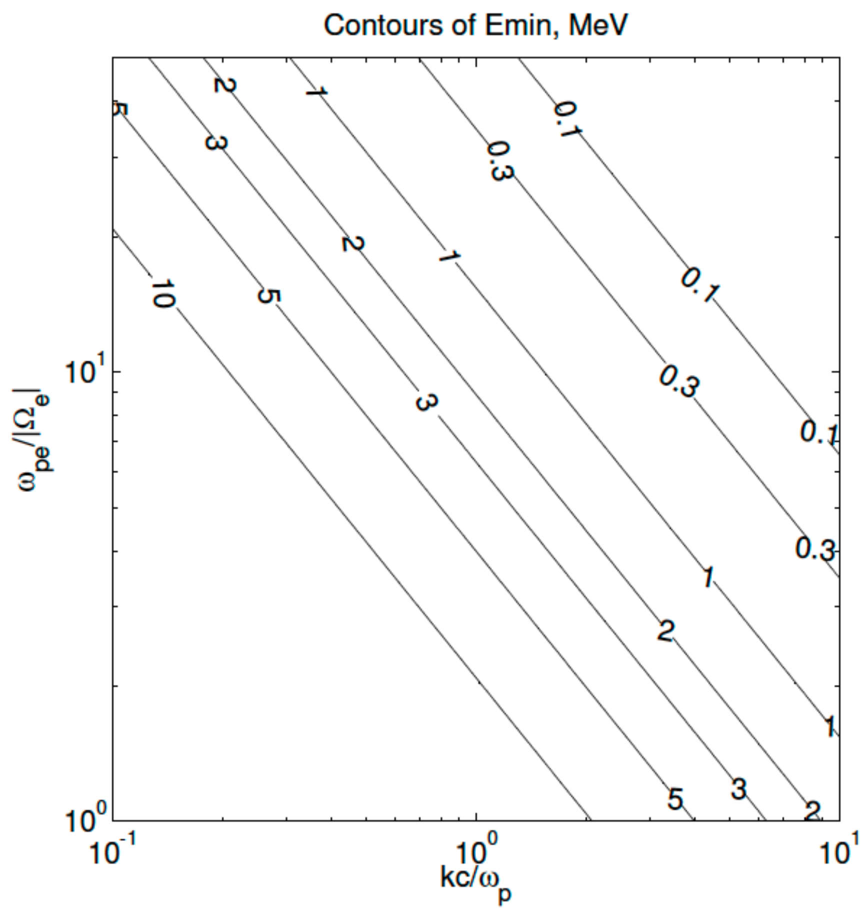
$$\omega - k v_{e\|} = \Omega_e$$



$$E^{-}_{min} = \left(\sqrt{\frac{m_{H+}}{m_e}\frac{1}{y^2 f^2} + 1} - 1\right) E_0$$

E_0 electron rest mass energy 511 keV
$y = kc/\omega_p$
$f = \omega_{pe}/|\Omega_e|$
ω_p proton plasma frequency

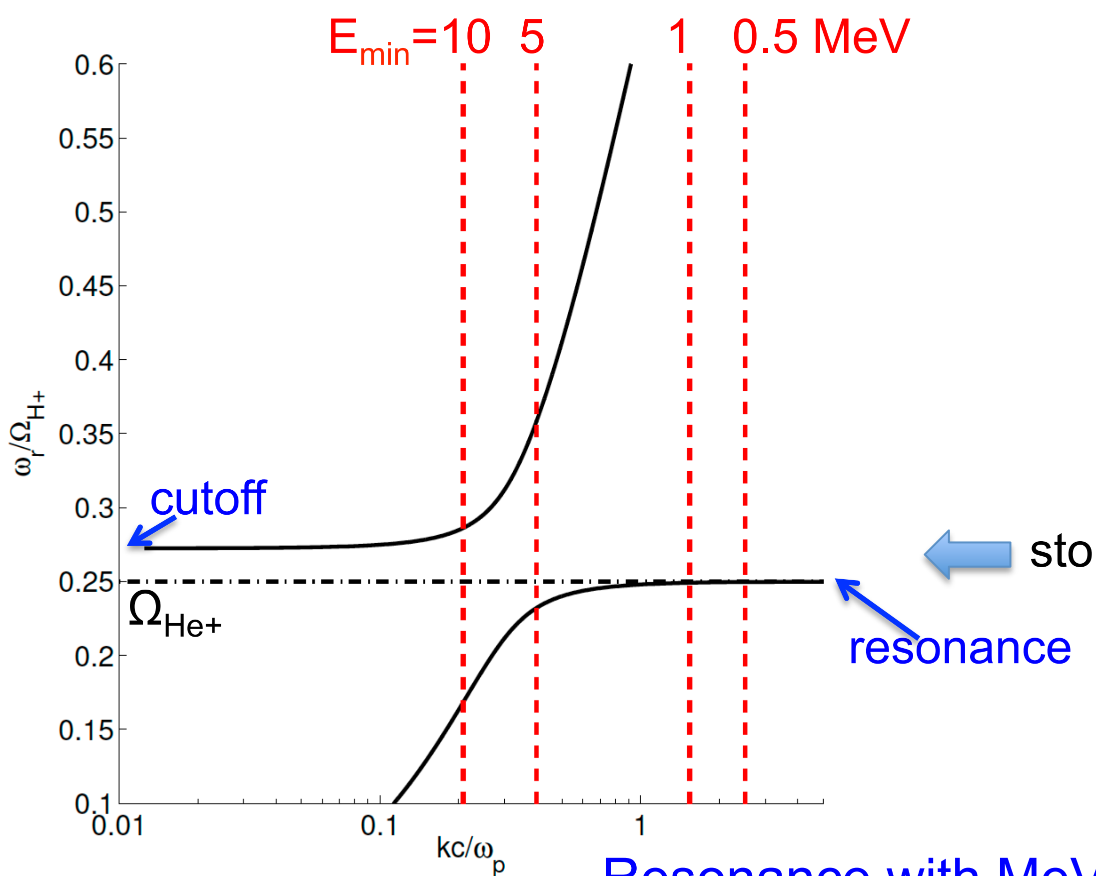
yf = 15.4 for Emin=1 MeV



Resonance with 1 MeV requires large wave number.

Dispersion Relation of EMIC waves in cold H+-He+ plasma

“cold” assumption:
thermal speed << wave phase speed



H+ band

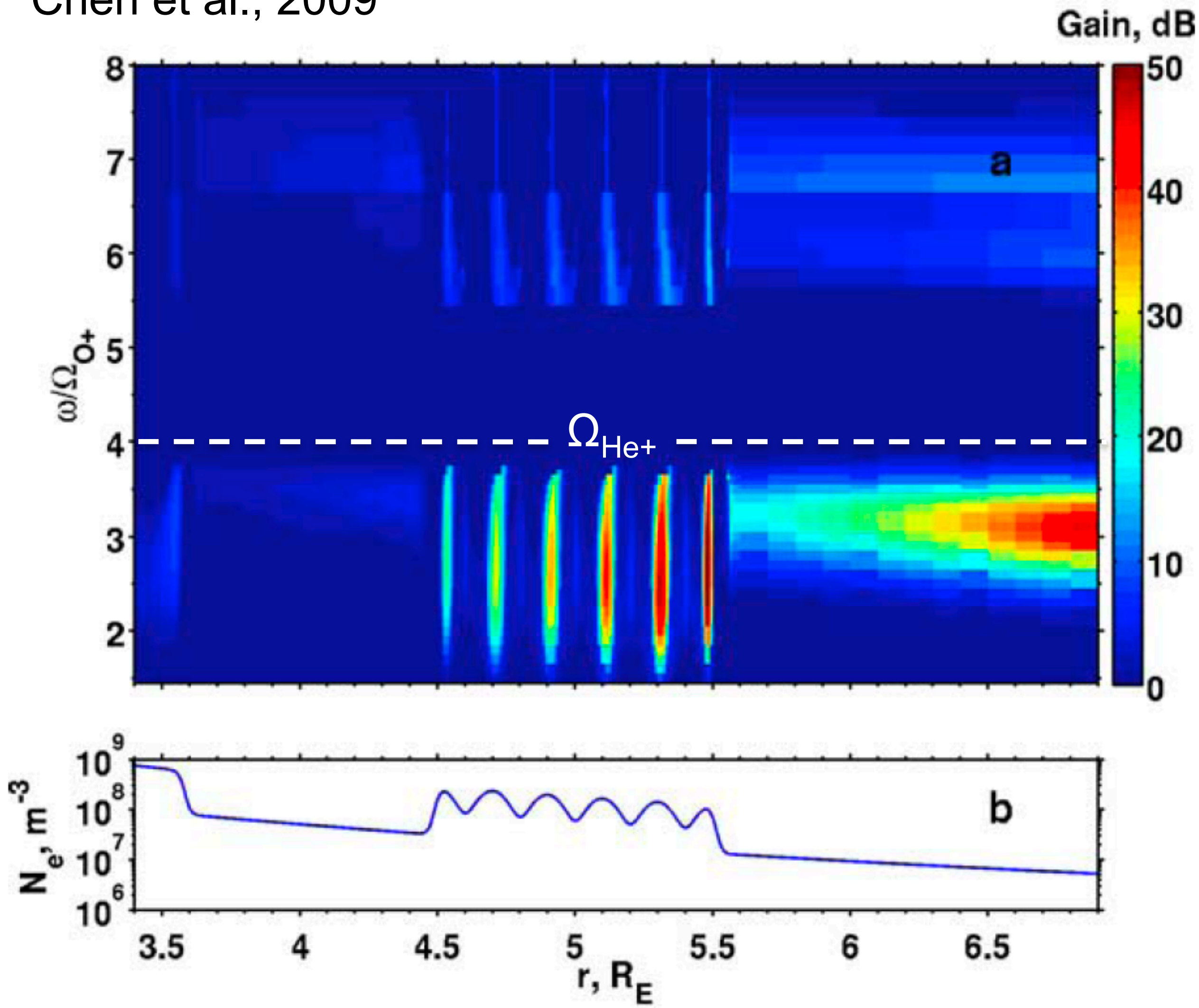
stop band

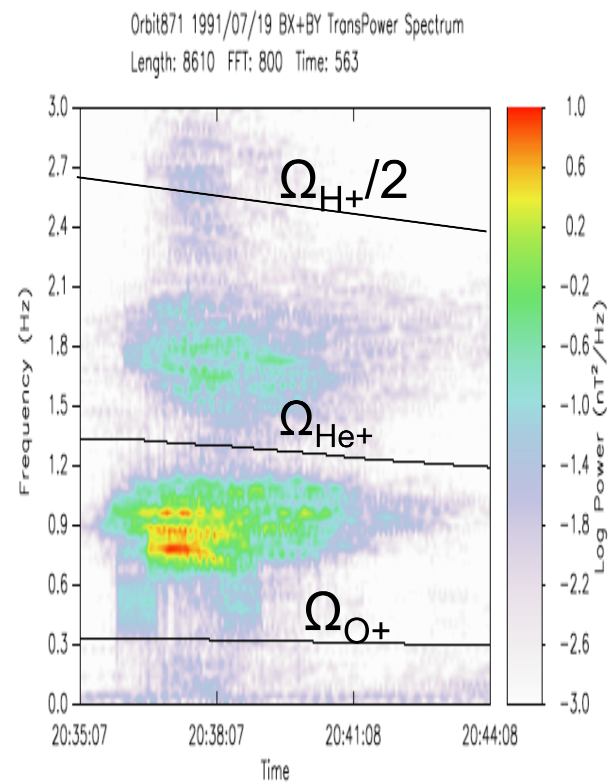
He+ band

Resonance with MeV electron requires EMIC waves very close to Ω_{he+}, from cold plasma theory

Simulation of EMIC wave spectrum

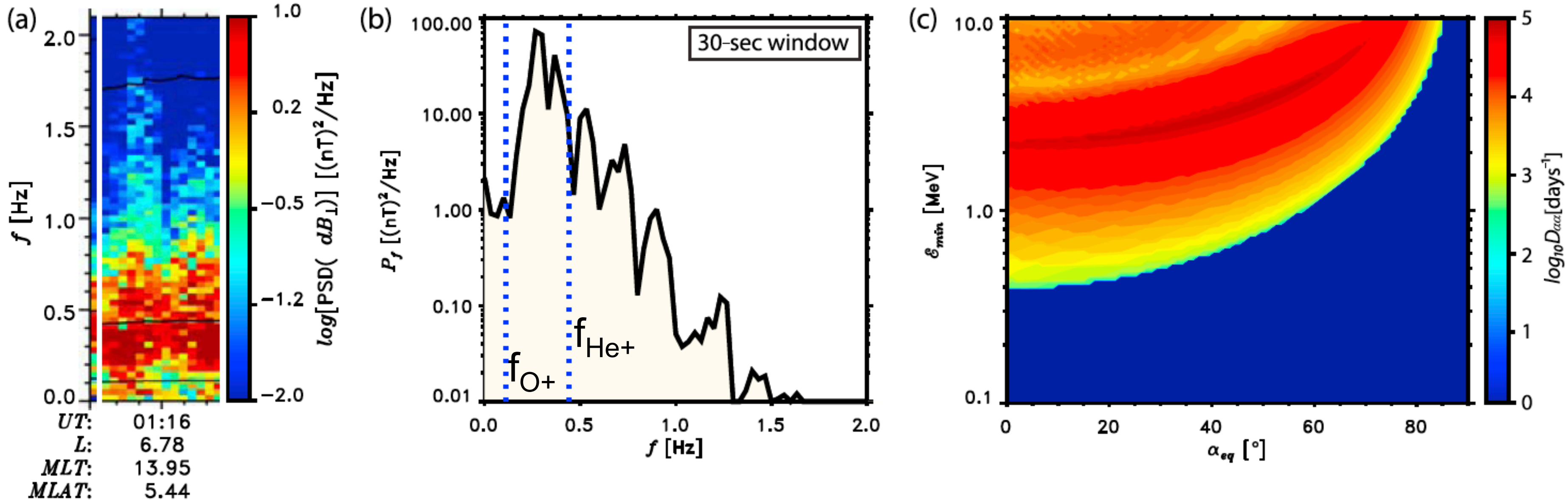
Chen et al., 2009





However, EMIC waves near Ω_{He+} are generally suppressed, due to strong cyclotron damping due to thermal He+.

Large amplitude EMIC wave activity measured at AMPTE CCE during storm main phase [Ukhorskiy et al., 2010]



Wave power as a function of *f*

Electron scattering rate

Cold plasma dispersion relation ?

How accurate?
Why no stop band?
Instability near Ω_{He+} ?

Wave number

Electron resonant energy

Resonant condition

EMIC waves in warm H^+-He^+ plasma

Chen et al., 2011

Displacement current | Cold e- | Cold H+ | Warm He+ (he)

$$y^2 = (x/f)^2 m_e/m_{H+} - x + (1 - \eta_{hh} - \eta_{he}) \frac{x}{1-x} + \frac{\eta_{he} x}{4x - 1} \zeta_{he} Z(\zeta_{he})$$
$$+ \eta_{hh} \left[A_{hh} + \left(A_{hh} + \frac{x}{x-1} \right) \zeta_{hh} Z(\zeta_{hh}) \right], \quad (1)$$

Anisotropic ring current H+ (hh)

$$x = \omega/\Omega_{H+} = \omega_r/\Omega_{H+} + i\omega_i/\Omega_{H+}$$
$$y = kc/\omega_p$$
$$f = \omega_{pe}/|\Omega_e|$$
$$\omega_p = \sqrt{N_e e^2/(\epsilon_0 m_{H+})}$$
$$A_{hh} = T_{hh\perp}/T_{hh\|} - 1$$

Z plasma dispersion function [Fried and Conte, 1961]

Cold plasma limit

$$\lim_{|\zeta|\to\infty} \zeta Z(\zeta) = -1$$
$$\zeta = \frac{\omega - \Omega}{k v_{th\|}}$$

1) Vth<<Vph
2) $\omega \neq \Omega$

"Simplified" Dispersion Relation

$$D(x, y; f, \eta_{he}, T_{he}, \eta_{hh}, T_{hh\|}, A_{hh}) = 0$$

A complex equation
Complex wave frequency $x=x_r+i\ x_i$
Real wave number y
6 free parameters

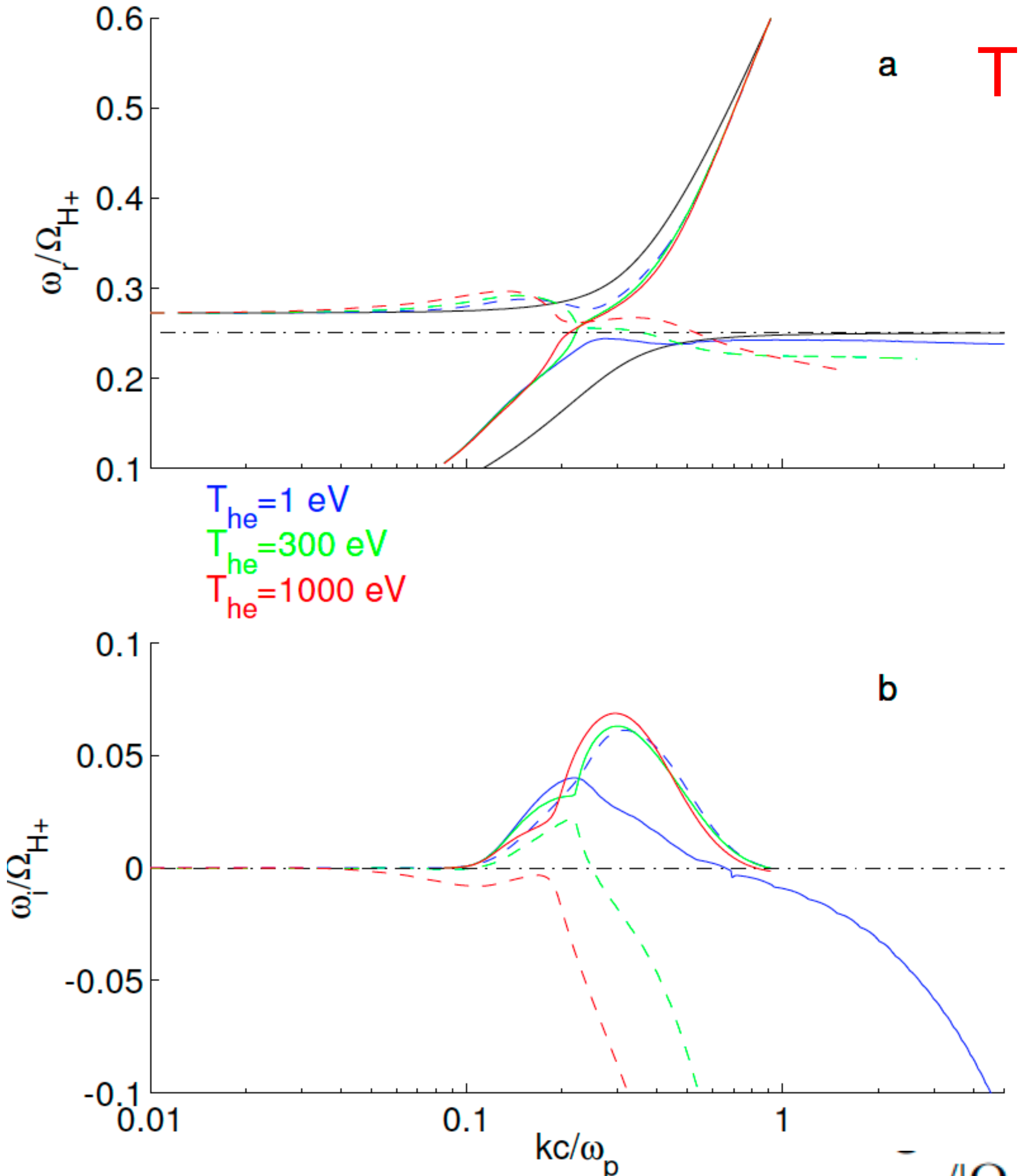
Nominal case:

$\omega_{pe}/|\Omega_e| = 10$

$\eta_{he} = 3\%,\ T_{he} = 300$ eV

$\eta_{hh} = 10\%,\ T_{hh\|} = 25$ keV, $A_{hh} = 1.5$

The effect of He+ temperature



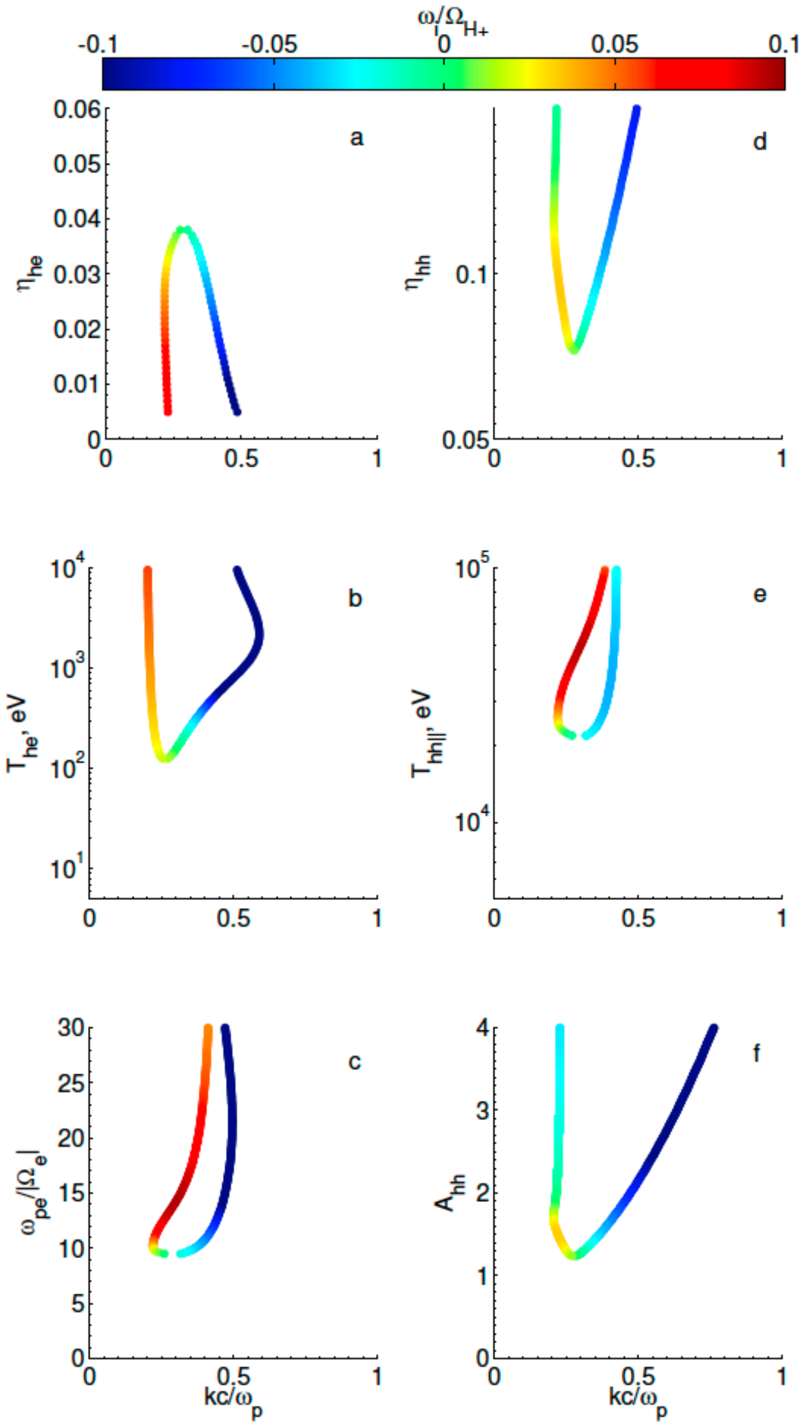
1) w-k not longer monotonic relation
2) Pronounced modification near Ω_{He+}
3) Allowable solution at exact Ω_{He+}
4) Two band structure and stop band disappear
5) Damping at high wave number (y>1)

$\omega_{pe}/|\Omega_e| = 10$

$\eta_{he} = 3\%,\ T_{he} = 300$ eV

$\eta_{hh} = 10\%,\ T_{hh\|} = 25$ keV, $A_{hh} = 1.5$

Green: nominal case



EMIC waves at Ω_{He+}

Solve for (x_i, y) with a fixed x_r=1/4 (i.e., $\omega=\Omega_{He+}$) and varying one of the six parameters

- The presence and instability of waves exactly at Ω_{He+} are due to the dominance of hot H+ growth over warm He+ damping, i.e., a less dense but sufficiently hot He+, a sufficiently dense, hot and anisotropic H+ together with a sufficiently dense cold plasma.

- Stop band must exist if any of these conditions fails.

- These waves can directly heat the thermal He+ ions.

- These waves, if excited, are not favorable to scatter 1 MeV because of limited wave number.

Resonance with 1 MeV electrons

Solve $D(x, y; f, \eta_{he}, T_{he}, \eta_{hh}, T_{hh\|}, A_{hh}) = 0$

for x with a fixed y=15.4/f and a huge set (7×10^5) of plasma conditions:
f= 5, 10, …, 30; η_{he}= 2%, 4%, …, 30%; T_{he}=1, 3, 5, 10, …, 3000, 5000 eV
η_{hh}= 2%, 4%, …, 20%; T_{hh}=5, 10, 20, 30, …, 100 keV; A_{hh}=0.5, 1, …, 3.

and require that solutions of x must satisfy x_i>0.01.

Table 1. Necessary (but Not Sufficient) Plasma Conditions That Are Unstable to L-Mode Waves Capable of Resonating With Relativistic Electrons of Energy Down to 1 MeV[a]

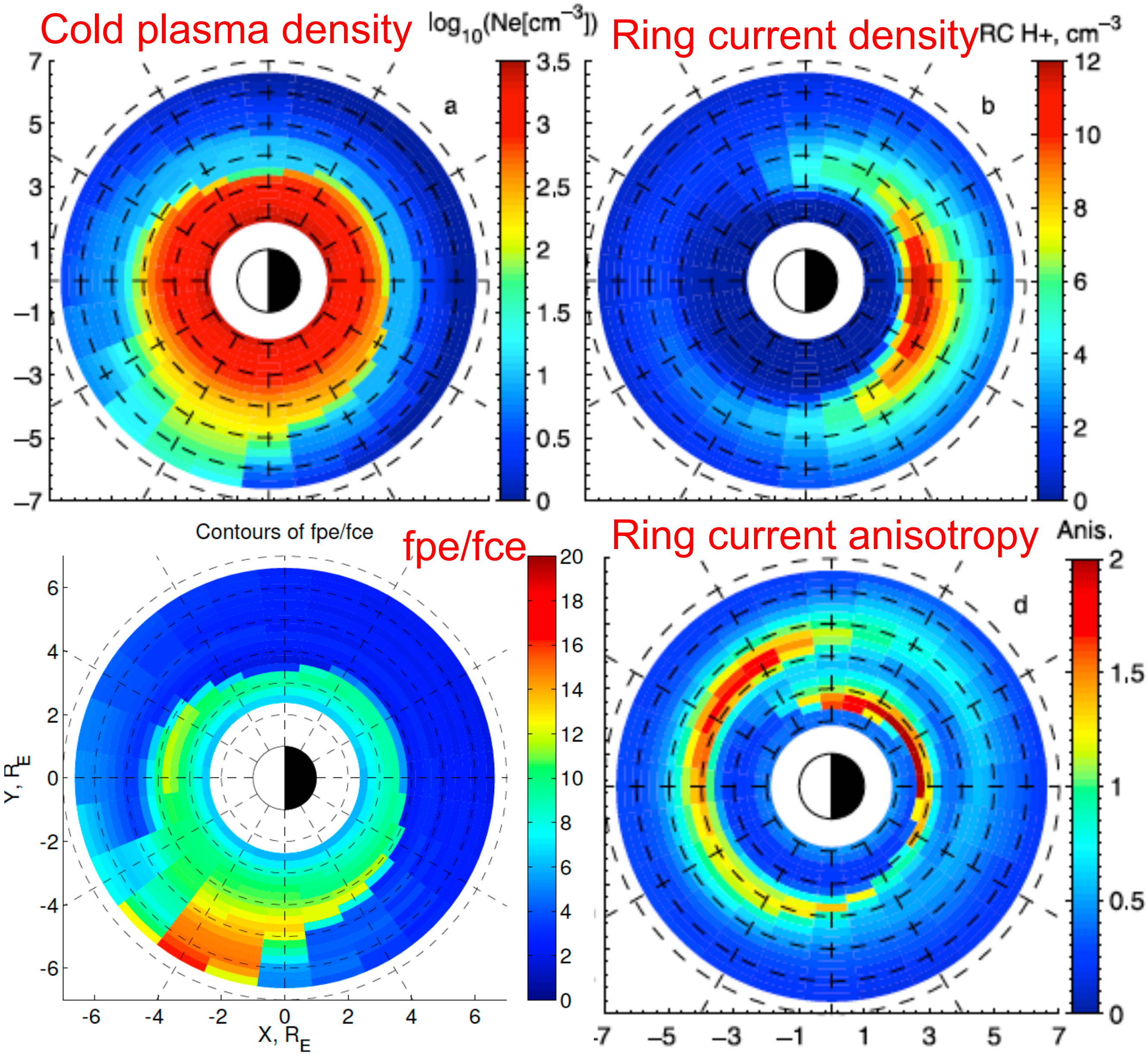
A_{hh} \ f	15	20	25	30
1	X	X	$\eta_{he} \geq 28\%, \eta_{hh} \geq 20\%, T_{he} \leq 1$	$\eta_{he} \geq 6\%$, $\eta_{hh} \geq 12\%, T_{he} \leq 10$
	X	X	X	$\eta_{he} \leq 8\%, \eta_{hh} \geq 10\%$
1.5	X	X	$\eta_{he} \geq 6\%, \eta_{hh} \geq 12\%, T_{he} \leq 10$	$\eta_{hh} \geq 8\%$
	X	$\eta_{he} \leq 4\%, \eta_{hh} \geq 18\%$	$\eta_{he} \leq 18\%, \eta_{hh} \geq 8\%$	$\eta_{he} \leq 26\%, \eta_{hh} \geq 6\%$
2.0	X	$\eta_{he} \geq 18\%, \eta_{hh} \geq 18\%, T_{he} \leq 3$	$\eta_{hh} \geq 10\%, T_{he} \leq 10$	$\eta_{hh} \geq 4\%$
	X	$\eta_{he} \leq 20\%, \eta_{hh} \geq 10\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$
2.5	X	$\eta_{he} \geq 8\%, \eta_{hh} \geq 14\%, T_{he} \leq 10$	$\eta_{hh} \geq 8\%$	$\eta_{hh} \geq 4\%$
	$\eta_{he} \leq 8\%, \eta_{hh} \geq 16\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$	$\eta_{hh} \geq 4\%$
3	X	$\eta_{he} \geq 4\%, \eta_{hh} \geq 12\%, T_{he} \leq 50$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$
	$\eta_{he} \leq 20\%, \eta_{hh} \geq 12\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$	Full

x_r<=0.25 x_r>0.25

Most favorable plasma condition occurs only in the large f (>=15) and A_{hh} (>=1) regime.

For x_r<=0.25, a dense, hot H+, and a dense colder He+

For x_r>0.25, a dense, hot H+, tenuous He+



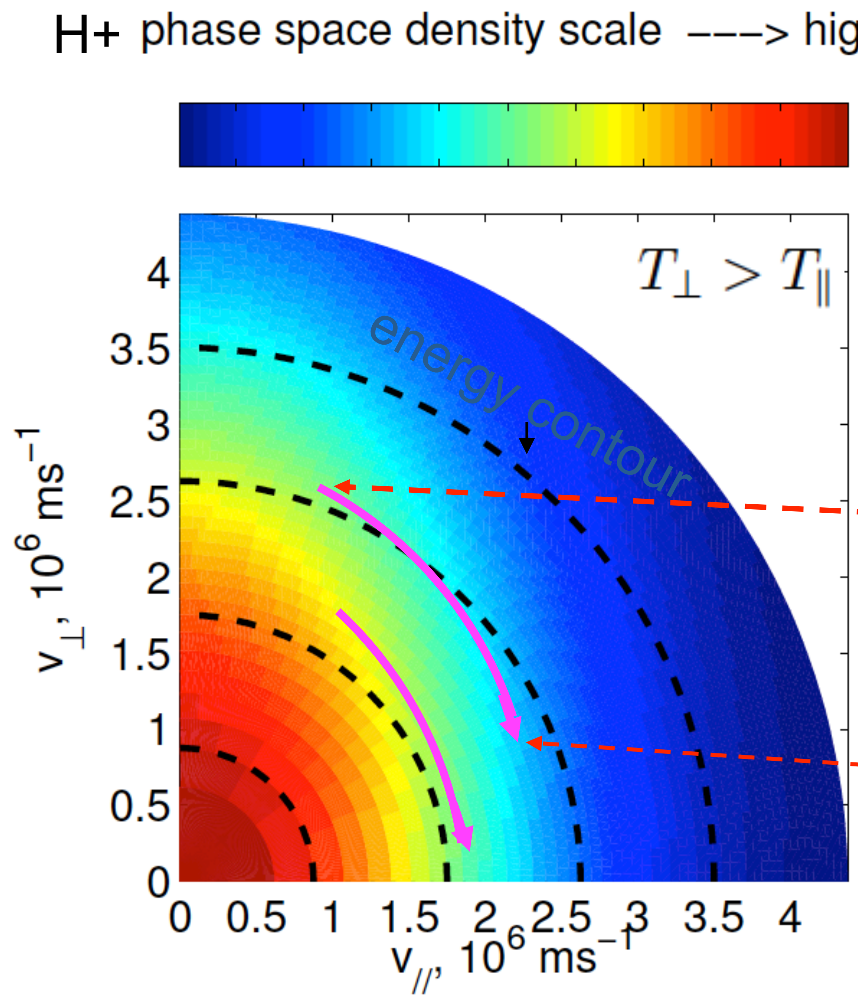
From RAM simulation
[Chen et al., 2010]

Within reasonable constraints η_{hh}<=10% and A_{hh}<=2, then a relatively extreme condition (f>~25, A_{hh}>1) is required to scatter MeV electrons.

Summary

- Hot plasma effects due to H+ and He+ produce a significant modification in the cold plasma description of EMIC waves, especially near Ω_{He+}
- The modification is important when evaluating relativistic electron scattering rate.
- Instability of EMIC waves at Ω_{He+} is due to the dominance of hot RC H+ over warm He+, and provides an efficient mechanism for heating He+.
- Extreme condition is required to excite waves capable of resonating MeV electrons.

Generation mechanism of EMIC waves

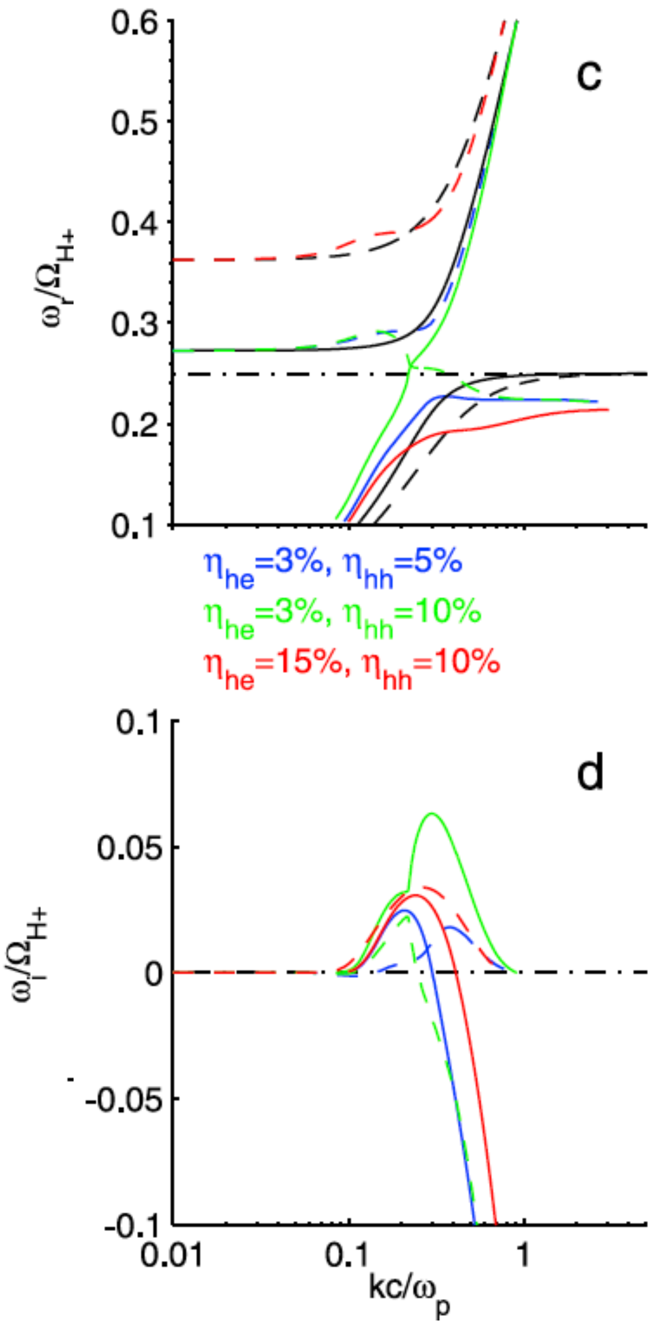


H+ diffusion path due to resonant interaction with EMIC waves

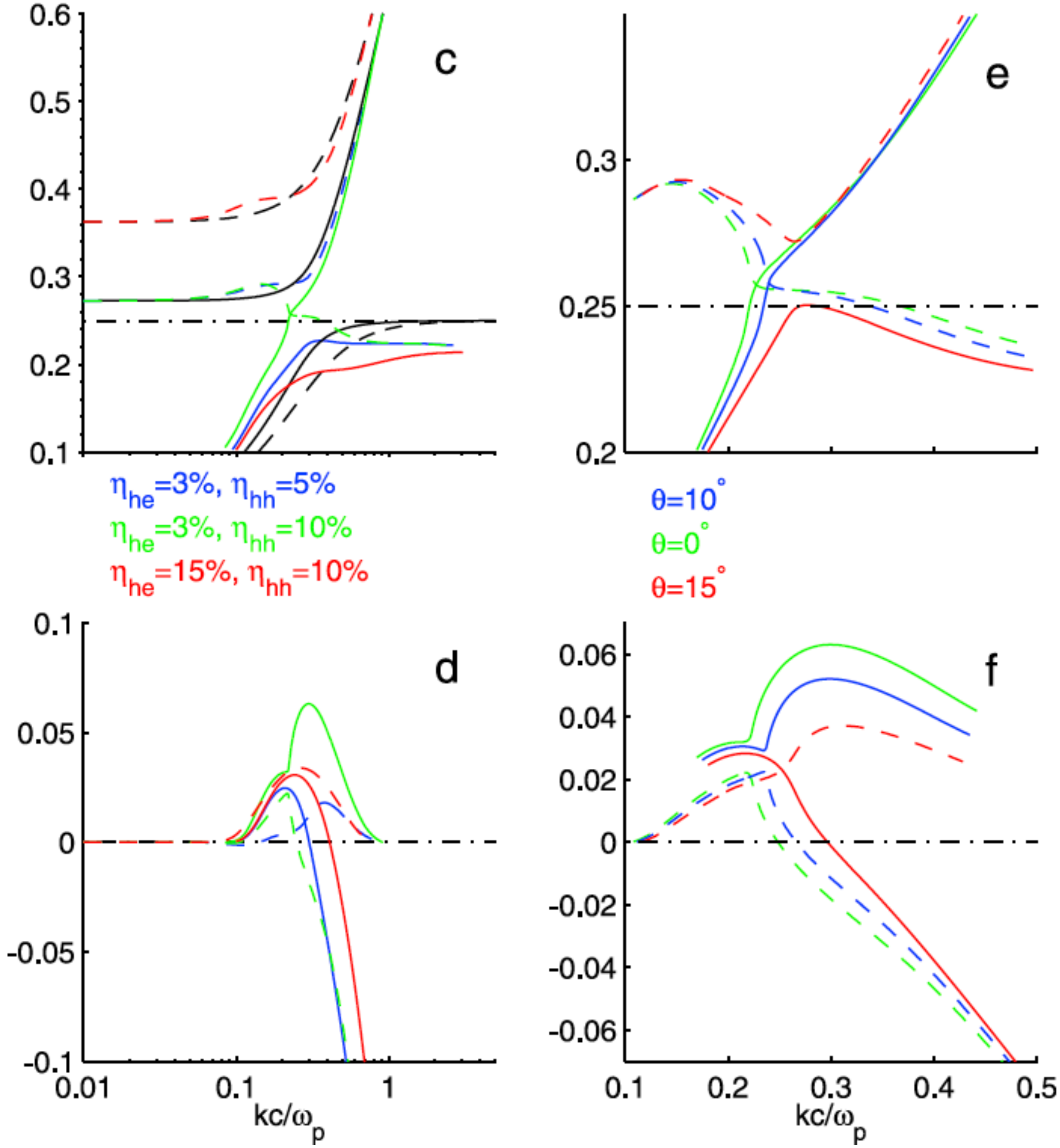
Higher PSD at higher energy and higher PA

Lower PSD at lower energy and lower PA

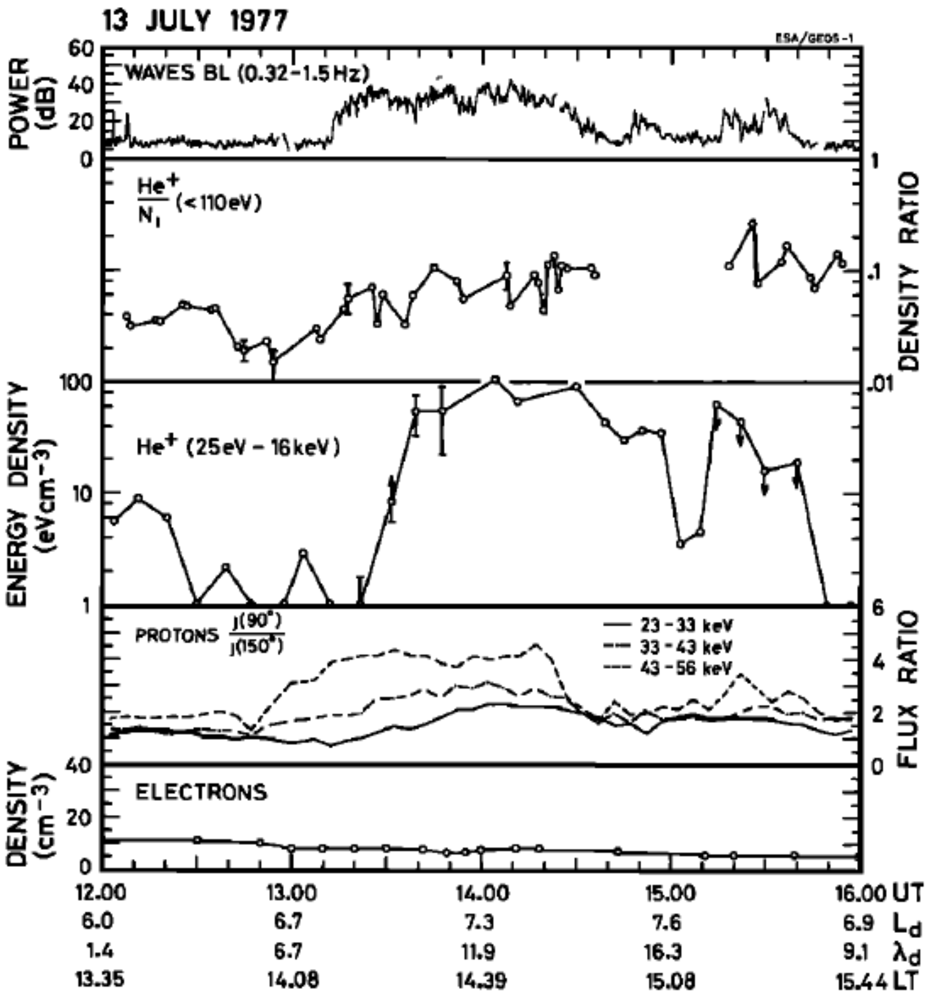
Ring current H+ population with temperature anisotropy $T_\perp > T_\parallel$ is unstable for EMIC waves near field-aligned propagation (k // B) [*Kennel and Petschek* 1966].



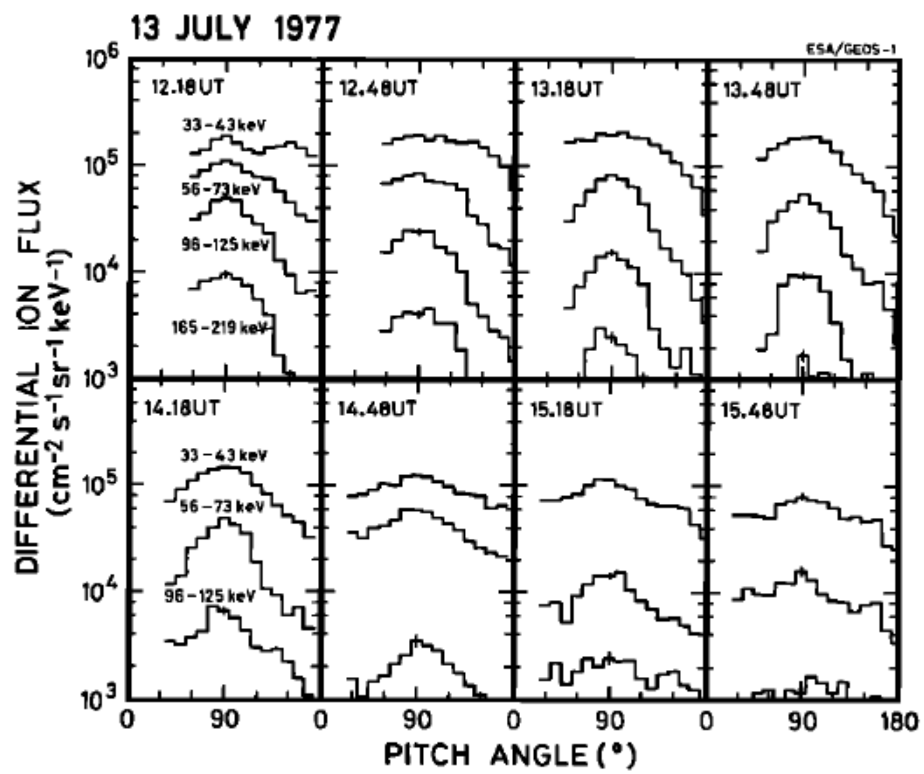
c
0.6
0.5
0.4
0.3
0.2
0.1
ω_r/Ω_{H+}
η_{he}=3%, η_{hh}=5%
η_{he}=3%, η_{hh}=10%
η_{he}=15%, η_{hh}=10%
d
0.1
0.05
0
-0.05
-0.1
ω_i/Ω_{H+}
0.01
0.1
1
kc/ω_p



c
e
d
f
η_{he}=3%, η_{hh}=5%
η_{he}=3%, η_{hh}=10%
η_{he}=15%, η_{hh}=10%
θ=10°
θ=0°
θ=15°
kc/ω$_p$
kc/ω$_p$



13 JULY 1977
ESA/GEOS-1
POWER (dB)
WAVES BL (0.32-1.5 Hz)
He+/N_I (<110eV)
DENSITY RATIO
ENERGY DENSITY (eVcm^-3)
He+ (25eV - 16keV)
PROTONS j(90°)/j(150°)
23-33 keV
33-43 keV
43-56 keV
FLUX RATIO
DENSITY (cm^-3)
ELECTRONS
12.00 13.00 14.00 15.00 16.00 UT
6.0 6.7 7.3 7.6 6.9 L_d
1.4 6.7 11.9 16.3 9.1 λ_d
13.35 14.08 14.39 15.08 15.44 LT



13 JULY 1977
ESA/GEOS-1
12.18UT
12.48UT
13.18UT
13.48UT
14.18UT
14.48UT
15.18UT
15.48UT
33-43 keV
56-73 keV
96-125 keV
165-219 keV
DIFFERENTIAL ION FLUX (cm^-2 s^-1 sr^-1 keV^-1)
PITCH ANGLE (°)

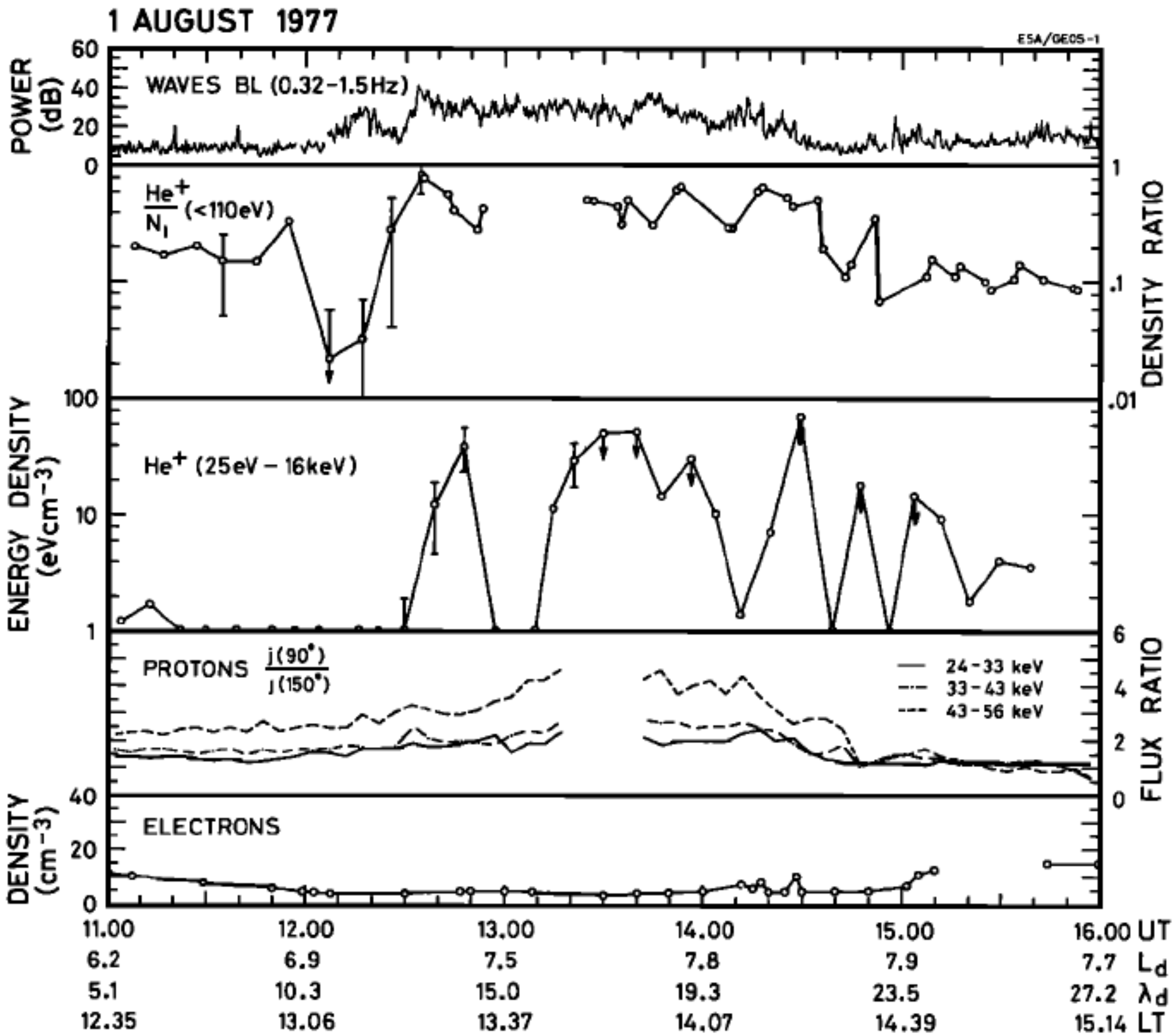


Fig. 11. Composite data for August 1, 1977 (see caption for Figure 9).

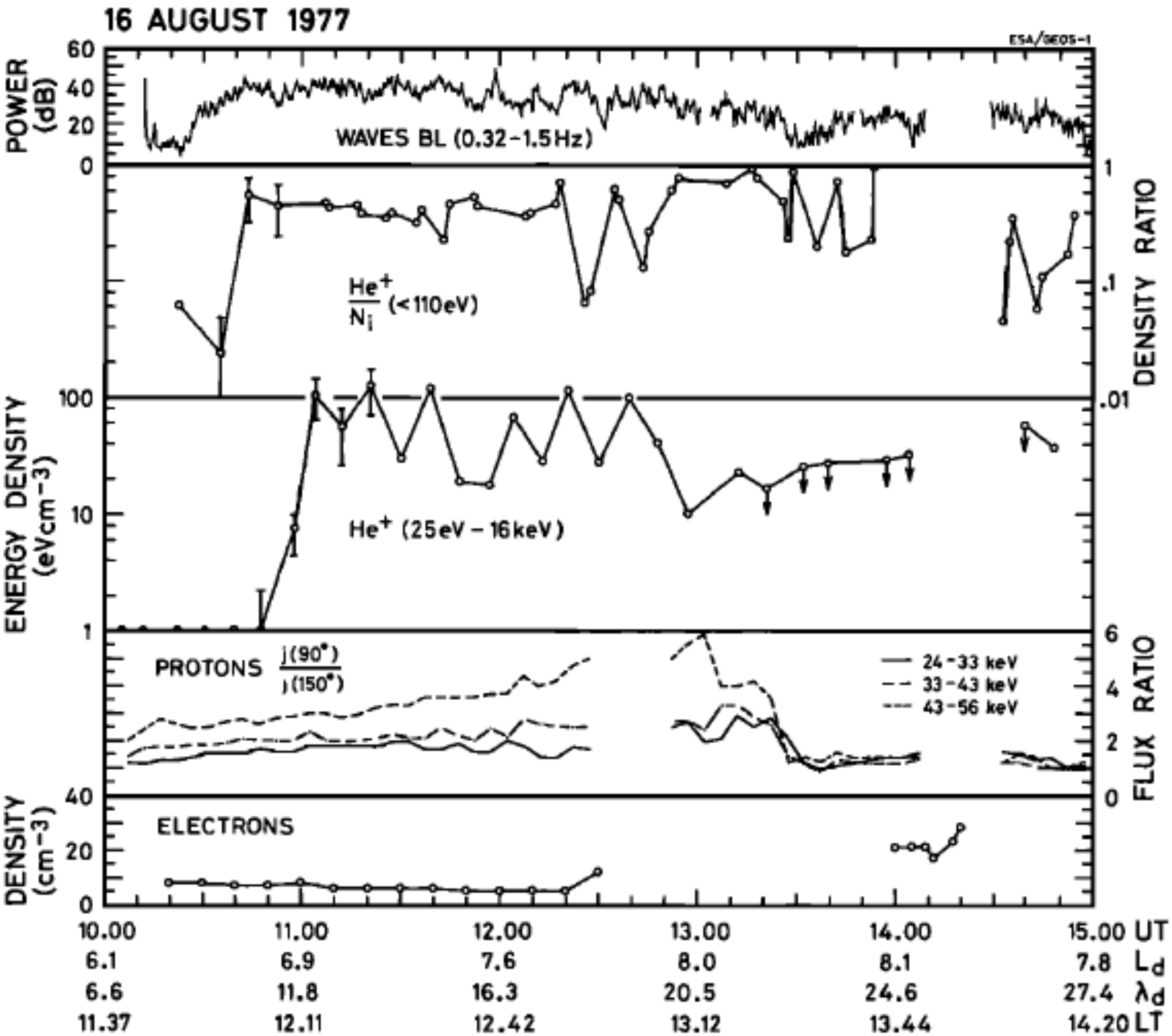


Fig. 12. Composite data for August 16, 1977 (see caption for Figure 9).

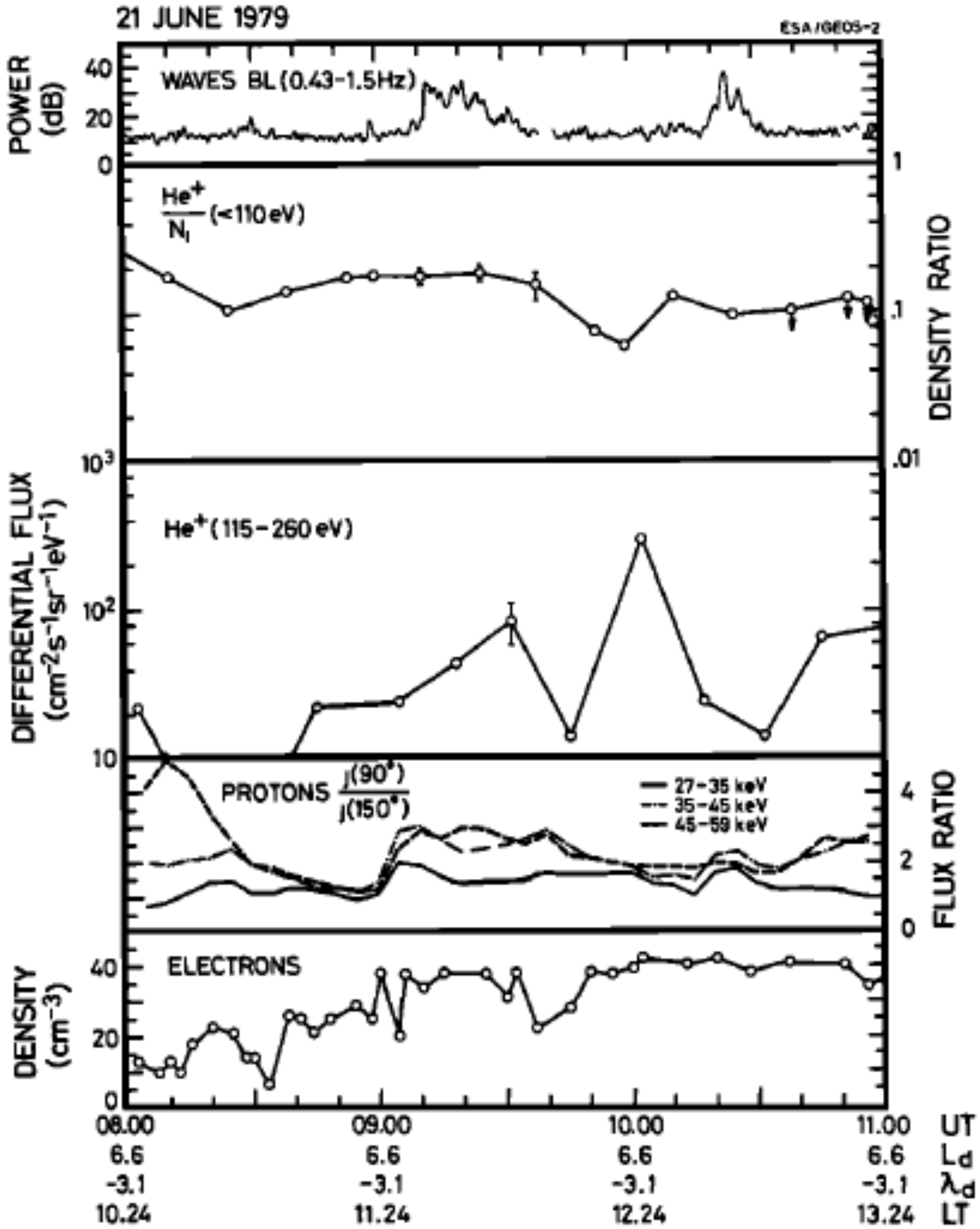


Fig. 13. Composite data for June 21, 1979 (see caption for Figure 9). Note that in the middle panel the differential He^+ flux at 115–260 eV has been plotted instead of the He^+ energy density (see text).

TABLE 3. Acceleration of He^+ Ions by ICWs

	(1) Coincident Strong He^+ Fluxes	(2) Coincident Weak He^+ Fluxes	(3) No Suprathermal He^+ Detected
Waves present	17 (31%)	20 (37%)	15 (28%)
No waves present		2 (4%)	