Hybrid simulation study of *highfrequency* **H-band EMIC waves in the Earth's magnetosphere**

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EMIC Waves in the Magnetosphere

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Typical vs. *High-frequency* **EMIC Waves**

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Throughout dayside

Within $±5°$ *magnetic latitude*

S Observations

- *•Relatively rare, recently discovered*
- *•LH polarized, quasiparallel propagation*

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- *•LH polarized, quasiparallel propagation*
- *•Low* ($\lesssim 500$ eV) energy *proton enhancement*
- *•90˚-peaked, very anisotropic low-energy proton pitch-angle distribution*

Free Energy Source of HFEMIC dispersion relation (Figure 2a) using the central frequency with the peak gyrofie das presentantes da line in die language da line da line da line da line da line da line indicative a
District da line da li \blacksquare \overline{P} + !² *^pA^p* !² *p A^p* + \mathbf{A} ◆ ^p⇡ erfi(*xp*)*xpex*² *^p* (3)

$$
\text{Growth Rate} \sim \omega_p^2 \left(A_p + \frac{\omega_r}{\omega_r - \Omega_p} \right) \sqrt{\pi} x_p e^{-x_p^2} \qquad \text{(Kernel & Peterschek, 1966)}
$$

• The HFEMIC instability requires a large temperature anisotropy.

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District da line da li \blacksquare \overline{P} $\frac{1}{2}$ \overline{f} ◆ ^p⇡ erfi(*xp*)*xpex*² *^p* (3)

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$$

Figure 2. (a) Dispersion relation and (b) corresponding minimum resonance energy at 1532–1533 UT on 4 January 2019. α are indicated α is calculated in the figure. *• The HFEMIC instability requires very small proton beta, equivalent to T|| ~ 1-10 eV in the magnetosphere.*

Theoretical Anisotropy Threshold tuation growth and is not useful in most real plasmas where an instability must have a growth rate substantially greater than the rate of macroscopic plasma change if it is to assert of/311 p does not change significantly among the threexamples. Yet both observations [equation (1)] and simulations (see below) typically yield larger values of this exponent at •906 GARY ET AL.' PROTON CYCLOTRON INSTABILITY

a threshold may correspond to any nonzero value of the Gary+ 1994 **maximum growth rate; since our concern here is with a variable value of** α Gary+ 1994

$$
\frac{T_{\perp p}}{T_{\parallel p}} - 1 = \frac{0.43}{\beta_{\parallel p}^{0.42}} \qquad (\gamma_m = 10^{-3} \Omega_p)
$$

$$
\frac{T_{\perp p}}{T_{\parallel p}} - 1 = \frac{0.65}{\beta_{\parallel p}^{0.40}} \qquad (\gamma_m = 10^{-2} \Omega_p)
$$

function function for the proton control for the proton control for the proton control of the proton control for the proton control of the proton control of the proton control of the proton control of the proton control o bility. The model is model in all the figures of the figures of the figure in all the figures of the figures of the figures of the figures of the figure in all the figures of the figures of the figure in all the figures o growth was excited and the anisotropies were reduced to-*Typical EMIC wave* **space plasmas are inactive; if, for example, ion anisotropies**

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 0.0010×0.010

Gary+ 1994

 \overline{T} 0.49 $\frac{1}{T_{\text{H}_{\text{c}}}} - 1 = \frac{0.43}{\beta_0 - 0.42}$ ($\gamma_m = 10^{-3} \Omega_p$) $T_{\parallel p}$ $\beta_{\parallel p}$ ^{0.42} $T_{\rm H}$ and $T_{\rm H}$ of 65 $\frac{I \perp p}{T} - 1 = \frac{0.43}{\rho - 0.42}$ $T_{\|p}$ $\beta_{\|p}^{0.42}$

$$
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$$

Figure 1. Linear dispersion properties of the properties of properties of properties and properties and parallel beta **THE DISCRETE SYMBOLS OF THE PROTOCOL** *High-frequency EMIC wave Typical EMIC wave*

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Can HF-EMIC waves by ion cyclotron instability grow in a realistic environment?

gives fise to wave growth at $r = 0.33$ rcp according to theory, can we prov Ma (2023). (a) Total electron density, (b) electron plasma-to-cyclotron frequency ratio, (c) aver-*amplitudes? Q. Given a plasma condition at L = 5.5 with a reasonable proton distribution that gives rise to wave growth at f = 0.95 fcp according to theory, can we prove wave growth with saturation amplitude commensurate with the observed wave*

Earth's Dipole Magnetic Field

Liouville's theorem:

density & anisotropy
$$
\propto \left[\left(1 - \frac{B_{0,\text{eq}}}{B_0(\lambda)} \right) (A_{\text{eq}} + 1) + \frac{B_{0,\text{eq}}}{B_0(\lambda)} \right]^{-1}
$$
 (bi-Maxwellian)

The more anisotropic the initial distribution is,

narrower the equatorial source region becomes in a constant *L*-shell surface instead of the meridional plane. This is to take into account the observational *the narrower the equatorial source region becomes.*

Initial distribution

 T_{thot} *Heavy ion density* : 20% (extreme case scenario) *Hot proton density* : 20% *Hot proton beta* \qquad : $\beta_{\parallel hot} = 10^{-4}$ (← $f_{\rm peak} \approx 0.95 f_{cp}$) *Hot proton anisotropy* : $\frac{1}{2} m \approx 31$ (← Teng+ 2019 estimate) *T*⊥*hot T*∥*hot* ≈ 31

Convective growth rate

Wave group velocity

$$
\frac{dx}{dt} = v_g \equiv \frac{\partial \omega}{\partial k_{\parallel}}
$$

Convective growth rate

1D Hybrid PIC Model Journal of Geophysical Research: Space Physics 10.1002/2014JA019820

- *• Usual hybrid PIC approach (kinetic ions + massless electron fluid)*
- *• 1D domain along the field line (parallel propagation only)*

$$
B_{\text{dip}} \approx B_{0,\text{eq}} \left(1 + \frac{4.5 \text{ s}^2}{L^2 \text{ R}_E^2} \right) \text{ with } L = 5.5 \text{ (realistic scale)}
$$

 \cdot *Similar models by Katoh & Omura (2007)* and *Shoji & Omura (2011)* d*J^c*

Simulation Results manuscript submitted to *JGR: Space Physics*

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Dispersion Relation

Theory, Simulation, Observation (1)

Saturation amplitudes within the range of observation

Theory, Simulation, Observation (2)

Theory, Simulation, Observation (2) 2 (b)

γmax/Ωp=0.001

On the other hand, measurements of β_{\perp} *and* $f_{\rm peak}$ *are more accurate. The data points seem to line up closely to the curves by the theoretical predictions.*

Conclusions

• New type of EMIC (HFEMIC) waves: $f_{\rm peak} \sim 0.95 f_{cp}, \, \Delta f \lesssim 0.1 f_{cp}$

→ *Left-hand polarized, quasi-parallel propagating electromagnetic ion cyclotron mode*

- *Rare in occurrence (mostly outside the plasmasphere), but the anisotropic, low-energy proton population is quite prevalent* → *How the latter comes about is an unanswered question!*
- *• The very anisotropic, low-energy proton population is likely the source of free energy*

→ *Qualitative agreement btw/ data and predicted anisotropy threshold*

→ *Hybrid PIC simulations support HFEMIC wave growth with saturation amplitudes commensurate with the observational ones*

