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Gyroresonance Between Electromagnetic Ion Cyclotron Waves and Particles in a Multi-ion Plasma*

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Abstract The gyroresonant interaction between electromagnetic ion cyclotron (EMIC) waves and energetic particles was studied in a multi-ion (H^+, He^+, and O^+) plasma. The minimum resonant energy $E_{\rm min}$, resonant wave frequency ω, and pitch angle diffusion coefficient $D_{\alpha\alpha}$ were calculated at the center location of the symmetrical ring current: $r \approx 3.5R_{\rm E}$ with $R_{\rm E}$ the Earth's radius. $E_{\rm min}$ is found to decrease rapidly from 10 MeV to a few keV with the increase in ω in three bands: H^+-band, He^+-band and O^+-band. Moreover, EMIC waves have substantial potential to scatter energetic (~100 keV) ions (mainly H^+ and He^+) into the loss cone and yield precipitation loss, suggesting that wave-particle interactions contribute to ring current decay.

Keywords: wave-particle interaction, ring current decay, EMIC waves, multi-ion plasma

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1 Introduction

Cyclotron wave-particle interaction is an active process occurring in space plasma since it can account for synchrotron radiation in the Jovian inner magnetosphere [1] and for stochastic acceleration and pitch angle scattering of energetic particles in the radiation belts of the Earth [2~11]. Fluxes of outer radiation belt electrons are highly variable [12] during geomagnetic storms, which are found to be driven by wave-particle interactions [13,14], together with drift resonance with ultra low frequency (ULF) waves [15,16]. Electromagnetic waves are found to easily propagate over a wide range of magnetosphere [17,18] and further enhance this variation in flux. The terrestrial ring current is usually located at distances between 2 $R_{\rm E}$ to 9 $R_{\rm E}$ and is found to be strongly associated with geomagnetic storms. There are three dominant mechanisms responsible for the ring current decay, namely Coulomb collision processes, charge exchange, and pitch angle diffusion by EMIC waves. In previous work, HE et al. [19] presented an evaluation of the characteristics of wave-particle interaction in a single hydrogen plasma and found that EMIC waves can efficiently scatter protons into the loss cone and lead to the ring current decay. However, since the main carriers of the storm ring current are positive ions (including H^+, He^+, and O^+), with energies from about 1 keV to a few hundred keV, it is important to study wave-particle interactions in a multi-ion plasma. Further, since the relativistic effect is found to be appreciable as resonant energies approach 10 keV [20,21], a fully relativistic method is needed to evaluate acceleration and loss mechanisms [22~24]. Here, we shall therefore further analyze gyroresonant interaction between EMIC waves and ring current ions using fully relativistic conditions, including minimum resonant energy, resonant wave frequency, and pitch angle diffusion coefficient.

2 Dispersion relation and minimum resonant energy

The refractive index $\mu = ck/\omega$ for parallel-propagating EMIC waves in a multi-ion plasma can be written to be

$$\mu^2 = 1 - \frac{\omega_{\rm pe}^2}{\omega(\omega + |\Omega_{\rm e}|)} - \sum_{\sigma=1}^{3} \frac{\omega_{{\rm p}\sigma}^2}{\omega(\omega - \Omega_\sigma)}, \qquad (1)$$

where $\sigma = 1, 2, 3$ refers to H^+, He^+ and O^+, respectively; k is the wave number, c is the speed of light, $\omega_{\rm pe}$ and $|\Omega_{\rm e}|$ denote the plasma frequency and gyrofrequency of electrons; $\omega_{{\rm p}\sigma}$ and Ω_σ are the plasma frequency and gyrofrequency of ions. In the following, we will focus on the location $r = 3.5R_{\rm E}$ where the symmetrical ring current primarily locates and choose H^+, He^+ and O^+ fractional ion number densities respectively as $\eta_1 = 0.7$, $\eta_2 = 0.2$, and $\eta_3 = 0.1$ throughout this study.

In Fig. 1, we present the EMIC wave dispersion curves for two cases $\rho = \omega_{\rm pe}^2/|\Omega_{\rm e}|^2 = 50$ and 100,

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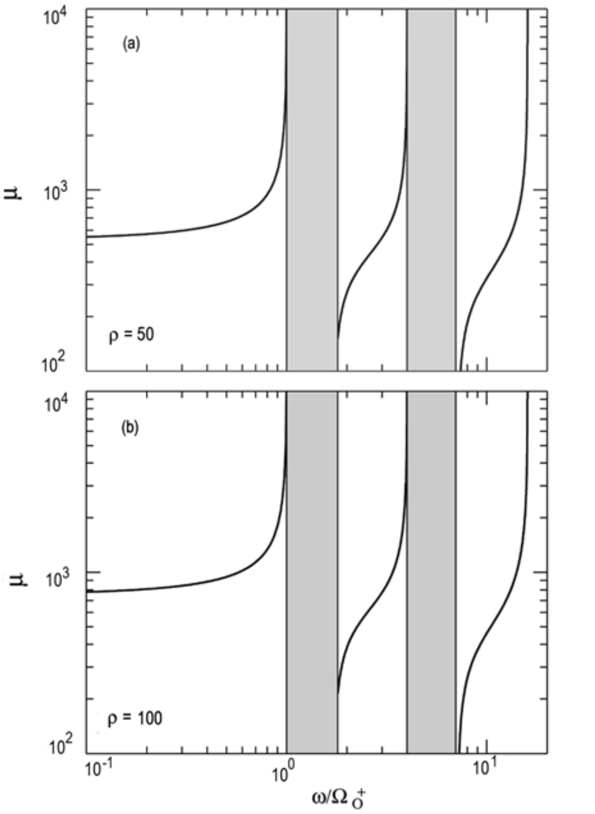

Fig.1 μ in dispersion relation Eq. (1) against the scaled wave frequency

respectively corresponding to higher and lower geomagnetic activities. We shall refer to three illustrated wave bands $0 < \omega < \Omega_{O^+}$, $\omega_{He^+} < \omega < \Omega_{He^+}$ and $\omega_{H^+} < \omega < \Omega_{H^+}$, as the oxygen, helium, and hydrogen bands. Here ω_{He^+} and ω_{H^+} stand for the respective cut-off frequencies for helium and hydrogen bands where the refractive index μ is zero. Field-aligned EMIC waves can not propagate in the stop-bands specified by $\Omega_{O^+} < \omega < \omega_{He^+}$ and $\Omega_{He^+} < \omega < \omega_{H^+}$.

The general resonant equation for interaction between field-aligned EMIC waves and ions (with velocity v and pitch angle α) can be written as

$$\omega - kv_{//} = \Omega_\sigma/\gamma, \tag{2}$$

where $v_{//} = v\cos\alpha$, the resonant relativistic Lorentz factor γ, can be derived by Eqs. (1) and (2):

$$\gamma = \frac{-1 + \mu[(\mu^2-1)(1+p_\perp^2/c^2)\omega^2/\Omega_\sigma^2 + 1]^{1/2}}{(\mu^2-1)\omega/|\Omega_\sigma|}, \tag{3}$$

where $p_\perp$ is the perpendicular component of momentum scaled by rest mass m; the minimum resonant kinetic energy $E_{\min} = (\gamma - 1)mc^2$ can be obtained by setting $p_\perp = 0$ in Eq. (3):

$$E_{\min} = \left\{\frac{-1 + \mu[(\mu^2-1)\omega^2/\Omega_\sigma^2 + 1]^{1/2}}{(\mu^2-1)\omega/|\Omega_\sigma|} - 1\right\}mc^2. \tag{4}$$

Fig. 2 shows examples of the minimum resonant kinetic energy $E_{\min}$ in Eq. (4) as a function of the scaled wave frequency. The minimum energy $E_{\min}$ is found to decrease very rapidly from an energy of 10 MeV to a few keV as wave frequency ω increases at each band,

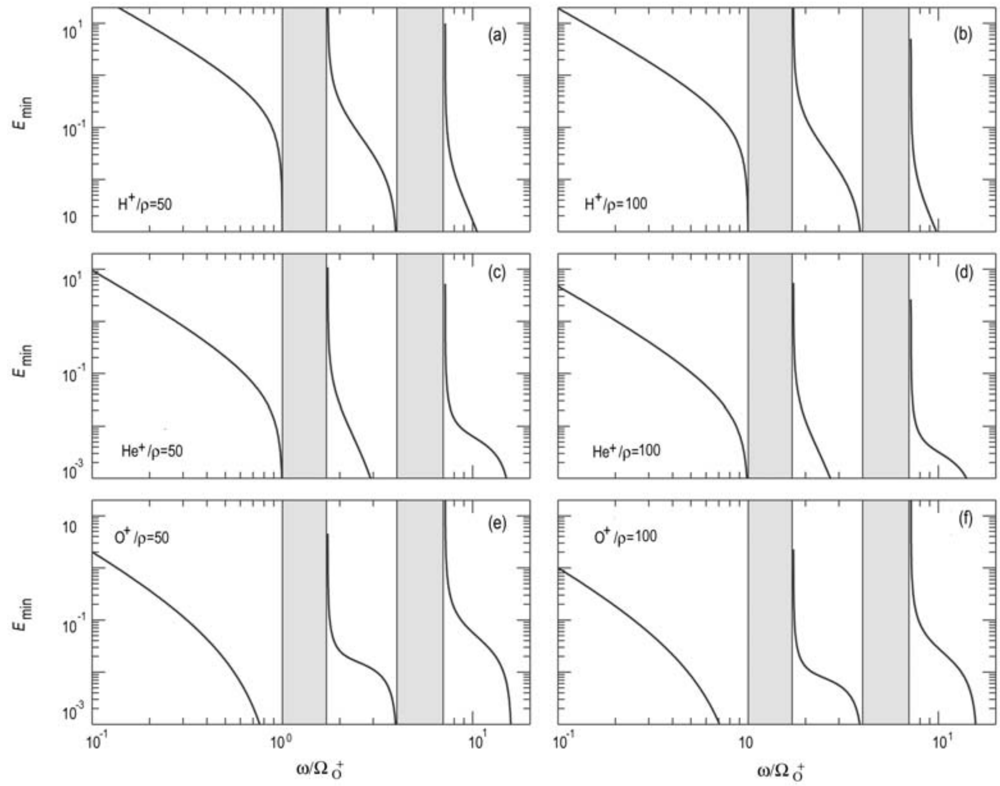

Fig.2 Minimum resonant energy $E_{\min}$ (MeV) as a function of ω/Ω_{O^+} for EMIC in gyroresonance with ions H^+ (a)∼(b), He^+ (c)∼(d), and O^+ (e)∼(f)

becoming very small as wave frequency approaches the cutoff frequency ω_{He^+} or ω_{H^+} since $\mu \to 0$ there. Meanwhile, as the parameter ρ increases, $E_{\min}$ basically decreases, implying that wave-particle interaction tends to occur in a higher density region (or a weaker ambient magnetic field region).

3 Resonant frequency and diffusion coefficient

The resonant frequency region is critical for understanding the features of wave-particle interaction. In Fig. 3, we present the scaled resonant wave frequency for EMIC-ion interactions at a specified kinetic energy of E_{k}=100 keV with $\rho = 50$ and 100. Resonant wave frequency range is found to increase with the increase in pitch angle α, particularly near $\alpha = 90°$. However, resonant wave frequency range is not sensitive to ρ since the refractive index μ is not sensitive to ρ (see Fig. 1).

In order to evaluate pitch angle scattering and, correspondingly, the ring current decay by EMIC-ion interaction, for EMIC wave power of B_{w}^2, we shall adopt the standard Gaussian frequency band with a peak ω_{m}, a half width $\delta\omega$, lower cutoff ω_1, and upper cutoff ω_2:

$$B_{\mathrm{w}}^2 = \begin{cases} B_{\mathrm{n}}^2 \exp[-(\omega-\omega_{\mathrm{m}})^2/\delta\omega^2] & \text{for } \omega_1 \le \omega \le \omega_2, \\ 0 & \text{otherwise,} \end{cases} \tag{5}$$

with the normalized parameter B_{n}^2 given by:

$$B_{\mathrm{n}}^2 = \frac{2B_{\mathrm{t}}^2}{\pi^{1/2}\delta\omega}\left[\mathrm{erf}\left(\frac{\omega_2-\omega_{\mathrm{m}}}{\delta\omega}\right) + \mathrm{erf}\left(\frac{\omega_{\mathrm{m}}-\omega_1}{\delta\omega}\right)\right]^{-1}, \tag{6}$$

where B_{t} is the wave magnetic field strength. The pitch angle diffusion coefficient $D_{\alpha\alpha}$ can be expressed by [27]:

$$D_{\alpha\alpha} = \frac{\Omega_\sigma^2}{p^2}\left(\frac{p^2}{\gamma^2}I_0 - 2\frac{cp}{\gamma}I_1\cos\alpha + c^2 I_2\cos^2\alpha\right) \tag{7}$$

and

$$I_n = \pi\sum_{\omega_{\mathrm{r}}}\left\{\frac{B_\omega^2}{B_0^2}\left(\frac{\omega_r}{ck_r}\right)^n\left|1-\cos\alpha\frac{p}{\gamma}\frac{\mathrm{d}k}{\mathrm{d}\omega}\right|_{\omega=\omega_r}^{-1}\right\}, \tag{8}$$

where $n = 0, 1, 2$; ω_r (or k_r) is the resonant frequency (or the resonant wave number) which obeys the resonant condition Eq. (2); $\mathrm{d}k/\mathrm{d}\omega$ is calculated by the dispersion relation (1) at each ω_r, B_0 is the equatorial ambient magnetic field.

Based on previous work [27,28], we choose the representative values of wave parameters listed in Table 1 where $\delta\omega = (\omega_2-\omega_1)/4$ and $\omega_{\mathrm{m}} = (\omega_1+\omega_2)/2$.

Table 1. Parameters for EMIC-ion interaction at $3.5R_{\mathrm{E}}$

	H^+ band	He^+ band	O^+ band
ω_1	$0.4\Omega_{\mathrm{H}^+}$	$0.5\Omega_{\mathrm{He}^+}$	$0.5\Omega_{\mathrm{O}^+}$
ω_2	$0.8\Omega_{\mathrm{H}^+}$	$0.95\Omega_{\mathrm{He}^+}$	$0.8\Omega_{\mathrm{O}^+}$
B_{t}	1 nT	1 nT	1 nT

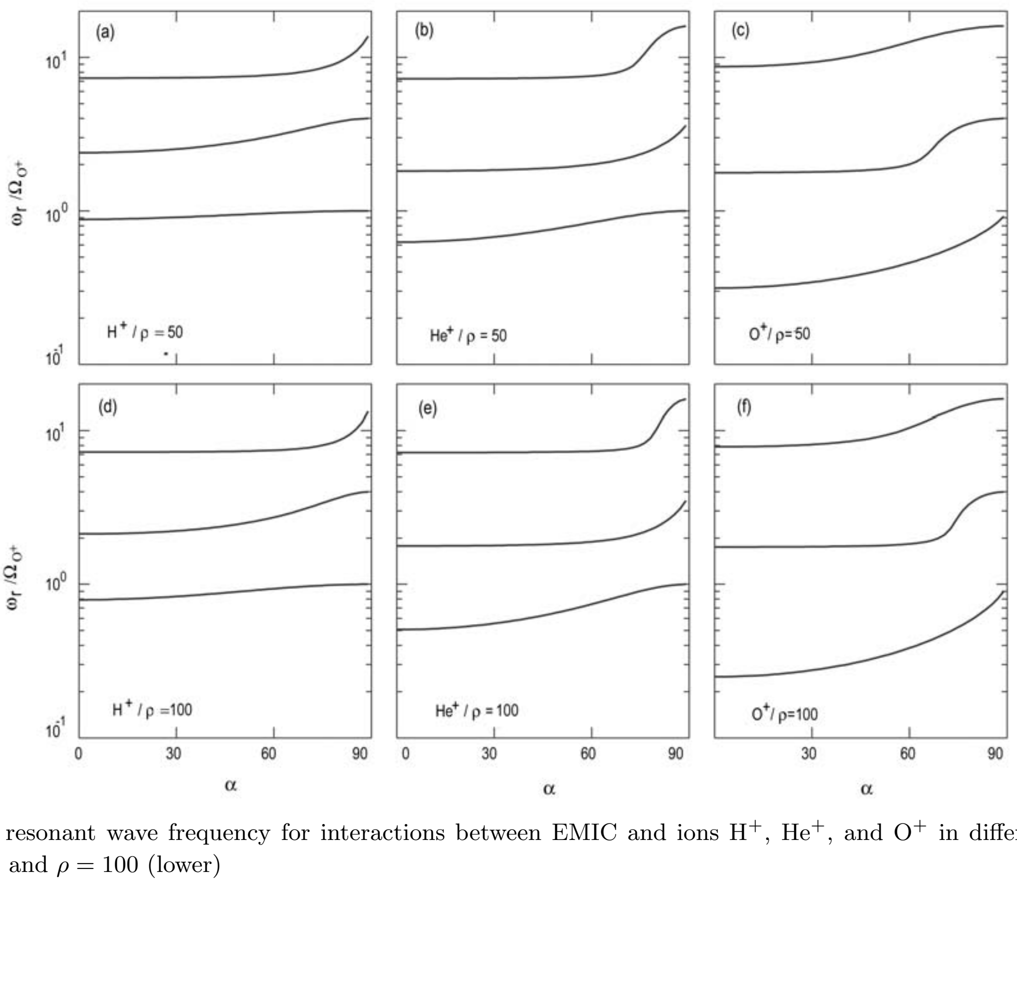

Fig.3 Scaled resonant wave frequency for interactions between EMIC and ions H^+, He^+, and O^+ in different bands for $\rho = 50$ (upper) and $\rho = 100$ (lower)

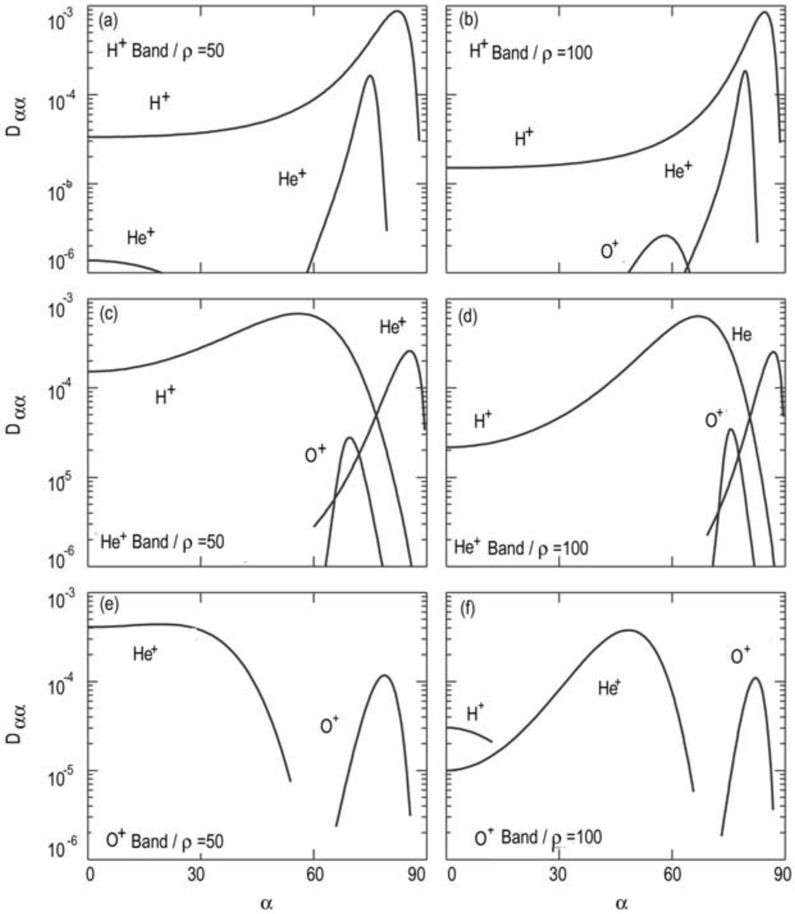

Fig.4 Pitch angle diffusion coefficient $D_{\alpha\alpha}$ (s^{-1}) due to interactions between ions with H^+ band (a) ∼ (b), He^+ band (c) ∼ (d), and O^+ band (e) ∼ (f)

In Fig. 4, we plot pitch angle diffusion coefficients as a function of pitch angle α due to interactions between EMIC waves in different bands with ions. It is shown that both H^+ and He^+ bands can efficiently drive energetic H^+ ions into the loss-cone since diffusion coefficients cover a wide range of angles and approach a peak of $\sim 10^{-3}$ s^{-1} (see Panels (a)∼(d)), while the O^+ band is capable of scattering those energetic He^+ ions into the loss-cone with a peak value of 4×10^{-4} s^{-1} (see Panels (e)∼(f)). However, EMIC waves are less efficient in scattering O^+ ions into the loss cone since diffusion coefficients are smaller and primarily located in higher pitch angle regions near or above 60°. Since the symmetrical ring current is found to occur primarily within $r = 4R_E$ during the strong geomagnetic storms, while the asymmetrical ring current generally stays beyond $r = 4R_E$, the above results indicate that EMIC waves could be an active candidate responsible for ring current decay.

4 Summary

In this study, a detailed investigation of the gyroresonant interaction between EMIC waves and energetic ions in a multi-ion (H^+, He^+, and O^+) plasma was presented. We calculated minimum resonant energy $E_{\min}$, resonant wave frequency ω, and the pitch angle diffusion coefficient for a specified kinetic energy $E_k = 100$ keV at $r \approx 3.5R_E$ where the symmetrical ring current primarily occurs. $E_{\min}$ is found to decrease with the increase in ω very rapidly for three bands, typically from energy of ~ 10 MeV to a few keV. It is shown that EMIC waves can cause efficient pitch angle scattering of energetic ions H^+ and He^+, and yields precipitation loss at $r = 3.5R_E$, further supporting the previous result that cyclotron wave-particle interaction indeed provides an efficient mechanism for the ring current decay.

References

1 Xiao F L, Thorne R M. 2006, Planet. Space Sci., 54: 405

2 Lu Q M, Wang L Q, Zhou Y, Wang S. 2004, Chin. Phys. Lett., 21: 129

3 Wang D Y, Huang G L, Lu Q M. 2004, Chin. Phys. Lett., 21: 1997

4 Xiao F L, Zheng H N, Wang S. 2005, Chin. Phys. Lett., 22: 1552

5 Xiao F L, Zheng H N, Wang S. 2005, Chin. Phys. Lett., 22: 517
6 Xiao F L, Zheng H N, Wang S. 2005, Plasma Sci. Tech., 7: 2973
7 Xiao F L, Feng X S. 2006, Plasma Sci. Tech., 8: 279
8 Xiao F L, Zhou Q H, Zheng H N, et al. 2006, J. Geophys. Res., 111: A08208
9 Xiao F L, Thorne R M, Summers D. 2007, Planet. Space Sci., 55: 1257
10 Xiao F L, Chen L J, Zheng H N, Wang S. 2007, J. Geophys. Res., 112: A10214
11 Xiao F L, Su Z P, Zheng H N, Wang S. 2009, J. Geophys. Res., 114: A03201
12 Baker D N, Blake J B, Klebesadel R W, et al. 1986, J. Geophys. Res., 91: 4265
13 Li X. 2004, Space Weather, 2: S03006
14 Li L, Cao J, Zhou G. 2005, J. Geophys. Res., 110: A03203
15 Zong Q G, Zhou X Z, Li X, et al. 2007, Geophys. Res. Lett., 34: L12105
16 Zong Q G, Wang Y F, Yang B, et al. 2008, Sci. China Ser E-Tech. Sci., 51: 1
17 Xiao F L, Chen L J, Zheng H N, et al. 2008, Chin. Phys. Lett., 25: 340
18 Xiao F L, Chen L J, Zheng H N, et al. 2008, Plasma Sci. Tech., 10: 546
19 He H Y, Chen L X, Li J F. 2008, Chin. Phys. Lett., 25: 3511
20 Xiao F L, Thorne R M, Summers D. 1998, Phys. Plasmas 5: 2489
21 Xiao F L, Thorne R M, Gurnett D A, et al. 2003, Geophys. Res. Lett., 30: 1479
22 Xiao F L. 2006, Plasma Phys. Control. Fusion, 48: 203
23 Xiao F L, Zhou Q H, Li C X, et al. 2008, Plasma Phys. Control. Fusion, 50: 062001
24 Xiao F L, Shen C L, Wang Y M, et al. 2008, J. Geophys. Res., 113: A05203
25 Lyons L R, Thorne R M, Kennel C F. 1972, J. Geophys. Res., 77: 3455
26 Glauert S A, Horne R B. 2005, J. Geophys. Res., 110: A04206
27 Summers D. 2005, J. Geophys. Res., 110: A08213
28 Summers D, Ni B, Meredith N P. 2007, J. Geophys. Res., 112: A04207

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