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Transverse eV ion heating by random electric field fluctuations in the plasmasphere

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Charged particle acceleration in the Earth inner magnetosphere is believed to be mainly due to the local resonant wave-particle interaction or particle transport processes. However, the Van Allen Probes have recently provided interesting evidence of a relatively slow transverse heating of eV ions at distances about 2–3 Earth radii during quiet times. Waves that are able to resonantly interact with such very cold ions are generally rare in this region of space, called the plasmasphere. Thus, non-resonant wave-particle interactions are expected to play an important role in the observed ion heating. We demonstrate that stochastic heating by random transverse electric field fluctuations of whistler (and possibly electromagnetic ion cyclotron) waves could explain this weak and slow transverse heating of H^+ and O^+ ions in the inner magnetosphere. The essential element of the proposed model of ion heating is the presence of trains of random whistler (hiss) wave packets, with significant amplitude modulations produced by strong wave damping, rapid wave growth, or a superposition of wave packets of different frequencies, phases, and amplitudes. Such characteristics correspond to measured characteristics of hiss waves in this region. Using test particle simulations with typical wave and plasma parameters, we demonstrate that the corresponding stochastic transverse ion heating reaches 0.07–0.2 eV/h for protons and 0.007–0.015 eV/h for O^+ ions. This global temperature increase of the Maxwellian ion population from an initial $T_i \sim 0.3$ eV could potentially explain the observations. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4976713]

I. INTRODUCTION

The near-Earth region where the co-rotation electric field dominates charged article motion (up to 4 Earth radii from the planet) is called the plasmasphere; it is filled with the cold plasma of ionospheric origin. Suprathermal 1–10 eV ions inside the plasmasphere co-rotate with Earth,[6] influence the magnetosphere-ionosphere coupling, and may affect spacecraft surface charging. A recently published study[36,45] of this population of 1–10 eV equatorially mirroring ions shows their apparent transverse heating over the sector 4–18 MLT (Magnetic Local Time) at $L = 2-3$ (L being the equatorial distance to the Earth center measured in Earth radii, see scheme in Fig. 1) and note a strong correlation between ion heating and 150–600 Hz hiss whistler-mode waves during relatively quiet times (characterized by a low value of geomagnetic activity index $Kp < 3$ indicating the absence of large-scale magnetospheric perturbations). However, usual (right-hand polarized) hiss cannot interact with ions through cyclotron resonance $\omega - k_\parallel v_{i,\parallel} = n\Omega_{ci}$ (with ω the wave frequency, Ω_{ci} the ion gyrofrequency, k the wave vector, $v_{i,\parallel}$ the parallel ion velocity, and n the resonance number) when $\omega/k_\parallel > v_{i,\parallel}$ as in this case (e.g., Ref. 20). Landau resonance $v_{i,\perp}k_\perp = \omega$ and ion heating through the electrostatic component of the wave electric field (e.g., see Ref. 16) can be similarly ruled out here. In Ref. 36, it was further emphasized that, in this region, there is a considerably lower occurrence (<1% of 150–500 Hz waves) of linearly polarized fast magnetosonic waves, which could interact resonantly with such low-energy ions.

At the present time, the dominant mechanism of eV ion heating at $L = 2-3$ during quiet periods is still unknown.[36,45] However, various past studies have suggested that diffusive resonant heating by fast magnetosonic waves was a worthy candidate. Fast magnetosonic waves are very oblique whistler-mode electromagnetic waves with frequencies between the proton gyrofrequency and the lower hybrid resonance frequency first reported in Ref. 32 and mostly localized within $\sim 3^\circ$ of the magnetic equator.[25] Years-long statistics from the Van Allen Probes, Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites, and CLUSTER satellites all show the presence of a higher fast magnetosonic wave power near the equator in the 3–18 MLT sector than in the 0–3 MLT sector during quiet periods ($Kp < 3$) at $L = 2-3$, albeit with a quite small time-averaged root-mean-square magnetic wave amplitude $B_w \sim 2-3$ pT (see Refs. 22, 23, and 25). This MLT modulation of magnetosonic wave power is, therefore, very similar to the MLT modulation of both the observed hiss wave power and the ion flux level.[36] It suggests that ion energy diffusion by fast magnetosonic waves might explain ion heating at 5–12 MLT and $L = 2-3$ during relatively quiet periods (as well as some ion losses occurring in the dusk sector). Near the plasmapause (the

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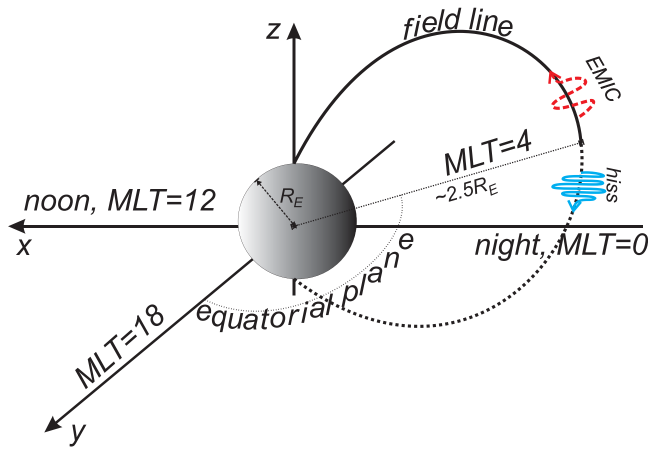

FIG. 1. Schematic view of the system ($R_E \approx 6400$ km is the Earth's radius). Range of Magnetic Local Time (MLT) is shown for the region where ion heating is expected.

boundary of the plasmasphere), a strong correlation was already found three decades ago between 20 and100 eV ion heating and magnetosonic wave occurrence;[29] the corresponding quasi-linear ion energization through cyclotron resonance was also estimated,[10] demonstrating a reasonable agreement with some satellite observations of 20–100 eV proton heating near the plasmapause at $L > 4$.

Another possible mechanism of eV ion heating is through resonant interactions with waves near the ion cyclotron frequency (e.g., see Refs. 3, 20, 21, 39, 40 and references therein). A mechanism relying on low frequency waves such that $\omega_1 + \omega_2 = \Omega_{ci}$ was also proposed in Ref. 43. Alfven electromagnetic ion cyclotron (EMIC) waves[13] (also called proton whistlers) produced by lightning strokes may efficiently heat thermal ions at low altitudes when their frequency becomes close to the local ion cyclotron frequency (see Ref. 39). However, they should be considerably less effective at heating equatorially mirroring ions, since only a very tiny fraction of these waves (in an extremely narrow very low frequency range) can propagate through the equatorial plane very close to the local ion cyclotron frequency. Moreover, EMIC waves recorded during quiet times at $L \leq 3$ are usually nearly uniformly spread over the 2–22 MLT region (e.g., see Refs. 33 and 36), sometimes with a larger occurrence on the nightside,[38] which is totally at odds with the observed ion heating confined to the sole 5–12 MLT sector. Furthermore, EMIC wave frequencies are generally[36] sufficiently far below the proton gyrofrequency to prevent cyclotron (as well as Landau) resonant interaction with nearly equatorially mirroring ions of low energy <10 eV (e.g., Ref. 3). Electrostatic ion cyclotron waves (also called ion Bernstein waves), occurring near harmonics of the ion gyrofrequency, may seem promising at first sight since any ion could eventually become cyclotron resonant with them. However, interactions with such waves should preferentially produce high-energy tails (>10 eV) rather than an increase in the global ion temperature.[21] Moreover, the generation of electrostatic ion cyclotron waves usually requires a sufficient transverse anisotropy $\partial f(v_{i,\perp})/\partial v_{i,\perp} > 0$ of the ion velocity distribution, possibly supplemented by parallel electric fields or parallel upflow.[2–4,21,37] Such conditions are easily fulfilled in the auroral region,[26] but they should not be satisfied in general at $L = 2 - 3$ when low energy ion distributions have initially isotropic temperatures. On the other hand, quasi-linear pitch-angle diffusion induced by electrostatic ion cyclotron waves[3] or EMIC waves[11,12] might play some role in the observed 1–10 eV anisotropic ion flux saturation after 8 MLT and its drop after 18 MLT.[34]

Yet another option is a non-resonant stochastic heating by successive, spatio-temporally limited, and random bursts of transverse magnetosonic, hiss, or EMIC wave electric field (e.g., see Refs. 27 and 42). Observations of a very slow heating of thermal eV ions over a time scale of several hours in MLT[34,36] indeed suggest that such a second-order wave-particle interaction could be sufficient. A random walk in energy due to random wave-field jumps is precisely a second-order mechanism such that the mean (first moment) is zero while the variance (second moment) is not (e.g., Refs. 7 and 15).

We shall first briefly examine in Section II the mechanisms of ion heating by fast magnetosonic waves (resonant or not). Next, in Sections III and IV, we shall consider in detail the mechanisms of non-resonant stochastic ion heating by hiss and EMIC waves, making use of numerical simulations and comparing all along with actual observations. It will be shown that non-resonant stochastic heating by plasmaspheric hiss (and possibly EMIC) waves could be a viable mechanism for transverse eV ion heating around dawn at $L = 2 - 3$.

II. ION HEATING BY FAST MAGNETOSONIC WAVES

The MLT distribution of fast magnetosonic waves at $L = 2 - 3$ (see Refs. 22, 23, and 25) is roughly similar to the observed distributions of transversely heated 1–10 eV ion fluxes,[36] prompting us to check below the possibility of a stochastic heating by these waves. However, the average wave electric field power E_w^2 during quiet periods ($Kp < 3$) is considerably smaller at $L \sim 2.5$ than at $L \sim 4.5$, with $E_w^2(L = 2.5) \leq E_w^2(L = 4.5)/100$ based on fast magnetosonic wave statistics, leading to typical amplitudes $E_w \sim 0.01$ mV / m (see Refs. 23 and 25). This is 10^5 and 200 times smaller than the wave power used, respectively, in Refs. 10 and 47, both near $L = 4.5$. Extrapolating from their simulation results (accounting for density and geomagnetic field variations with L), the energization of <10 eV ions over several hours should be negligible during quiet times at $L = 2.5$.

Moreover, when considering different ion masses, it is worth noting that the ion energy diffusion coefficient is proportional to $J^2_{n(i)}(x_i)/m_i^2$ where the argument $x_i = k_\perp v_{i,\perp}/\Omega_{ci}$ of the Bessel function is proportional to $(T_{i,\perp} m_i/m_p)^{1/2}$ and $n(i) \sim \omega/\Omega_{ci}$ (see Ref. 10). Fast magnetosonic waves are such that $\omega/k \simeq \omega/k_\perp \sim v_A$ with an Alfven velocity $v_A \sim 900$ km/s at $L \sim 2.5$, using the plasmaspheric density model from Ref. 31. This gives $x_i \sim (T_{i,\perp} m_i/m_p)^{1/2} \omega/(90\Omega_{cp}) \ll (\omega/\Omega_{cp})(m_i/m_p)$ when $T_{i,\perp} \leq 300(m_i/m_p)$ eV. Considering low energy 1–20 eV ions, it allows us to use a series expansion of Bessel functions $J_n(x) \sim (x/2)^n/\Gamma(n+1)$ for $x \ll n$, showing that for a given ion temperature, the ratio of

$J^2_{n(i)}(x_i)/m_i^2$ terms for heavy ions (He^+ or O^+) over the same terms for protons is extremely small

$$\sim \frac{\Gamma(n+1)}{\Gamma(nX_m+1)}\left(\frac{x_p}{2}\right)^{n(X_m-1)} X_m^{nX_m/2} \ll 10^{-10},$$

for $X_m = m_i/m_p \geq 4$, $n = \omega/\Omega_{cp} \geq 3$, and $T_{i,\perp} < 20\,\text{eV}$. For a fixed wave frequency, cyclotron resonance with heavier ions occurs for higher cyclotron harmonics n, leading to a considerably smaller wave-particle coupling strength. It implies that time scales for resonant heating of low energy He^+ and O^+ by fast magnetosonic waves are many orders of magnitude larger than for protons.

This simple theoretical result stands in total contradiction with recent Van Allen Probe observations of H^+ and O^+ heating at $\sim 2\,\text{eV}$ occurring over roughly comparable time-scales (certainly within less than a factor of 10) at $L = 2-3$ in the 4–15 MLT sector.[34,36] It strongly suggests the presence of some *non-resonant* stochastic energy diffusion, which could provide much more comparable heating rates for ions of different masses. Such a non-resonant energization requires random kicks in velocity space produced by random electric fields (e.g., see Refs. 27 and 42). These random electric fields can originate from a sufficient wave incoherency, either spatial or temporal, such that an ion feels a temporal wave incoherency during its motion.

One such mechanism could be transit-time scattering by strongly localized fast magnetosonic waves, with a wave amplitude decreasing sensibly along a geomagnetic field line over a distance smaller than the long parallel wavelength on both sides of the magnetic equator.[5] However, $\sim 1\,\text{eV}$ ions bounce between mirror points with a long period between two passages at the equator $T_b \geq 2LR_E/v_i \sim 0.7$ h at $L = 2.5$. Thus, only a few random kicks can be obtained over several hours. Moreover, the parallel wavelength $\lambda_\parallel = (2\pi/\omega)v_A$ of fast magnetosonic waves is typically 10 times smaller at $L = 2.5$ ($R_E \approx 6400$ km is the Earth radius) than outside the dense plasmasphere, making it smaller than the spatial localization and strongly reducing this effect. Thus, the spatial localization of magnetosonic waves should induce a truly negligible transverse heating for low energy ions during relatively quiet times at $L = 2-3$.

III. STOCHASTIC TRANSVERSE ION HEATING BY PLASMASPHERIC HISS RANDOM FLUCTUATIONS

A. Simplified model of stochastic ion heating by hiss

Using high-resolution Polar satellite and Van Allen Probe measurements, Refs. 41 and 44 have recently shown that near the magnetic equator at $L \leq 4$, the plasmaspheric hiss is composed of wave-packets remaining relatively coherent over at most several wave cycles. Such observations of hiss incoherency suggest that successive, random bursts of hiss electric field could play an important role in the very slow (likely stochastic) eV ion heating reported in Ref. 36 on the dayside in fair correlation with higher intensities of right-hand polarized hiss waves (see scheme in Fig. 1). Such random phase jumps of the electric field can be produced by fast damping (or growth) of the waves by suprathermal electrons or by the superposition of many waves of different phases, wave vectors, and frequencies, leading to a small but finite (positive or negative) net time-integrated E-field over a wave-packet duration. However, we also assume that the time-integrated electric field tends toward zero as $t \to +\infty$ (see an example in Fig. 2).

We consider typical nearly parallel right-hand polarized hiss waves with a transverse (to the geomagnetic field) root-mean-square electric field E interacting with nearly equatorially mirroring ions of energy $<5\,\text{eV}$. Such ions can be regarded as practically motionless. Since their velocity is much smaller than ω/k (ω denoting wave frequency and k its wave vector), they cannot interact resonantly (through either Landau or cyclotron resonance) with these waves (e.g., see Refs. 20 and 36). Further assuming that the hiss wave phase is relatively incoherent, with a coherency time scale τ_c of the order of several wave periods $T = 1/f$ (with f the wave frequency) as in observations, we can use a random phase approximation.[15,28] The time scale of variation of the wave amplitude is then $\approx \tau_c$, corresponding to a typical wave-packet duration. Here, we should generally have $\tau_c < T_{ci} = 2\pi/\Omega_{ci}$, where Ω_{ci} denotes the ion gyrofrequency.

Such a process corresponds to a two-dimensional random walk in velocity space.[15,27,28,42] When considering a large number $N = t/\tau_c \gg 100$ of independent steps $\delta v_\perp$ in the random walk, the transverse ion velocity distribution should become a normal distribution with mean variance $\Delta\langle v^2\rangle \sim (t/\tau_c)(\delta v_\perp)^2$, characteristic of a Wiener process.[15,27] To derive rough analytical estimates, we consider for simplicity a constant step size in velocity and thus in electric field jumps. The actual step size may rather possess a gaussian distribution. In this maybe more realistic case, the step size $\delta v_\perp$ (or E) would correspond to the standard deviation. It was rigorously demonstrated in Ref. 28 that the transverse temperature of ions should then increase like $T_i(t) \simeq T_i(t=0) + 4Dt$, according to a Fokker-Planck equation with diffusion coefficient $D \simeq (\delta v_\perp)^2/4\tau_c$.

In our special case of relatively incoherent hiss waves, a near-thermal ion experiences a finite shift $\delta v_\perp$ of its transverse velocity by the non-zero net effect of transverse hiss electric field during each time step τ_c. The effect of this random non-zero net electric field can be approximated as the effect of E over only a small fraction $\epsilon \approx 1/4 - 1/30$ of the coherency (or wave-packet) time scale—likely corresponding also to a fraction $\Delta t = \epsilon\tau_c < T = 1/f$ of the wave period. It is worth emphasizing here that in this realistic scheme, only a few percent (at most) of the full wave-packet power make a truly random impact on the ion velocity, i.e., only a few percent of the total wave power can be considered as fully incoherent. This is much less than in previous heating schemes[17,27,42] where it was assumed that nearly 100% of the wave power consisted of random wave-field jumps.

Here, we get random velocity jumps $\sqrt{(\delta v_\perp)^2} \approx (eE/m_i)\Delta t = (eE/m_i)\epsilon\tau_c$. Accordingly, ions experience a slow, stochastic transverse heating $\Delta T_{i,\perp}(t) \approx (\epsilon eE\tau_c)^2 t/(m_i\tau_c) = e\epsilon^2E^2t\tau_c/m_i$ in MKSA units,[27,28] or equivalently

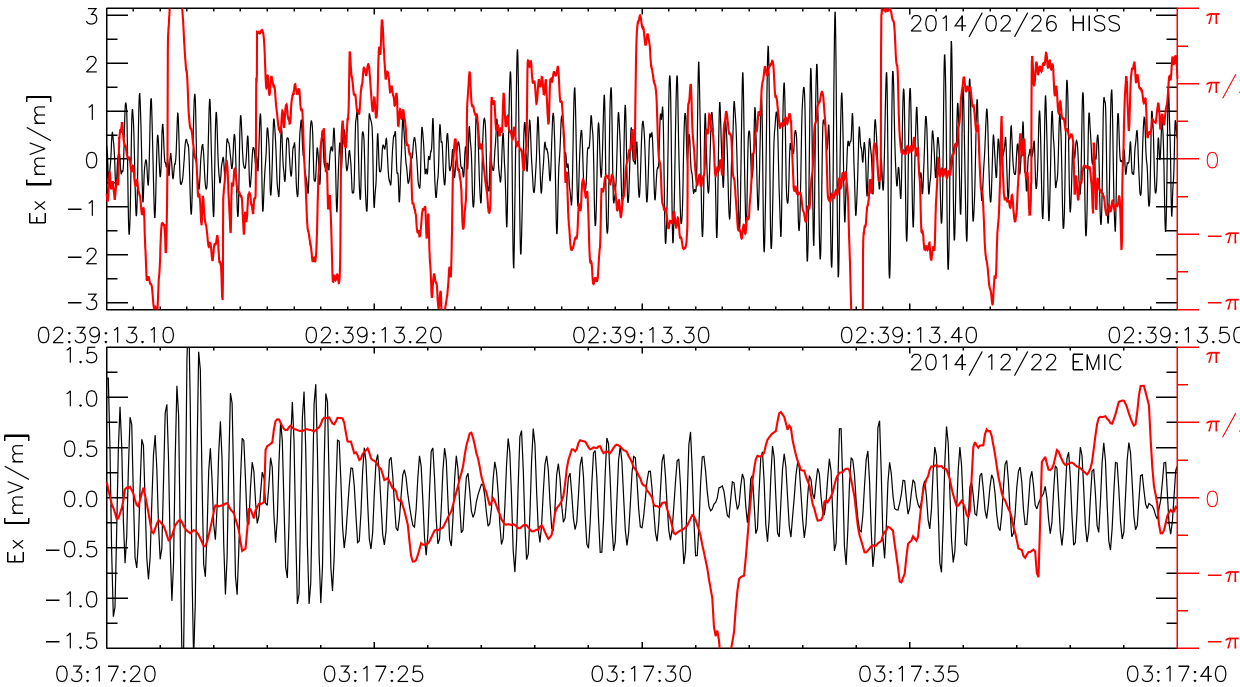

FIG. 2. Examples of hiss (top panel) and EMIC (bottom panel) waves observed by the Van Allen Probes around $L \sim 2.5$ during periods of low geomagnetic activity $Kp \le 2$. Black color shows the transverse component of the wave electric field measured by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) payload.[19] Red color shows the detrended wave phase calculated via Hilbert transform.[1] On time intervals of approximately constant phases (constant within 30°) we considered ~100 wave-packets and calculated ϵ parameters. This parameter was calculated as the mean value of the net time-integrated field over such periods divided by the peak absolute electric field. The corresponding distribution of ϵ for the hiss wave event gives $\epsilon \approx 0.1 \pm 0.03$. Although this ϵ value is within the range required to reproduce the observed proton heating rates, further investigations would be needed to determine this parameter statistically. The presence of a rather strong (amplitude ~0.3 mV/m) background ultra-low frequency wave during the EMIC wave event prevented any reliable determination of ϵ in this case.

$$\Delta T_{i,\perp}[\text{eV}] \sim \frac{100\,(\Delta t)^2 E^2 m_p\, t}{m_i\ \tau_c} = 100\, t\, \frac{\epsilon^2 E^2 \tau_c m_p}{m_i}, \qquad (1)$$

with E in mV/m and all time variables in seconds. Ion heating varies like $\sim m_p/m_i$, corresponding to He^+ (O^+) heating only 4 (16) times smaller than H^+ heating.

B. Comparisons with proton flux observations

Let us now compare the above first-order estimate of stochastic heating by hiss with observations. On the basis of 2 years of Van Allen Probes measurements, it was shown (see Ref. 36) that the median power density of right-hand hiss waves is about $\approx 10^{-11}$ V^2/m^2/Hz over 9–15 MLT at $L = 2.5$, corresponding to $E \sim 0.05$ mV/m for an effective bandwidth $\Delta f \sim 250$ Hz centered about a mean frequency $f \sim 250$ Hz. It gives $\Delta T_{i,\perp}(t) \sim 0.25\epsilon^2 t\tau_c(m_p/m_i)$ eV. Moreover, $\tau_c \approx 0.01$ s $\sim 2.5/f$ is a realistic order of value for hiss coherency at $L \sim 2-4$ in the equatorial region of the plasmasphere (see Fig. 2 and Ref. 41). One finally obtains

$$\Delta T_{i,\perp}[\text{eV}] \sim (5\epsilon)^2 \frac{m_p}{m_i} \frac{t}{3\,\text{h}}. \qquad (2)$$

It is worth noting that the *median* hiss wave power (over 2 years of measurements) was substituted in Equation (1) to derive Equation (2). A more accurate estimate would rather make use of the *mean* hiss wave power, provided that coherency and ϵ wave packet properties remain roughly similar for waves corresponding to the mean time-averaged (over a period much longer than wave packet duration) intensity and for the most frequent waves corresponding to median time-averaged intensity (a precise statistics of wave packet properties at $L = 2-3$ would be necessary to assess this point). The mean wave power of whistler-mode waves is sensibly larger in general (by factors $\approx 2-5$) than the median, due to the important contribution of more rare bursts of exponentially higher wave power (e.g., see Refs. 9, 24 and references therein). For a given ϵ, the above estimate (2) of $\Delta T_{i,\perp}(t)$ might, therefore, represent a lower bound for the actual heating rate, which could be $2-3$ times larger.

The heating rate estimate (2) depends crucially on the small parameter ϵ, which corresponds to the relative time-integrated amount of non-zero net electric field over a typical wave coherency time scale τ_c, divided by the wave electric field amplitude. Unfortunately, such a small value cannot be accurately determined statistically from Van Allen Probes data, due to a significant low-frequency noise level and a high but still barely sufficient time resolution. Although we provide an estimate of ϵ during one hiss event shown in Fig. 2 (see figure caption), more precise and sophisticated analyses would be necessary to obtain statistically representative values of ϵ. However, the theoretical heating rate can be compared with observed heating rates to provide an estimate of the value of ϵ needed to match observations.

A first estimate of the observed time scale of proton heating near $L \sim 2$ in the magnetosphere can be deduced mainly from the proton ion flux distributions in energy plotted as a function of MLT in Figure 9 from Ref. 34. It clearly shows a global proton temperature increase from 3 to 9 to 15 MLT at $L \sim 2$, which correlates well with a strongly enhanced hiss wave power at 150–600 Hz recorded after 3–4 MLT, reaching its maximum level near 6 MLT and remaining high until 15 MLT (see Figures 4–5 from Ref. 36). Moreover, as measured fluxes mostly correspond to high equatorial pitch-angle protons,[35] such flux distributions in energy can be considered as flux distributions in transverse energy. Assuming a Gaussian energy distribution and fitting the phase space density from Figure 9 of Ref. 34, one can derive approximate Maxwellian temperatures $\sim 0.3 \pm 0.1$ eV at 3 MLT and $\sim 0.5 \pm 0.1$ eV at 9 MLT, corresponding to a global $+0.2 \pm 0.1$ eV transverse temperature increase in less than 6 h in MLT. Since ions co-rotate with Earth,[6] it should correspond to similar universal time scales.

This rough upper-bound estimate of the heating time scale can be further refined. Indeed, Figures 2–3 and 5 from Ref. 36 and Figures 6–7 from Ref. 34 indicate that 1.3–2.2 eV protons fluxes quickly recover their maximum level in about 1.5 h in MLT from the last minimum near 4.5 MLT (a minimum caused by the cooling of the ionospheric source particles in the night sector, probably aided by some ion loss mechanisms in the pre-midnight sector). It means that it likely takes less than 2 h in MLT as well as in universal time to transversely heat protons so that they reach high flux levels similar to the 9 MLT levels.

On this basis, we can now infer that the theoretical estimate (2) can allow to recover approximately the observed proton heating rate for ϵ values comprised in the range $\epsilon \approx 0.13 \pm 0.03$. Such small values of ϵ look reasonable and realistic (see, e.g., the caption of Fig. 2). Thus, observations from Refs. 34–36 of eV proton transverse heating in the dawn sector at $L = 2 - 3$ during quiet times appear to be roughly consistent with stochastic heating by the simultaneously measured partially incoherent hiss waves.

C. Comparisons of eV H^+ and O^+ flux behaviors

The above estimates (1)–(2) of transverse ion heating seem to imply a 16 times weaker transverse heating rate for O^+ ions than for protons. Is it compatible with satellite observations in the dawn sector at $L = 2 - 3$? Van Allen Probe measurements discussed by Ref. 34 in their Figures 3, 5, 6, and 7 indicate that eV O^+ fluxes reach a high level near 7.5 MLT, about 3 h in MLT later than their last minimum near 4.5 MLT, i.e., it takes nearly twice more time in MLT for O^+ fluxes than for proton fluxes to recover. Their Figure 5 also shows flux increases between 3 and 7 MLT by factors 40 and 150, respectively, for O^+ and H^+ ions. In addition, Figure 7 from Ref. 34 indicates that the actual H^+ flux increase (and thus their heating) can be much stronger than the median value considered by Refs. 34 and 36, whereas O^+ measurements have a much smaller spread. All this suggests that O^+ transverse heating is only 2–3 times weaker than H^+ heating, rather far from the factor 16 expected from (1)–(2).

But the above considerations rely on the simplifying assumption that transverse heating of azimuthally travelling Maxwellian ions by hiss waves is the only important mechanism. However, various other phenomena may be simultaneously present around 6 MLT (and later), which can modify this simple picture. Let us examine some of them below.

First of all, both the H^+ and O^+ energy distributions may be somewhat different from the above-assumed Maxwellian global shapes. If the initial H^+ distribution decreases slightly less quickly at suprathermal energies than a Maxwellian (like a kappa distribution—e.g., see Ref. 8) while the O^+ distribution decreases slightly faster in this energy range than the bulk Maxwellian, then a small fraction of $\sim 1/10$ of the H^+ heating rate might really suffice to increase suprathermal O^+ fluxes by a similar factor to proton fluxes, reconciling theory and observations. However, measured O^+ fluxes[34] are much smaller and much noisier than proton fluxes above 3 eV, preventing us from accurately checking this conjecture.

Second, hotter ion outflow from the sun-heated topside dayside ionosphere (and accidental charge exchange between H^+ and O^+ or H^+ and O^+ populations) may be non-negligible and might account for part of the H^+ and O^+ flux increases near dawn, explaining the existence of some level of similarity between O^+ and H^+ flux behaviors (e.g., see Ref. 34 and references therein). Assuming that half of the proton flux increase (i.e., the square root of the proton flux increase factor) near dawn stems from hotter ion outflow (likely an upper-bound for this effect, see Ref. 36) and assuming a simultaneous increase of O^+ flux via hot ion outflow by the same factor as the proton flux, then high-altitude ion heating by hiss would only need to provide flux increases by factors 12 for H^+ and 3 for O^+ (instead of 150 and 40). It would correspond to a smaller hiss-related heating at $L \sim 2$ with $\Delta T_{H+,\perp} \sim +0.072$ eV and $\Delta T_{O+,\perp} \sim +0.025$ eV (starting from initial temperatures $\sim$0.22 eV) over $\sim$1.5 and $\sim$3 h, respectively. This scenario would correspond to a $\sim$6 times weaker O^+ heating rate than the H^+ heating rate, already much closer to estimates (1)–(2).

Third, ion loss to the ionosphere could become significant once ions have been sufficiently heated in the transverse direction. The anisotropic 1–10 eV proton fluxes observed on the dayside,[35,36] strongly peaked at equatorial pitch-angles near 90°, are prone to diffusion toward the loss-cone by any kind of really random pitch-angle scattering due to wave-particle interaction, since Fick's law then ensures that ions should be preferentially scattered toward the domain of lower ion phase space density (see Ref. 46). Such an additional ion loss (or isotropization) mechanism might explain the saturation of the proton and O^+ fluxes observed after 7–8 MLT.

There are at least three candidates for this job: electrostatic or electromagnetic ion cyclotron waves or fast magnetosonic waves. As discussed in Section II, the resonant interaction with fast magnetosonic waves (with maximum occurrence in the day sector) could be efficient at scattering protons (not heavier ions) but their very weak wave power at $L \sim 2.5$ during quiet times and the very small argument $x_i = k_\perp v_{i,\perp}/\Omega_{ci}$ of $J_n^2(x)$ Bessel functions at small energy suggest that this effect is very weak. A low level of self-generated electrostatic or electromagnetic ion cyclotron waves could also contribute to a very slow resonant pitch-angle diffusion of ions, leading to a self-saturation of the temperature anisotropy.[3,11] Once heated ion pitch-angle distributions reach a

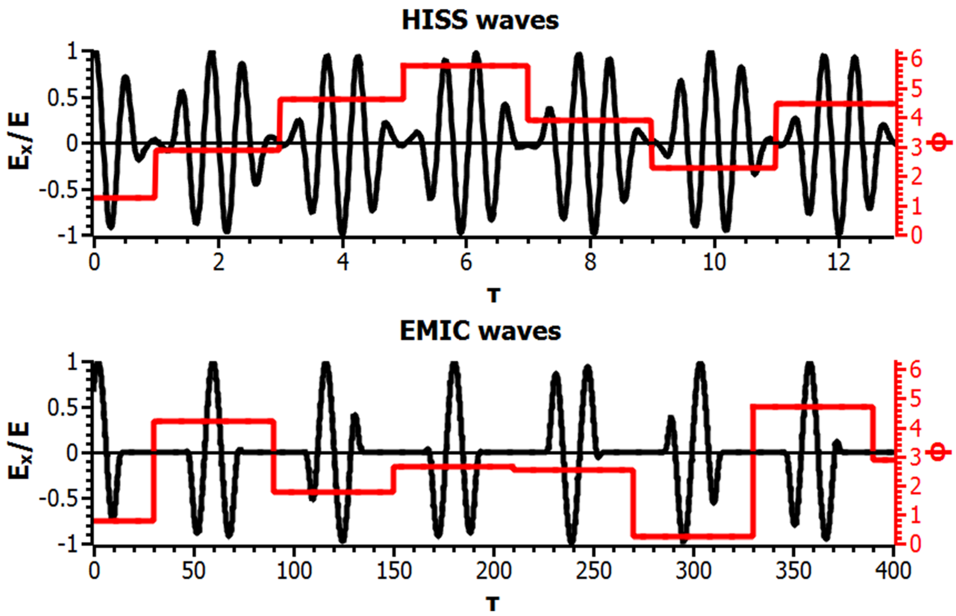

FIG. 3. Fragment of the considered model of wave electric field (black) and wave random phase (red) for hiss (top panel) and EMIC (bottom panel) waves.

sufficiently strong perpendicular anisotropy after 7 MLT, combining an important loss-cone with a significant temperature anisotropy $T_{i,\perp}/T_{i,\|} > 2$ (possibly aided by a weak parallel flow, e.g., Ref. 37), low amplitude electrostatic ion cyclotron waves could be generated in the very close vicinity of ion cyclotron harmonics (e.g., see Ref. 2) with $\omega - n\Omega_{ci} \simeq k_\| v_{i,\|} < \Omega_{ci}/150$ and $v_{i,\|} \ll v_{i,th}$ or $>2v_{i,th}$ (i.e., with very weak Landau damping from thermal electrons and cyclotron damping from thermal ions) and reduce the temperature anisotropy. Alternatively, the heated ion populations could generate Alfven ion cyclotron (EMIC) waves at $\omega < \Omega_{ci}$ when their temperature anisotropy becomes sufficient after 4 MLT. Such self-generated EMIC waves are known to induce a self-saturation of the temperature anisotropy of low $\beta \ll 1$ bi-Maxwellian proton distributions to a maximum level $(T_{i,\perp}/T_{i,\|})_{max} \sim 1 + A/(\beta_{i,\|} + 0.0004)^{0.4}$ corresponding to the linear threshold of EMIC instability.[11,14] The maximum anisotropy, moreover, depends on the considered threshold (or maximum) EMIC growth rate γ through the parameter $A \sim 0.8(\gamma/\Omega_{ci})^{0.105}$ (see Refs. 11, 12, and 14). Since A varies very weakly with γ, one can safely assume that the EMIC wave intensity needs to grow from the noise level by approximately $\sim 5 - 15$ e-foldings to induce a saturation of the anisotropy. To match the observations, this should, moreover, occur in $\sim 5 - 7$ h (between 4–5 MLT and 9–12 MLT). Taking $2\gamma \times 6\,\text{h} \sim 5 - 15$ one gets $\gamma/\Omega_{cp} \sim 3 - 9 \times 10^{-7}$ at $L \sim 2$, corresponding to an anisotropy saturation at $(T_{i,\perp}/T_{i,\|})_{max} \sim 4 - 4.5$ in our case. This would be roughly consistent with the observed 1.5–5.4 eV proton average anisotropy levels[35] $T_{i,\perp}/T_{i,\|} \approx 2.0 - 3.5$ at 7–24 MLT, which necessarily include successive periods of strong and weak transverse heating and should, therefore, stay below the estimated upper-limit. Although the EMIC waves have been observed in this MLT range at $L = 2$ with significant average amplitudes $\approx$ 0.01–0.015 mV/m,[36] yet there is no available statistics allowing to separate waves self-generated by the considered eV proton anisotropy from waves sporadically generated by higher energy ions.

Thus, pitch-angle diffusion from self-generated electrostatic and/or electromagnetic ion cyclotron waves could become sufficient after 7–8 MLT to balance parallel hiss-induced transverse heating by progressively scattering heated ions toward the loss-cone where they get lost, leading to a self-saturation of the perpendicular anisotropy and also limiting transverse ion heating at 1–10 eV. Such a saturation would be stronger (see Refs. 11 and 12) and would occur earlier for the more quickly heated protons than for O^+ ions, potentially reducing the difference between proton and O^+ time-integrated heating rates. However, getting a definitive answer would require a full numerical investigation of the generation of electrostatic and Alfven ion cyclotron waves by the observed proton anisotropy, their scattering of eV ions in our parameter range, as well as statistics of these waves measured at $L = 2 - 3$: this is beyond the scope of the present study and is left for future work.

D. Simulations of hiss-induced ion heating

Test particle simulations of ion heating by random hiss waves have been performed, considering a realistic scheme where hiss waves are taken in the form of trains of finite wave-packets, with random phases for each wave-packet. Accordingly, we use transverse components of the wave electric field in a form

$$\begin{aligned} E_x &= E\sin(4\pi\tau + \phi(\tau))G(t) \\ E_y &= E\cos(4\pi\tau + \phi(\tau))G(t), \end{aligned} \tag{3}$$

with $G = \exp(-f^2 - (bf)^{10})$, $f = a\,\sin(\tau/a)$, $a = 2.5/\pi$, and $b = 5$, a dimensionless time variable $\tau = \omega t/(4\pi)$, $\phi(\tau)$ a phase uniformly distributed between 0 and 2π changing randomly for each new wave packet (see Fig. 3). In such a case, the corresponding time scale between the wave packets is $\Delta\tau = 2.5$, but the wave packet duration is only $\delta\tau \sim \Delta\tau/2$. It corresponds to $\epsilon \approx 1/20$ in Equations (1)–(2). We have here $\tau_c \sim 5/f$ in dimensional units. Considering a hiss frequency $f \sim 350$ Hz, it corresponds to $\tau_c \sim 0.014$ s and $4-5$ wave periods inside one wave packet, as in Van Allen Probes observations at $L \sim 2.5$ (e.g., see Fig. 2). Typical quiet time parameters at $L = 2.5$ are used. Namely, the time-averaged root-mean-squared hiss electric field is such that $\langle E^2\rangle_t^{1/2} = \sqrt{\langle E_x^2\rangle_t + \langle E_y^2\rangle_t} \sim 0.05$ mV/m (see Ref. 36). The proton gyroperiod at $L = 2.5$ in dimensionless units is $\tau_{cp} = 6.25$, equivalent to $T_{cp} = 1/28$ s.

Corresponding ion equations of motion are

$$\begin{aligned} \frac{\partial v_i}{\partial \tau} &= \Omega_0 v_D \cos(4\pi\tau + \phi(\tau) - \theta)G(t) \\ \frac{\partial \theta}{\partial \tau} &= \Omega_0 + \frac{\Omega_0 v_D}{v_i}\sin(4\pi\tau + \phi(\tau) - \theta)G(t), \end{aligned} \quad (4)$$

where $v_D = cE/B_0$ is the drift velocity from the Lorentz force and $\Omega_0 = 4\pi\Omega_{ci}/\omega$. Considering nearly equatorially mirroring ions of more than 0.1 eV initial energy at $L = 2-3$ and time-averaged root-mean-squared transverse amplitude of hiss waves $E \leq 0.05$ mV/m, one gets $v_D \ll v_i$. Then, a fairly good approximation of (4) is simply

$$\frac{\partial v_i}{\partial \tau} = v_D \frac{m_p}{m_i} \cos\big((4\pi - m_p/m_i)\tau + \phi(\tau)\big)G(t). \quad (5)$$

Equation (5) suggests that the ratio of transverse ion heating for O^+ and H^+ can sometimes become slightly smaller than m_p/m_i, because the $(4\pi - m_p/m_i)\tau$ term inside the cosine indicates that fast time averaging should more easily reduce heating for higher ion mass.

Equatorially mirroring protons and O^+ ions have been considered, and 10^4 test particle trajectories have been calculated over 1 h of physical time. Note that here we elected to use well-separated wave packets (i.e., large $b = 5$) with $E \simeq 0$ between them, to prevent any spurious numerical effect caused by the strong gradients of the electric field at the edges of a wave packet. The simulation results presented in Figure 4 demonstrate a stochastic ion heating by hiss proportional to time, reaching magnitudes roughly similar to values given by approximate expressions (1)–(2). Taking into account the possible presence of a multiplicative factor $\sim 2-3$ when using the mean hiss wave power instead of the median power, one gets ion heating rates of the order of $\sim 0.05 - 0.15$ eV/h for protons and $\sim 0.004 - 0.01$ eV/h for O^+ ions. Such levels are roughly compatible with observations, especially with regard to proton heating (see Section III C).

IV. STOCHASTIC TRANSVERSE ION HEATING BY RANDOM EMIC WAVE PACKETS

Although the ratio of the O^+ heating rate over the H^+ heating rate is close to the mass ratio (1/16) when considering non-resonant heating by hiss waves, it is interesting to check if this ratio cannot get closer to unity when considering a similar non-resonant heating by EMIC waves. Figure 3 from Ref. 36 shows that EMIC waves with $f \sim 10-13$ Hz ($\omega/\Omega_{cp} \sim 0.3$) are present at $L = 2-3$ for nearly all MLT except 22–02 MLT during quiet times, in agreement with other satellite statistics.[33] During relatively quiet times, the full time-averaged root-mean-squared transverse electric field amplitude of EMIC waves can be estimated as $E \approx 0.01 - 0.015$ mV/m (e.g., Ref. 36). This order of value agrees with the previous statistics giving magnetic amplitudes $B_w \approx 15$ pT for EMIC waves at $L \sim 3.5$ when $Kp < 3$ (see Ref. 18), corresponding through Faraday's law to $E \simeq B_w\omega/k \simeq 0.015$ mV/m. This reduces v_D by a factor 3 as compared with the previous hiss case. EMIC wave spectra from Cluster satellites at $L \sim 4$ show typical wave packet durations $\sim 2 - 20$ wave periods (see Figure 7 from Ref. 30 and an example of recent Van Allen Probe measurements at $L \sim 2.5$ in Fig. 2). Thus, one can use $f = 0.03 \cdot a \sin(\tau/a)$ with $a = 60/\pi$ to consider realistic EMIC wave packets including 2 wave periods (see Fig. 3). In this case, Equation (5) becomes

$$\frac{\partial v_i}{\partial \tau} = v_D \frac{m_p}{m_i} \cos\big((4\pi\chi - m_p/m_i)\tau + \phi(\tau)\big)G(t), \quad (6)$$

with $\chi = 1/30$ and $b = 3$. As a result, the $(4\pi\chi - m_p/m_i) \simeq (0.42 - m_p/m_i)$ term inside the cosine now corresponds to a faster time averaging for H^+ than for O^+. The corresponding test particle simulations have been performed in the same way as before for hiss. The results are displayed in Figure 5, demonstrating that the O^+ to H^+ transverse ion heating ratio increases significantly up to $\approx 1/5 - 1/8$ as the heating rates reach ~ 0.018 eV/h for H^+ and ~ 0.003 eV/h for O^+ ions.

The corresponding H^+ heating rates are sensibly smaller than for hiss in Section III. In contrast with hiss, moreover,

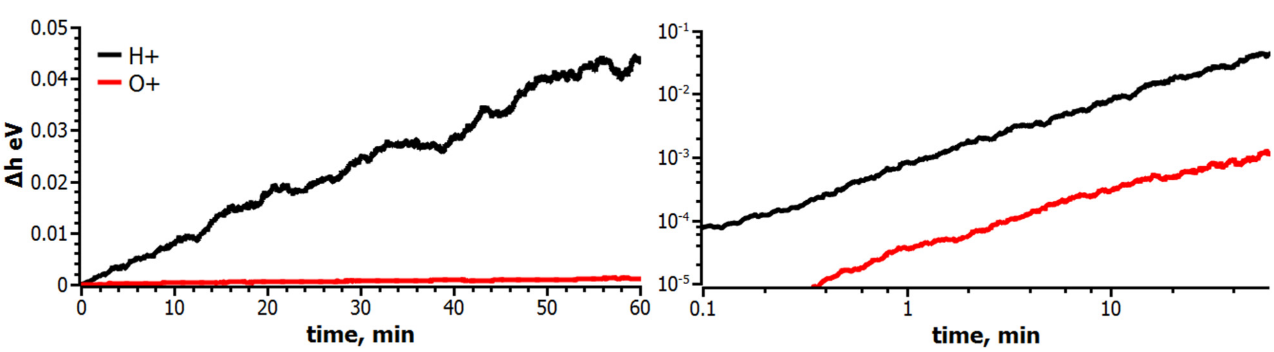

FIG. 4. Transverse ion heating by random hiss wave packets at $L = 2.5$, using realistic time-averaged root-mean-squared hiss amplitude $E = 0.05$ mV/m, $f = a \sin(\tau/a)$, $a = 2.5/\pi$, and $b = 5$ in Equation (5), corresponding to hiss frequency $f \sim 350$ Hz, $\tau_c \sim 0.014$ s, and $T_{cp} = 1/28$ s. Black and red curves show proton and O^+ ion heating, respectively, as a function of time (left and right panels show linear and logarithmic scales).

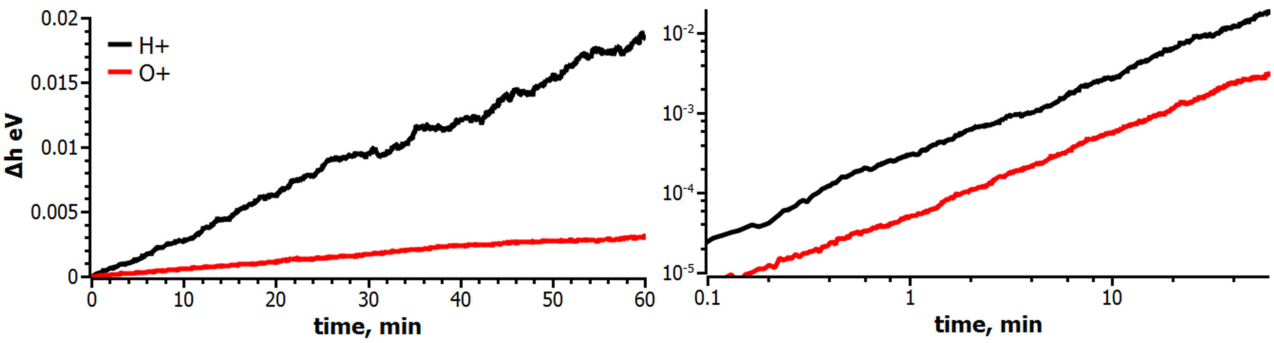

FIG. 5. Transverse ion heating by random EMIC wave packets at $L = 2.5$, using realistic time-averaged root-mean-squared EMIC wave amplitude $E = 0.015$ mV/m, $f = 0.03a\ \sin(\tau/a)$, $a = 60/\pi$, and $b = 3$ in Equation (5), corresponding to EMIC frequency $f \sim 12$ Hz, $\tau_c \sim 0.2$ s, and $T_{cp} = 1/28$ s. Black and red curves show H^+ and O^+ ion heating, respectively, as a function of time (left and right panels show linear and logarithmic scales).

EMIC waves do not show a peak of occurrence after 5 MLT coinciding with observed H^+ heating. Thus, EMIC waves alone probably cannot explain the relatively fast transverse H^+ heating observed at $L = 2 - 3$ near 4–8 MLT. However, EMIC waves could concur with hiss waves to produce overall O^+ ion heating rates closer to H^+ heating rates, as in observations.[34] Although such a scenario looks promising, drawing a more definitive conclusion will require considering the average EMIC wave packet characteristics observed at $L = 2 - 3$, not yet available at this time.

V. CONCLUSIONS

Possible mechanisms leading to transverse heating of thermal ions at $L = 2 - 3$ in the quiet-time plasmasphere have been considered. It turns out that stochastic ion heating by random transverse electric field fluctuations of plasmaspheric hiss (and maybe EMIC) waves could account for the weak and slow transverse heating of eV H^+ and O^+ ions observed by the Van Allen Probes in the dawn sector.[34–36] The linchpin of the proposed model of ion heating is the presence of trains of random hiss (and possibly EMIC) wave packets showing important amplitude modulation, such that the time-integrated electric field inside each wave packet (representing several wave periods) is small but non-null, while the net field over a long time interval is zero. Such large wave amplitude modulations could stem from strong nonlinear wave damping, or rapid nonlinear wave growth, or from a superposition of many wave packets of different frequencies, phases, and amplitudes, or from a combination of all these phenomena (note that fast, nonlinear wave intensity variations often correspond to spatio-temporally localized and relatively moderate variations in the particle distribution, which can exist even during relatively quiet global geomagnetic conditions). Such wave characteristics actually correspond to the measured characteristics of hiss waves[41,44] (see also Fig. 2). Using test particle simulations, we have demonstrated that the resulting very slow stochastic transverse heating of the global Maxwellian ion population from an initial $T_i \sim 0.3\,\text{eV}$ is sufficient to explain observations, reaching levels of the order of $0.07 - 0.2\,\text{eV/h}$ for protons and $0.007 - 0.015\,\text{eV/h}$ for O^+ ions.

More generally, the theoretical heating rate provided here can be compared with observed ion heating rates to provide an estimate of the value of ϵ needed to match the observation. In turn, this ϵ value can be compared with the estimates of ϵ obtained from a careful analysis of actual wave samples, to check the applicability of the proposed model. However, it is worth emphasizing that very high resolution measurements and careful calculations will be needed to determine whether the actual wave field can be described as a sum of separate wave-packets with non-zero net field and to derive accurate ϵ values.

In the future, a more precise estimation of EMIC wave effects will require better statistics of these waves at $L = 2 - 3$, with a high resolution. In addition, the eventual saturation of transverse ion heating would be worth studying in numerical simulations to check its efficiency for eventually balancing ion heating beyond noon. Finally, we note that the thermal O^+ to H^+ ion heating ratio could be higher than the inverse of their mass ratio for resonant interactions with two different EMIC waves close to their respective gyrofrequencies (see Ref. 39), if the average amplitude of such EMIC waves is sufficiently higher in the O^+ band as compared with the H^+ band. Statistics of these particular EMIC waves in the equatorial region at $L = 2 - 3$ would be needed to examine this possibility.

ACKNOWLEDGMENTS

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