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THE HEATING OF SUPRATHERMAL IONS ABOVE THUNDERSTORM CELLS

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Abstract. We estimate ion heating in the topside ionosphere directly over thunderstorm cells. The primary heating is due to lower hybrid waves excited through linear mode coupling as intense electromagnetic (EM) whistler mode radiation from lightning is scattered from small scale (2 – 20 m) magnetic-field-aligned plasma density irregularities in the topside ionosphere. For typical radiated EM fields, we find that suprathermal H$^+$ ions in the ≥ 6 eV energy range can be heated by 20 to 40 eV as a result of a single lightning discharge. We also show how the number density of ≥ 6 eV H$^+$ ions is enhanced by preheating resulting from the absorption of proton whistlers in the 500 – 1000 km altitude range. For lightning discharge rates of one or more per second over a 10^4 km^2 area, our model predicts a total energy gain for the H^+ ions of 400 eV to 2 KeV and a perpendicular ion flux of $j_\perp \sim 10^5$ to 10^6cm^{-2}sec^{-1}. These fluxes should be observable on low altitude spacecraft using presently available instrumentation.

1. Introduction

Suprathermal ion heating by lower hybrid (LH) waves in the auroral regions has been a topic of much study recently [*Lysak et al.*, 1980; *Chang and Coppi*, 1981; *Retterer et al.*, 1986; *Bell et al.*, 1991], and LH wave broadband amplitudes of 50 mV/m or more appear sufficient to produce the observed heating. Similar heating can be expected wherever intense LH waves coexist with suprathermal ions. We suggest that one of these regions is the topside ionosphere directly over thunderstorm cells and herein estimate the H^+ ion heating by both LH waves and proton whistlers [*Gurnett and Brice*, 1966] that may take place there. In our model the main ion heating is due to the LH waves, while the proton whistlers act as preheating agents which raise the suprathermal ion energy to the level necessary for LH wave heating to begin [*Bell et al.*, 1992]. Figure 1 shows a sketch of our model.

We suggest the LH wave turbulence is excited through linear mode coupling [*Bell and Ngo*, 1990] as intense VLF electromagnetic (EM) whistlers excited by a lightning discharge scatter from small scale (2-20 m) magnetic-field-aligned electron density irregularities, possibly like those observed on the Viking spacecraft [*Holmgren and Kintner*, 1990]. Typically the electric field amplitude (E) of the LH waves exceeds that of the input EM wave by 15 to 30 dB for frequencies $f \geq f_{LHR}$, the lower-hybrid-resonance frequency [*Bell et al.*, 1983; *Bell and Ngo*, 1990]. Thus the high amplitude lightning-generated (LG) whistlers may excite very intense LH wave turbulence in the topside ionosphere directly over the thunderstorm cells.

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Examples of LG whistlers exciting intense LH waves are shown in the ISIS-2 spacecraft data of Figure 2. The whistlers propagated along a short $\sim$1400 km path from the ground and exhibit very little temporal dispersion for $f > 5$ kHz. For $f < f_{LHR}$, the whistlers do not excite LH waves and their duration at fixed f is $\sim$ 10 msec. For $f \geq f_{LHR}$ the whistlers excite slowly propagating LH waves, and those excited at altitudes below the spacecraft arrive well after the whistler, resulting in a LH wave spectrum with a relatively long 50 to 100 msec duration, where the maximum duration occurs for $f \sim f_{LHR}$.

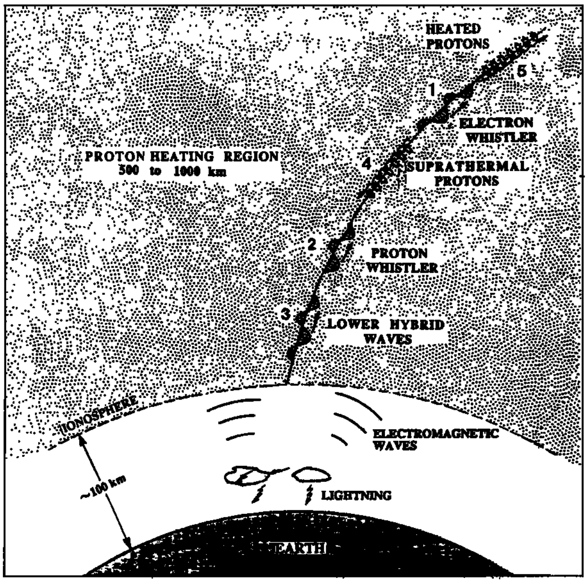
Although Figure 1 suggests the total lightning discharge rate R from all nearby thunderstorm cells is: $R \sim 20$ sec^{-1}, R can vary widely. For *Kelley et al.* [1990], $528 \leq R \leq 6500$/hour as measured by the SUNY-Albany Lightning Detection Network, which records only cloud-to-ground discharges and not cloud discharges [*Orville et al.*, 1987]. Across the continental US, the ratio of cloud flashes to cloud-to-ground flashes is thought to be 3-4:1 [*Prentice and Mackerras*, 1977]. Thus for *Kelly et al.* [1990], R may have exceeded that quoted by a factor of 3.

Recent calculations [*Rodriguez et al.*, 1992] indicate that each lightning discharge strongly illuminates a horizontal ionospheric region at $\sim$90 km altitude of $\sim$ 100 km radius, centered on the discharge location. Thus for present purposes we define R as the total lightning discharge rate over a $\pi \times 10^4$ km^2 area centered approximately on the foot of the magnetic field line through the observation point.

2. Wave Intensities and Available Power

Calculations [*Inan et al.*, 1991; *Rodriguez et al*, 1992] suggest that the typical peak broadband electric field (E$_\text{p}$) amplitude of LG whistlers near 300 km altitude (h) during night are $\sim 100\ \frac{\text{mV}}{\text{m}}$, assuming that the observation point is within a horizontal distance $d_o \sim 100$ km from the lightning discharge point. Actual measurements of LG whistlers from $200 \leq h \leq 400$ km have been obtained on rockets, but generally only for $d \gg 100$ km [*Kelley et al.*, 1990; *Li*, 1993]. However, we can use the rocket data to infer E$_\text{p}$ at 300 km altitude for $d \leq d_o$ if we make the reasonable assumption that the EM energy falls off with radial distance r as r^{-2} before it reaches the lower ionosphere at $\sim$ 60 km altitude.

In this case, assuming that D-region losses are independent of d, E$_\text{p}$ $\sim$ E$_\text{m}$ (d/d_o), where E$_\text{m}$ is the peak broadband E field measured on the rocket. Thus for example, Figures 2.3 and 3.5 of *Li* [1993] show E$_\text{m}$ $\sim 12\frac{\text{mV}}{\text{m}}$ for a lightning discharge with $d \sim 300$ km, which is equivalent to E$_\text{p}$ $\sim 36\frac{\text{mV}}{\text{m}}$ at $d \sim 100$ km, and E$_\text{m}$ $\sim 5\frac{\text{mV}}{\text{m}}$ and $\sim 4\frac{\text{mV}}{\text{m}}$ for two discharges with $d \sim 650$ km, which is equivalent to E$_\text{p}$ $\sim 33\frac{\text{mV}}{\text{m}}$ and $\sim 26\frac{\text{mV}}{\text{m}}$ at $d \sim 100$ km. As a middle ground between theory and observation, we assume E$_\text{p}$ $\sim 50\frac{\text{mV}}{\text{m}}$ for a typical whistler at night near 300 km altitude. Figure 5 of *Kelly et al* [1990] shows the spectral intensity $I(f)$ of a LG whistler



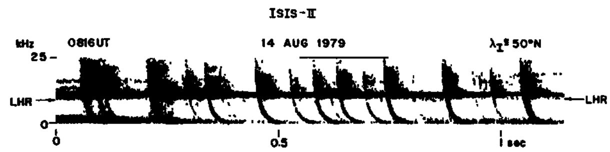
1. Electromagnetic radiation from a lightning discharge enters the ionosphere and propagates upward as a right hand circularly polarized electron whistler (1). As the electron whistler propagates through the heating region it excites a left hand circularly polarized proton whistler (2) as well as intense lower hybrid waves (3). Suprathermal protons (4) are first heated by the proton whistler and are then heated by the lower hybrid waves. As the transverse velocity of the heated protons increases, the magnetic mirror force accelerates the protons upward and out of the heating region (5).

at ~300 km altitude. Although $I(f)$ peaks near 4-5 kHz, it is roughly uniform over the 0-10 kHz range, and for an order of magnitude estimate of $I(f)$ we assume that all 0-10 kHz components contribute equally to the peak amplitude $E_p \sim 50$ mV/m. In this case since $|E|^2 = \int I(f)df$:

$$I(f) \cong 2.5 \times 10^{-7} \frac{V^2}{m^2\mathrm{Hz}}. \qquad (1)$$

Note that while (1) is consistent with the results of *Kelly et al.* [1990], it appears to be at odds with the results of *Li* [1993] which show a sharp intensity peak near 1 kHz and less intensity at both higher and lower frequencies. This disparity may result from storm specific lightning characteristics. Associated with each whistler component is a Poynting power flux $\vec{P}_\omega = \vec{E} \times \vec{H}$. Because of the high refractive index $n(f)$ of VLF waves in the topside ionosphere the wave normal direction of the whistler components is nearly vertical [*Neubert et al.*, 1987]. At midlatitudes with little error $\vec{k} \| \vec{B}_o$ and $P_\omega = |\vec{P}_\omega| = n(f)I(f)/377$ w/m^2, where $\vec{B}_o$ is the Earth's magnetic field, $n(f) \cong \frac{f_{oe}}{\sqrt{f_{He} f}}$, where $f_{oe} \cong 9N_e^{\frac{1}{2}} kH_z$ is the electron plasma frequency, N_e is the electron density, and f_{He} is the electron gyrofrequency.

For $\vec{k} \| \vec{B}_o$, the input LG whistler is a right hand circularly polarized wave whose E vector rotates about $\vec{B}_o$ in the same sense as the ambient electrons [*Helliwell*, 1965]. We refer to these whistlers as "electron" whistlers. The input electron whistlers can excite left hand circularly polarized waves known as proton whistlers [*Gurnett and Brice*, 1966]. The EM power carried by the proton whistlers and LH waves comes from the power initially carried by the electron whistlers. In



2. Spectrogram showing lightning generated electron whistlers exciting intense lower hybrid waves at all frequencies above the local lower-hybrid-resonance frequency, f_{LHR}, where $f_{LHR} \sim 10$ kHz. The spectrogram was produced with an effective filter bandwidth of 120 Hz.

general in the topside ionosphere $f \sim 500$ Hz for proton whistlers, while $6 \le f \le 10$ kHz for the LH waves. In addition, in a centered dipole model of $\vec{B}_o$ with a magnetic latitude of 45° and an altitude of 300 km, $f_{He} \cong 1.1$ MHz, and assuming $N_e \cong 7 \times 10^4$ at 300 km altitude, [*Kelley et al.* 1990], we have $f_{oe} \cong 2.4$MHz, and thus $n(f \cong 500\mathrm{Hz}) \cong 100$ and $n(f \cong 6\ \mathrm{kHz}) \cong 30$. For these values of $n(f)$ the available power flux in the input electron whistler is:

$$P_\omega(f \sim 6\ \mathrm{kHz}) \cong 2 \times 10^{-8}\ \frac{\mathrm{w}}{\mathrm{m^2Hz}} \qquad (2a)$$

$$P_\omega(f \sim 500\ \mathrm{Hz}) \cong 7 \times 10^{-8}\ \frac{\mathrm{w}}{\mathrm{m^2Hz}} \qquad (2b)$$

In general, taking multiple return strokes into account, the duration of the electron whistler is ~5 msec for $10 \ge f \ge 6$ kHz, and ~ 20 msec for $300 \le f \le 500$ Hz [*Kelley et al.*, 1990]. Thus the average total available whistler power is $P_A(f \sim 6\ \mathrm{kHz}) \cong R \times 10^{-10}\ \frac{\mathrm{w}}{\mathrm{m^2Hz}}$ and $P_A(f \sim 500Hz) \cong R \times 10^{-9}\ \frac{\mathrm{w}}{\mathrm{m^2Hz}}$.

Assuming that at night near 500 km at mid-latitude $\mathrm{N_e} \sim 3 \times 10^4$ and that P_ω is conserved, then here $I(f{=}6\ \mathrm{kHz}) \cong 4 \times 10^{-7} \frac{V^2}{m^2Hz}$. In general the intensity of the excited LH waves can be expected to exceed that of the whistler by 15 to 30 dB, where the highest gain commonly applies when $f \sim f_{LHR}$ [*Bell et al.*, 1983; *Bell and Ngo*, 1988]. Assuming a 20 dB ratio of intensities, we obtain: $I_{LH} \cong 4 \times 10^{-5} \frac{V^2}{m^2\mathrm{Hz}}$. Typically for $f \sim f_{LHR}$ the LH wave spectrum endures for ~100 msec after excitation by electron whistlers (see Figure 2). Thus the time average E-field spectral intensity is:

$$\bar{I}_{LH} \sim 4R \times 10^{-6} \frac{V^2\mathrm{sec}}{\mathrm{m^2\ Hz}}. \qquad (3)$$

For $R \sim 1\ \mathrm{sec}^{-1}$, we note that over a 1 kHz bandwidth (3) represents a broadband amplitude of ~70 mV/m, well within the range believed necessary to create ion conics in the auroral regions [*Chang and Coppi*, 1981].

3. Heating by Lower Hybrid Waves and Proton Whistlers

To first order, ions interact with the excited LH waves through a transverse resonance [*Lysak et al.*, 1980; *Chang and Coppi*, 1981] when: $v_\perp \cong \omega/k_\perp$, where $v_\perp$ is the ion velocity perpendicular to $\vec{B}_0$, and $k_\perp$ is the perpendicular wave number of the LH wave. Under the influence of the LH waves, the diffusion of H^+ ions in energy is governed by the quasi-linear velocity diffusion tensor $\overline{\overline{D}}$. For simplicity we assume that the $k_\perp$ are uniformly distributed around $\vec{B}_o$ and consider only those LH waves with $\omega \cong \omega_{LHR}$. In this case the transverse velocity diffusion rate is [*Retterer, et al.*, 1990]:

$$D_\perp = \frac{q^2}{M^2}\int \frac{d\omega \bar{I}_{LH}(\omega)\omega^2}{8\pi^2 v_\perp^2}\int_{k_{\perp o}}^{+\infty}\frac{dk_\perp}{k_\perp}\frac{S_\perp(k_\perp)}{[k_\perp^2 v_\perp^2-\omega^2]^{1/2}} \quad (4)$$

where $S_\perp(k_\perp)$ is the normalized spectral density, $k_{\perp o} = \omega/v_\perp$, M is the ion mass, and q is the ion charge. Recent spacecraft observations [*Bell et al.*, 1993] suggest that when $\omega \cong \omega_{LHR}$, $S_\perp(k_\perp)$ has the form: $S_\perp(k_\perp) = 4\pi k_o^{-4}k_\perp^2 e^{-k_\perp^2/k_o^2}$ where k_o = 1.3m^{-1}. Performing the $k_\perp$ integration in (4) we find for H^+ ions: $D_\perp \cong 5R \times 10^9 \int_{x_o}^{+\infty} x^2 e^{-x^2}dx \quad \mathrm{m}^2/\mathrm{s}^2$, where $x_o = \frac{\omega_{LHR}}{k_o v_\perp}$, and $x = \frac{\omega}{k_o v_\perp}$. For $x_o \leq 1/2$, we can set $x_o = 0$ in the integral for $D_\perp$ with less than 10% error. Thus for $v_\perp \geq 2\frac{\omega_{LHR}}{k_o}$, the heating of the average suprathermal ion is:

$$\dot{\epsilon}_\perp = 2MD_\perp \cong 40R \text{ eV} \quad (5)$$

where $\epsilon_\perp = \frac{1}{2}Mv_\perp^2$ is the transverse ion kinetic energy. For R = 1/sec we have $\dot{\epsilon}_\perp$ = 40 eV/sec, and the average energy gain per lightning discharge is ≅ 40 eV.

Equation (5) applies to those ions with $v_\perp \geq v_{\perp m} = 2\frac{\omega_{LHR}}{k_o}$. At h ~ 500 km, f_{LHR} ~ 6 kHz and $v_{\perp m}$ ~ 58 km/sec, corresponding to $\epsilon_\perp$ ~20 eV. For $\epsilon_\perp$ = 6 eV, $\dot{\epsilon}_\perp \approx$ 24 R eV. Ions of lower energy will be heated initially at a much lower rate but the total heating can still be substantial. For example the initial heating rate of 1 eV ions for R = 1/sec is $\dot{\epsilon}_\perp$ ~ 0.3 eV/sec, but after 5 seconds, $\epsilon_\perp$ ~ 30 eV. On the other hand H^+ ions with $\epsilon_\perp$ < 0.5 eV experience negligable heating. Although H^+ ions with $\epsilon_\perp \geq$ 1 eV may be rapidly heated by the LH waves, the nighttime H^+ ion thermal energy is ~ 0.16 eV, and only ~ 10^{-4} of these ions will possess the necessary energy. Thus a preheating mechanism is required.

At midlatitude the LG electron whistler components with f ~ 500 Hz couple strongly to the proton whistler mode when f exceeds the "cross-over" frequency [*Gurnett and Brice*, 1966; *Rodriguez and Gurnett*, 1971]. As the proton whistler propagates to higher altitude, $\omega \rightarrow \omega_{HP}$, and H^+ ions are heated by the wave through cyclotron resonance when:

$$\omega + k_\| v_\| = \omega_{HP} \quad (6)$$

where $k_\|$ is the component of $\vec{k}$ parallel to $\vec{B}_o$, $v_\|$ is the parallel component of the H^+ ion velocity, and ω_{HP} is the proton gyrofrequency.

For example at h ~ 650 km with T_i = 1200°K, N_e = 2×10^4 cm^{-3}, relative ion abundances of 87% oxygen, 1% H_e^+, and 12% H^+, and f_{He} = 1 MHz, it can be shown from equations (28) and (32) of *Gurnett and Brice* [1966] that protons with $\epsilon \geq$ 0.4eV can be heated significantly by proton whistlers. Since $P_\omega(f)$ is conserved between 300 and 650 km altitude, $I(f)$ is proportional to the inverse ratio of $n(f)$ at the two altitudes. For f ~ 500 Hz this ratio is roughly unity. Thus $I(f)$ at 650 km is given by (1), and since the duration of the proton whistler near $\omega \sim \omega_{HP}$ is 20 msec, then the average spectral intensity associated with proton whistlers is: $I_{PW} \cong 5 \times 10^{-9}R\ \frac{V^2\mathrm{sec}}{\mathrm{m^2Hz}}$. According to *Retterer et al* [1987], for H^+ ions in gyroresonance with left-hand-polarized proton whistlers $D_\perp \cong \frac{1}{2}(\frac{q}{M})^2 I_{PW}$. Using (5) we find: $\dot{\epsilon}_\perp \cong 0.4R$ eV. Thus H^+ ions with $\epsilon_\perp \geq$ 0.4 eV can be heated to ~1 eV within a few seconds or less for $R \geq$ 1 sec^{-1}. Note that if the results of *Li* [1993] prove more typical than those of *Kelley et al* [1990], the above heating rate should be reduced by ~ 10.

4. Energetics

To estimate the time T during which an H^+ ion remains in the heating region (500-1000 km altitude) we use the adiabatic mirror force relation [*Chen*, 1974]:

$$v_\| = -\frac{1}{2}v_\perp^2\frac{\partial}{\partial z}[\log B_o] \cong \frac{3v_\perp^2}{2r} \quad (7)$$

where $B_o = |\vec{B}_o|$, z is measured along $\vec{B}_o$, r is the radial distance from the center of the earth, and where it is assumed that $\vec{B}_o$ is roughly radial. Since r varies little over the heating region we can integrate (7) twice directly to find T in terms of Δz, the distance travelled along $\vec{B}_o$ during the heating:

$$T = [\frac{2rM\Delta z}{\dot{\epsilon}_\perp}]^{1/3} \quad (8)$$

where the value of $\dot{\epsilon}_\perp$ is given in (5). Taking Δz = 250 km, r = 7000 km and R ~ 1/sec, (8) yields: $T \cong$ 10 sec. Thus from (5) the total energy gain is $\Delta\epsilon_\perp$ ~ 400 eV for a typical ~ 20 eV H^+ ion which begins at the center of the heating region at h ~750 km and is eventually accelerated out of this region by the magnetic mirror force. All else being constant (5) and (8) predict that $\Delta\epsilon_\perp \propto R^{2/3}$. Thus a high discharge rate of R ~ 10/sec produces $\Delta\epsilon_\perp$ ~ 2 keV, while a low rate of 10^{-1}/sec produces $\Delta\epsilon_\perp$ ~ 90 eV.

The power available to heat the ions originates in the LG electron whistler, as given by (2a). For 500 ≤ h ≤ 1000 km, 6 ≤ f_{LHR} ≤ 10 kHz, and the total wave power available is $P_T = P_\omega \times 4kHz \cong 8 \times 10^{-5}$watts/m^2. The % of P_T coupled into LH waves has not yet been measured in the topside ionosphere but a value of 20% is not unreasonable [*Bell and Ngo*, 1990]. If we further assume that 50% of the LH wave power goes into ion heating, the available power for heating by each lightning discharge is $P_A \cong 8\times10^{-6}$watts/m^2 and we can write:

$$P_A R\Delta t = v_{\|f}N_i\epsilon_{\perp f} \quad (9)$$

where the left hand side is the average input power, Δt is the average duration of the electron whistler, $v_{\|f}$ and $\epsilon_{\perp f}$ are the average ion velocity and energy leaving the heating region at 1000 km altitude, and N_i is the number density of the heated ions. In general $\Delta t \cong$ 5 msec, and if $R \cong$ 1/sec, $\epsilon_{\perp f}$ ≅400 eV, $v_{\|f} \cong$ 85 km/sec, $v_{\perp f} \cong$ 280 km/sec and $N_i \cong 10^{-2}$/cm^3. Thus the perpendicular (90° pitch angle) flux of the heated ions is: $j_\perp = N_i v_\perp \cong 3 \times 10^5$/cm^2-sec. Furthermore for R = 10/sec, $\epsilon_\perp$ ≅2 keV and $j_\perp \cong 10^6$/cm^2-sec, while for R = 10^{-1}/sec, $\epsilon_\perp$ ~ 90 eV with $j_\perp \sim 10^5$/cm^2-sec. Fluxes of these magnitudes would be readily observable with present spacecraft instrumentation.

5. Discussion

Since any ion can be heated by the LH waves as long as: $v_\perp = \omega/k_\perp$, the minimum ion energy $\epsilon_{\perp m}$ necessary for heating by LH waves will be proportional to the ion mass. From the results of Section 3 we conclude that $\epsilon_{\perp m}$ ~ 4 eV for He^+, while that for O^+ and O^{++} would be 16 eV. However the calculation of the total heating for these ions is beyond the scope of the present paper.

At $h \sim 500$ km, collisions of H^+ ions with neutrals will limit the amount of heating. The most important collisional process is that of charge exchange, which removes H^+ ions directly from the heated population. The charge exchange collision frequency $\nu_{ce} = v_p N \sigma_{ce}$, where v_p is the proton velocity, N is the number density of the dominant neutral species, and σ_{ce} is the charge exchange cross section. According to *Jasperse and Basu*[1982], $\sigma_{ce} < 10^{-15}\text{cm}^2$ for H^+ energy <1 keV. At $h \sim 500$ km, atomic oxygen is the dominant neutral with a night time density of $N \sim 5 \times 10^6$ cm^3 [*Rees*, 1986]. Thus for a 10 eV H^+ ion at 500 km altitude, $\nu_{ce} \leq 2 \times 10^{-2}$ sec^{-1}. Since the heated ions remain near ~500 km altitude for only a few seconds, it is clear that charge exchange will not be an important loss process during heating.

Although our results assume a nighttime ionosphere, the same processes will occur during daylight hours. However becaused of increased D-region absorption during the day [*Helliwell*, 1965] the ion heating will be much less than at night.

Suprathermal ion heating above thunderstorm cells represents a new type of coupling between the lower atmosphere and the ionosphere/magnetosphere plasma system. Since the heated ions escape into the magnetosphere, this coupling results in a new source of energetic ions for the magnetosphere. The relative significance of this new source of energetic ions remains to be evaluated.

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