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Insights From Optical Emissions, Into Physics Of High Power Radio Wave Interactions With Plasmas

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ABSTRACT

The fact is noted that sufficiently high power density HF radio waves incident on the bottom side ionosphere will produce optical emissions. It was previously suggested that the mechanism for such excitation will switch from thermal electron collision excitation to supra-thermal electron collision excitation, as the ionospheric plasma density at the reflection height switches from much below 5 MHz to much above 6 Mhz. Experimental data more directly supporting the assertion is presented. The physical basis for the assertion, including more recent theoretical work, is presented.

INTRODUCTION

An HF radio wave propagating through the ionosphere, exchanges energy with ionospheric electrons. In the absence of collisions by the electrons, the radio wave alternately gives energy to an electron as it accelerates it during one half of each rf cycle, and during the other half of the rf cycle, recovers the same energy from that electron, as it decelerates and re-radiates rf energy. The perturbation to the electron motion is maintained as ordered motion. If the electron suffers a collision before it can re-radiate, sending into some randomly different direction, that energy is lost from the rf wave, going instead into random motion, i.e. heat, in this case initially electron gas heating. If the energy lost by the rf wave is small compared to the internal energy of the electron gas, the increase in electron gas temperature is modest or undetectable.

A vertically upward propagating HF radio wave, incident on an ionosphere with maximum plasma density foF2 exceeding the HF frequency, the wave will reflect, slowing very significantly near the reflection height. For a night-time bottom-side electron density profile (with no plasma density inflection points as e.g. in an F1 region layer or lower altitude plasma density maxima as e.g. an E Region), the maximum rate of rf energy loss along its trajectory, is near this height of reflection. This is because the wave is greatly slowed near its height of reflection.

If the HF wave carries rf energy density that is not negligible compared to the electron gas energy density, one can anticipate an increase in the bulk electron gas temperature. However, for HF energy densities sufficiently large to notably heat the electron gas, the associated electric field can be sufficiently intense to excite plasma instabilities in the ionosphere, bringing in collective electron and plasma interactions. This is significantly enhanced by the standing wave interference near the height of reflection, giving strong (Airy) amplification of the incident rf wave amplitude. Such phenomena have been observed, and well studied for decades, with much progress in our understanding.

EXCITATION OF OPTICAL EMISSIONS

At still higher power densities than needed to produce both detectable electron gas heating, and a host of plasma instabilities, another manifestation of HF energy deposition has been seen on many occasions. At sufficiently high power densities, HF radio waves can excite optical emissions from the ionosphere. Most observational work on HF excited optical emissions has concentrated on 630.0 nm emissions, as they are the easiest to observe experimentally. Unfortunately they are also easiest to excite, by either moderately high electron temperatures or suprathermal electron fluxes. This in turn introduces a challenge in arriving at a correct interpretation. For years the literature swung between interpreting these as due to one or the other of these two mechanisms. In [1] it was suggested that for electron densities near 10^6 cm^{-3} (F layer critical frequency, foF2 of about 9 MHz) suprathermal electrons dominated 630.0 nm excitation, while for electron densities near 10^5 cm^{-3} (F layer critical frequency, foF2 of about 3 MHz) hot thermal electron excitation dominated, with the switch-over occurring near 3-5 10^5 cm^{-3}. Both thermal and supra-thermal could apply, but it was suggested that one or the other is strongly favored depending on the conditions, in particular the background plasma density conditions. The physics behind this suggestion was that of the thermal balance of the electron gas.

The electron gas cooling rate to ions, which with downward heat conduction is the dominant cooling term near the F layer peak, is proportional to the number of electrons times the number of ions with which they collide. This is proportional to the square of the electron density, and fourth power of foF2. For an electron density of 10^6 cm^{-3} the electron gas is in very good thermal contact with the ion gas, for an electron density of 10^5 cm^{-3} the electron gas is in very poor thermal contact with the ion gas. In the latter case, the electron gas must cool through downward heat conduction to lower altitudes where it can loose energy directly to collisions with neutral atmospheric particles. The dominant term for this cooling term is energy loss to atomic oxygen. For this loss, fine structure of the $O(^3P)$ state dominates for electron temperatures much below 3000 K, but loss to $O(^1D)$ excitation increases very rapidly with temperature and dominates near and above 3000 K. This was the rationale [1] for switching between thermal excitation being of minor vs. major concern, with the switch occurring about 5-6 MHz plasma frequency.

More definitive statements can now be made, based on observational data with very clear signatures of both suprathermal and thermal processes, but first it is necessary to clarify differences and similarities between the thermal vs. supra-thermal excitation of observed optical emissions. Consider the six panels at the top section of Fig. 1, everything plotted with the same abscissa scale of electron energy in eV, and with the vertical logarithmic scales of parameters as labeled. Every abscissa has the same linear scale. The vertical scale of each of these six semi-log panels covers many decades, with scales chosen only to demonstrate the relevant simple principles. The upper left panel shows the electron population for both a thermal distribution (solid line), and a lower temperature thermal distribution supplemented by a suprathermal component, or “tail” (dashed line). Just below this is a pair of electron energy dependent cross-sections for excitation of the atomic oxygen state that could emit 630.0 nm emission (upper curve) and 557.7 nm (lower curve). The upper central panel illustrates, as the product of these two pairs of plots, the excitation rates of those states that could emit 630.0 nm and 557.7 nm, due both to the thermal and the suprathermal-enhanced electron population. Note the number of 630.0 (red) excitations is significantly greater than 557.7 (green) excitations. Just below this is the volume emission rate curve. The red to green ratio is now smaller because many of the oxygen atoms excited to the long-lived state that could have emitted a 630.0 nm photon, are de-activated (quenched) by a collision of that oxygen atom (O) with a nitrogen molecule (N2). This quenching, which is dependent on the N2 to O ratio. is thereby strongly dependent on altitude, varying over a range exceeding a factor of two (from 30 second effective chemical lifetimes to over a minute, for excited O at low to high altitudes).

There is another N2 dependent term as well, illustrated in the right hand pair of panels in this upper section of Fig. 1. Many of the 2-4 eV electrons that might have excited atomic oxygen to emitting states, are in fact lost instead to excitation of vibrational states of N2, particularly depleting the excitation rate of atomic oxygen by electrons in the 2-4 eV range (reducing excitation rates of states that could have emitted red, with it’s threshold of 1.96 eV, but with no change to those emitting green, with it’s threshold of about 4 eV). N2 also competes against O for electron energies above about 7 eV. The net reduction in red to green line emission intensity ratio due to this, is again quite altitude sensitive, as the scale height (altitude difference for a factor of e change) of N2 is about half that of O, and thus changes about twice as fast with altitude. N2 to O ratios at a given altitude depend also on the temperature of the thermosphere.

The effects of the combination of these two N2/O ratio dependent factors, illustrated in the upper section of Fig. 1, are the issues one must address before saying too much about electron energy distributions or other conclusions drawn from “red to green line” ratios. Now we’ll discuss some optical observations containing more direct information.

Data collected at Arecibo [2], Fig 1, middle section, have shown coincident optical emissions from atomic oxygen at 630.0, 555.7, and 777.4 nm excited by high power HF radio waves, for foF2 above 7 MHz. These are unequivocally due to suprathermal electrons since 777.4 nm excitation requires >10 eV electrons, entirely beyond the reach of any consequential thermal electrons in the Earth’s atmosphere.

Data collected at both Arecibo and HAARP have seen 630.0 nm emissions under low plasma density conditions consistent with thermal excitation, either based on thermal balance calculations of electron temperatures, and of actual electron temperature measurements at other times under similar plasma density conditions. Going beyond consistency arguments, data collected at HAARP [3], reproduced here in the lower section of Fig. 1, have shown strong peak 630.0 nm emissions, for foF2 near 3 MHz, from locations well off the vertical, near and beyond the HF half power beam width. Further, the peak intensities are seen closest to the direction of the earth's magnetic field through the HF heater, and elongated along the magnetic meridian. These emissions can only be explained by a mechanism that would excite 630.0 nm emission by thermal electron excitation. That mechanism, [4], [5], operates through self-focusing on striations, leading to formation of large-scale magnetic-field-aligned nonlinear structure, with bunches of striations

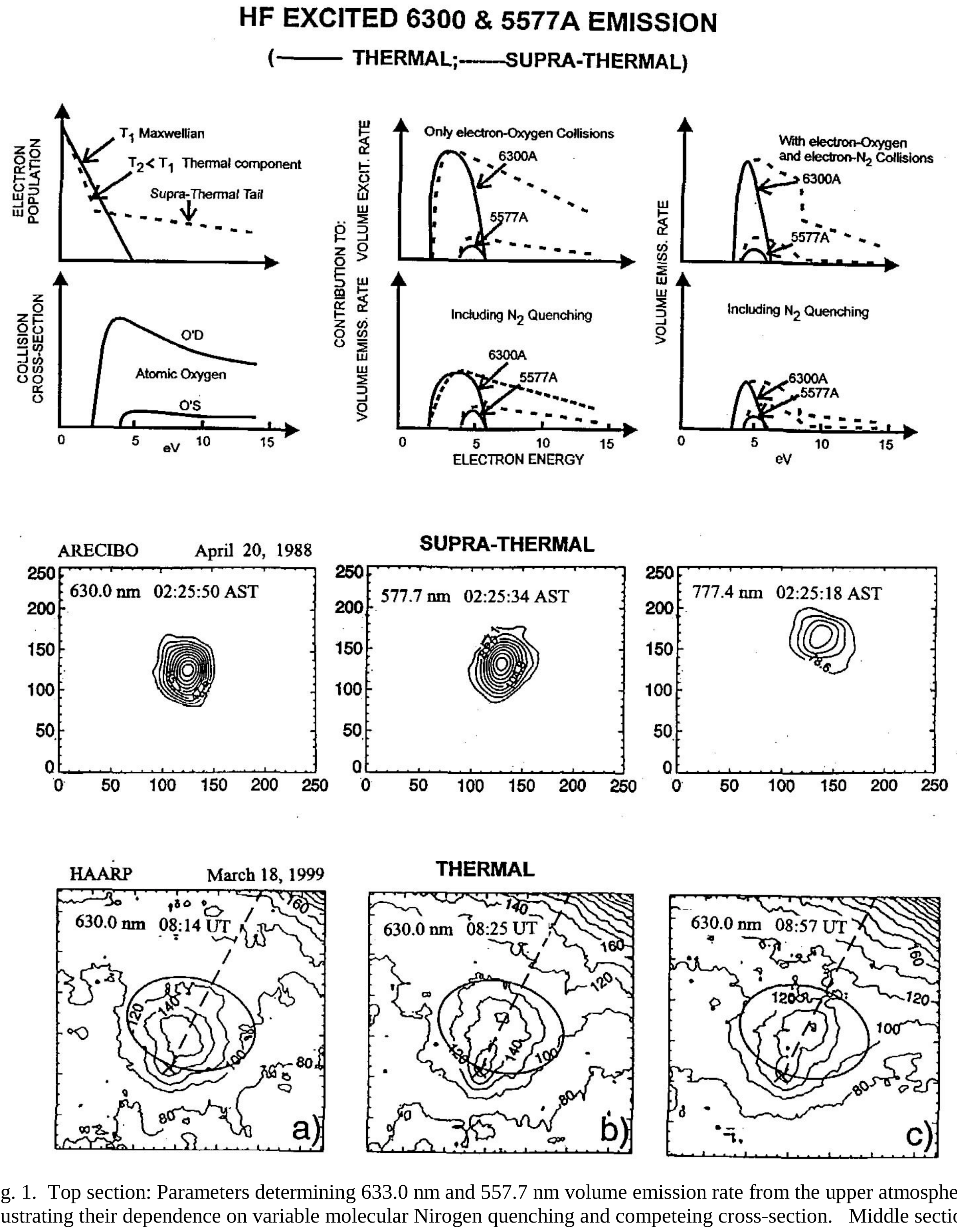
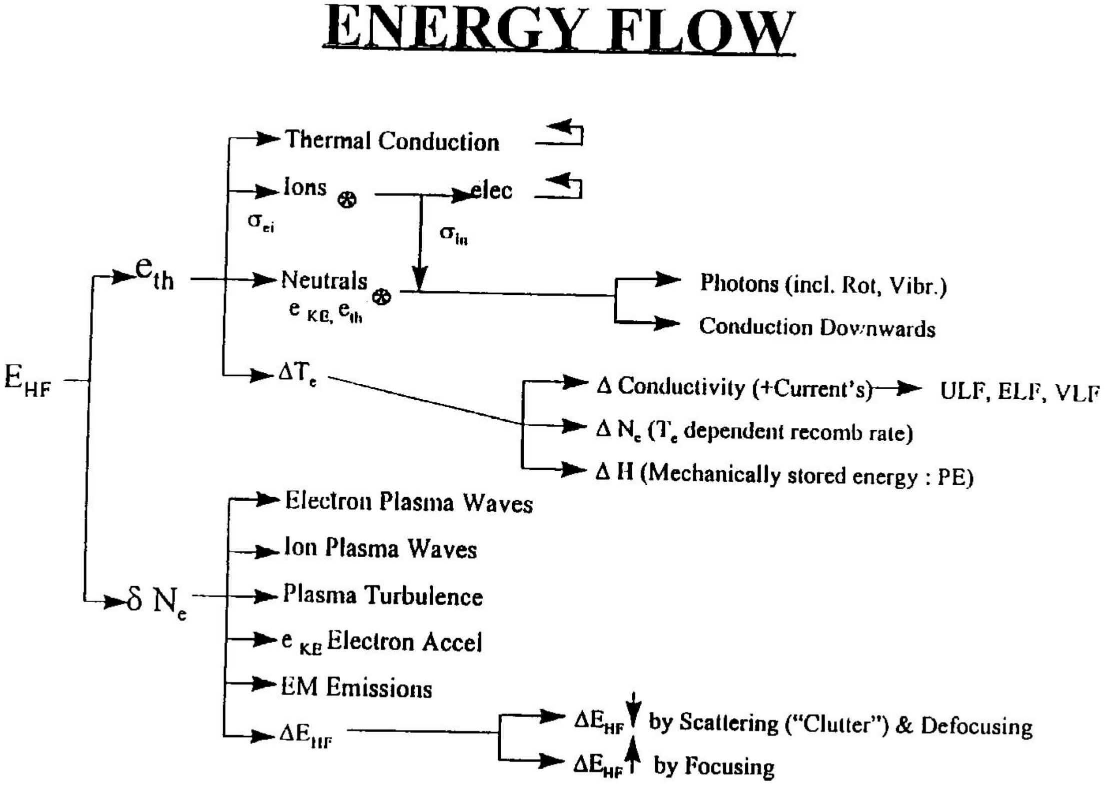


Fig. 1. Top section: Parameters determining 633.0 nm and 557.7 nm volume emission rate from the upper atmosphere, illustrating their dependence on variable molecular Nirogen quenching and competeing cross-section. Middle section: Observations of unambiguously supra-thermal HF excited 630.0 nm, 557.7 nm, and 777.4 nm emissions. Observations of unambiguously thermal HF excited 630.0 nm emissions.

capable of trapping the wave energy. The wave trapping occurs only over a range of angles to the magnetic field, and maximizes where the driving electric field is closest to the direction of the earth's magnetic field. The associated trapped upper hybrid waves lose their energy to ohmic heating, raising the electron temperatures to levels well able to thermally excite significant 630.0 nm emissions. The location, shape, and size of such region all match that of the off-axis 630.0 nm enhancement in the lower (HAARP) panel of Fig. 1. The weaker overhead 630.0 nm HF excited emission, of location, shape, and size matching the HF heater beam, is presumably that due to the simple deviative absorbtion described in the introduction.

Note that the HF energy lost to upper hybrid wave absorbtion at altitudes tens of km below the height of HF reflection, can thus not reach the reflection heights where electron plasma waves can lead to electron acceleration to suprathermal energies.) Effects on the electron acceleration leading to suprathermal electron impact emissions, of going from higher to lower plasma densities and temperatures, and greater flow of energy from thermal electrons to ions, will be the topic of another paper.

In closing, it is suggested that future progress in the field as a whole, would benefit from thinking within an overall energy flow framework, tracing the flow of energy from the incident HF to other processes, as sketched in Fig 2.



ENERGY FLOW

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