An Ionospheric Modification Facility at the Magnetic Equator

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Summary

This is a proposal to deploy an ionospheric modification facility, sometimes called an ionospheric heater, near the geomagnetic equator. A heater is a powerful high-frequency (HF) transmitter that can induce a number of phenomena in ionospheric plasmas. Some of these phenomena provide insights into complicated plasma physics processes that may occur elsewhere in nature but that are impractical to explore in the laboratory or numerically. Other processes provide diagnostics of naturally occurring ionospheric phenomena at work. Ionospheric modification experiments affect the propagation of radio signals passing through the ionospheric volume, which is how the phenomenon was first discovered (i.e. the Radio Luxembourg effect). They generate airglow and radio emissions which can be observed from the ground. They create field-aligned plasma density irregularities that can be interrogated by small coherent scatter radars. They generate low-frequency radiation which has practical societal utility. They also cause electron acceleration. Finally, they modify plasma density and electron and ion temperatures and enhance the plasma and ion lines observed by incoherent scatter. They offer a way to study cause-and-effect relationships that may be impenetrable to passive experimental methods.

Heaters have been deployed in Plateville, Colorado, Fairbanks and Gakona, Alaska, Islote and Arecibo, Puerto Rico, as well as in Tromsø, Norway, Longyearbyen (Svalbard), and Nizhniy Novgorod, Russia. These are all high- and middle-latitude sites. However, the most spectacular heater-induced phenomena are thought to be waiting to be discovered at low latitudes, under the geomagnetic equator.

Heating background and utility

In the ionosphere, a pump electromagnetic wave emitted from a high-power HF transmitter decays parametrically into a high-frequency byproduct wave (Langmuir, electron Bernstein/upper hybrid) and a low frequency byproduct wave (lower hybrid, ion acoustic, ion Bernstein, purely growing). These can decay further, with the allowed transitions governed by the Manley Rowe equations. Some of these byproducts can be observed directly using incoherent scatter. Others result in the stimulated emissions of electromagnetic waves (SEE) which can then be observed on the ground with simple HF receivers. While linear theory predicts the onset and early behavior of the waves produced in heating experiments, turbulence paradigms (e.g. strong and weak Langmuir turbulence) involving wave trapping and caviton production and collapse are required to account for all of the ISR spectral features and SEE emission lines that are observed.

Another feature of ionospheric modification experiments is electron heating and suprathermal electron production and electron acceleration. Instabilities driven by the pump wave heat the electrons up to about 3500 K, which can result in ion upwelling, and ion temperatures up to a few hundred K. While the specific mechanisms involved are still under study, heater-induced plasma instabilities are also known to accelerate electrons up to 60 eV or more.The electrons then collide with the oxygen atoms and nitrogen molecules and produce optical emissions much as natural electron impact from precipitation does in the aurora. Numerous artificially stimulated emissions have been observed, with the brightest emissions at 630 and 557.7 nm. Both thermal and suprathermal processes can be at work, with red line excitation being accessible through direct electron heating and green line excitation through electron acceleration. The red-line emission has a lower excitation energy and dominates green-line emission at F region altitudes. Since the red-line emission is collisionally quenched at E region altitudes, however, green line dominates there. Suprathermal electrons can therefore be diagnosed both through incoherent scatter techniques and optically. Coordinated experiments provide the most direct path towards resolving the processes involved in electron acceleration.

A signature feature of ionospheric modification experiments is the production of small-scale artificial field-aligned plasma density irregularities (AFAIs) just below the HF reflection height The mechanism responsible is the thermal parametric instability (linear regime) followed by the resonance instability (nonlinear regime) The resulting irregularities give rise to coherent radar backscatter that can be detected by coherent scatter radars. It is possible to generate three-dimensional images of the heater-induced irregularities using space-receiver imaging rethniques. Because of the generous signal-to-noise ratios involved, the spatial and temporal resolution of the imagery can be excellent (of the order of a second and a few hundred meters, respectively). AFAIs offer an incisive diagnostic, not only of ionospheric modifications but also of naturally occurring processes which might be affected. Ionospheric heating effectively "shines a light" on existing ionospheric features which can then be monitored and analyzed with much greater precision and accuracy than conventional remote sensing techniques generally afford.

Another method for imaging the background ionosphere using ionospheric modifications has been used in experiments on sporadic E ionization layers at Arecibo. The method, termed "radio-induced aurora" or RIA, combines ionospheric modification with optical imaging. The idea involves emitting pump-mode radiation at a frequency below the F region critical frequency. Where there are no sporadic E layer patches, the radiation propagates into the F region and produces red-line emissions at the F region interaction height. Where there are sporadic E layer patches, however, the pump-mode radiation interacts in the E layer. Not only does this produce gaps or "shadows" in the red-line emissions, it also produces green-line emission at E region altitudes. Airglow imagers can detect both phenomena, leading to spatial maps of the E layer structure in two horizontal dimensions.

Among the more practical applications of ionospheric modifications are the generation of radio signals in the VLF (3 –30 kHz), ULF (300 – 3000 Hz), and ELF (3 – 30 Hz) bands. Such signals are useful for undersea communications and subsurface imaging and have strategic significance for the nation. Conventional antennas used for radiation in these bands are electrically short by necessity (compared to a wavelength) and therefore inefficient. Using heating experiments, one attempts to alter the currents flowing in the ionosphere (periodically in time and perhaps also in space) and, thereby, to turn it into an antenna. Currents are altered by varying the temperature and, consequently, the conductivity of the ionosphere in regions where currents flow.

Investigations along many of the lines outlined above could also be conducted with a heating facility near the geomagnetic equator. More importantly, a number of new and potentially spectacular phenomena could also be explored. The most obvious objectives of an equatorial heater are outlined below.

Artificial periodic irregularities A standing wave pattern is formed when the PUMP HF wave reflects back to Earth at the critical height. Quasiperiodic plasma density irregularities are consequently produced by the spatially varying heating. These irregularities can be probed using low-power HF waves at the same frequency as the pump wave. An ionosonde can be used for this purpose. By timing the irregularity onset and decay times, relaxation processes, state parameters, and transport coefficients in the upper atmosphere can be determined. Most notably, the technique can be used to measure neutral densities and drifts. The technique can function at altitudes up through the F peak and obviously does not depend on favorable optical conditions to function.

At middle and high latitudes, the geomagnetic field subtends different phases of the standing wave and the artificial periodic irregularities. This subjects the irregularities to rapid dissipation by parallel ambipolar diffusion. Rapid dissipation limits the amplitude of the irregularities that can be generated and also limits the utility of the technique as a practical diagnostic. At the magnetic equator, however, the standing wave and the artificial periodic irregularities will form normally to the geomagnetic field. The dissipation of the irregularities will consequently be much slower, particularly in the F region, where dissipation will tend to be limited by the electron cooling rate rather than by transverse diffusion, which proceeds very slowly. As a consequence, it has been estimated that the artificial irregularity amplitude will be three to four orders of magnitude larger than for comparable high-latitude experiments. API therefore has great promise as an incisive exploratory tool for equatorial aeronomy.

Triggering equatorial spread *F* Equatorial spread F (ESF) has been the cause celebre of equatorial aeronomy since its discovery over 80 years ago. The term refers to ionospheric interchange instabilities that occur frequently after sunset at latitudes between the Appleton ionization anomalies, generating ionospheric irregularities which evidence themselves through radar scatter and clutter, optical signatures, and radio scintillation and refraction. ESF disturbs a number of operational communication and navigation systems, including GPS, and also causes interference in SAR imagery. Forecasting it is a priority of the National Space Weather Program and was the mission behind the Air Force C/NOFS satellite program. Forecast efforts have proceeded slowly, however, and undetected triggers or inhibitors are often suspected to be at work.

Ionospheric modification offers a means of experimenting with ESF triggering processes and testing the sensitivity of the stability of the ionosphere to different perturbations. Electron heating in F region modification experiments is due mainly to anomalous absorption associated with the excitation of various plasma instabilities. The subsequent effect on the plasma number density in the lower F region is mainly controlled by photochemistry and depends on the altitude and the temperature dependence of the recombination coefficient. Since the recombination rate is a decreasing function of temperature, the tendency is for electron density to actually increase during heating experiments there, whereas density decreases during heating at higher altitudes.

By introducing plasma density perturbation into the marginally unstable postsunset F region ionosphere through ionospheric modification, it should be possible to investigate ESF triggering systematically.

Equatorial electrojet current modulation Attempts to generate low-frequency radio waves at high latitudes with HF heating have suffered from the unpredictability of the auroral electrojet as well as from the adverse effects of precipitation and deviative absorption, which prevents the pump radiation from reaching the electrojet current. The equatorial electrojet, meanwhile, exhibits extremely reliable diurnal behavior, and low-latitude heating experiments do not suffer from the effects of precipitation. Preliminary tests using the Jicamarca radar as an underdense heater were carried out in the 1980's which demonstrated the plausibility of VLF generation using the equatorial electrojet. The installation of a true heating facility under the dip equator would provide a true operational capability.

A number of other factors suggest that the equatorial electrojet is more suitable for low-frequency wave emission than the auroral electrojet. The radiation generated in the equatorial electrojet will couple much more efficiently into the Earth-ionosphere waveguide than radiation generated at high latitudes, which tends to be coupled into the magnetosphere. In the equatorial electrojet, there exists a significant vertical current component which, when modulated, acts like a vertical dipole element, which is well suited for exciting the Earth-ionosphere waveguide.

The aforementioned theories suggest that an important operational capability could emerge from an equatorial heater. From a space physics perspective, the scientific utility of the heater would come from tests of the theories and explorations of the related plasma physics.

Benefits

Below, we briefly describe some of the practical benefits of this conceptual proposal to the scientific and broader communities. Some of these were fleshed out more fully in the workshop report "Opportunities for High-Power, High-Frequency Transmitters to Advance Ionospheric/ Thermospheric Research" published by the National Research Council in 2014 (see `https://www.nap.edu/catalog/18620`).

Important science questions This project addresses some of the most pressing basic science questions in AIM including the physics behind electron acceleration, wave-wave coupling, wave-particle interactions, and ionospheric instability. It also has the potential of providing a new diagnostic of ionospheric parameters, rate constants, and transport coefficients, adding to and going beyond what incoherent scatter techniques already supply. The ability to probe the neutral atmosphere via radio using the API method is novel.

Societal benefits and operations Low-frequency electromagnetic waves have an important strategic role to play in the areas of submarine communication and subsurface remote sensing. An equatorial heater represents a cost effective means of achieving the needed capability. ESF forecasting is important to a number of space weather interests, but conventional research methods are producing results only slowly. Active experiments with ionospheric modifications could accelerate the progress by promoting controlled cause-and-effect experiments.

International plans and activities An equatorial heater will necessarily involve international participation. Furthermore, this project would have the interest of the international community, particularly across the EU which already maintains a high-latitude heating facility and supports a broad community of experimentalists and theorists.