ENHANCED AIRGLOW BY HIGH FREQUENCY ELECTROMAGNETIC PUMPING WITH THE EISCAT-HEATING FACILITY AND OBSERVED BY THE MULTI-STATION AURORAL LARGE IMAGING SYSTEM (ALIS)

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ABSTRACT

Experimental results on enhanced airglow by pumping the ionosphere with the EISCAT-Heating facility obtained since our first measurements in 1999 are presented. The airglow was detected with the multi-station Auroral Large Imaging System (ALIS) in northern Sweden. The multi-station imaging technique enabled for the first time tomographic inversion to estimate the spatial extent of the pumped airglow cloud. Further, simultaneous images in the red and green line have been obtained. Recently obtained images at 427.8 nm are direct evidence of pump-induced ionization of molecular nitrogen in the thermosphere.

INTRODUCTION

A high frequency (HF) wave transmitted into the ionosphere from the ground may enhance the emission of airglow, which can be detected by optical methods from the ground. The airglow results from, e.g., excitation of the two lowest states in atomic oxygen, due to dissipation of the electromagnetically driven plasma turbulence. Electron collisions with energies above about 1.96 eV produce the excited $O(^1D)$ state that radiates at 6300 Å and collisions with energies above 4.17 eV give the $O(^1S)$ state that radiates at 5577 Å. For comparison, typically the ionospheric background electron temperature is 0.1–0.2 eV. With its dependence both on plasma turbulence energizing electrons and the interaction of the electrons with the ambient thermospheric neutral gas, HF-enhanced airglow is useful for studies both of fundamental aspects of the dissipation of plasma turbulence as well as to to determine certain thermospheric parameter values that are not easily accessible by other means [1]. In addition, enhanced airglow has been used to study the structure of sporadic E layers [2]. However, all results discussed in the present treatment have been obtained in the ionospheric F region.

Here experimental and analysis results obtained with the European Incoherent Scatter (EISCAT) Heating facility near Tromsø, Norway, and detected with the Auroral Large Imaging System (ALIS) since our first successful measurements on 16 February 1999 are reviewed. ALIS is a low-light imaging facility with six remote controlled stations located in the Kiruna area in northern Sweden [3]. Each station has a non-intensified charge-coupled-device (CCD) camera with 1024×1024 pixels and 16 bits/pixel.

Following the first unambiguous observations of HF enhanced airglow at auroral latitudes by ALIS [4, 5, 6], experiments have been pursued both at the EISCAT-Heating facility [7] as well as at the High Frequency Active Auroral Research Program (HAARP) facility in Alaska [8]. These high latitude experiments with their stronger excitation of upper hybrid phenomena at long time scales complement low latitude experiments at Arecibo [9, 10, 11] where Langmuir turbulence appears to dominate.

EXPERIMENTAL RESULTS

Airglow at 6300 Å

The first unambiguous detection of HF enhanced airglow at auroral latitudes was obtained on 16 February 1999, with EISCAT-Heating transmitting in ordinary mode at 4.04 MHz at an effective radiated power of 125 MW cycled 4 min on/4 min off and directed 6° south from the vertical [4]. The airglow was observed at 6300 Å by all ALIS stations in operation and by up to three stations simultaneously. The e-folding growth time of the 6300-Å emission following HF-on was approximately 60 s.

By using altitude-averaged effective life times and neglecting transport processes a model-independent estimate of the altitude-averaged excitation can be made [11, 6]. Images of the excitation show that initially the airglow has a speckled spatial structure with typical scales of 5–15 km [6]. At about 15–25 s after HF-on the excitation grows significantly in a smaller region, while that in the surrounding region either saturates or decreases slightly.

The decay time after HF-off was approximately 35 s, which is significantly shorter than the radiative life time of the meta-stable $O(^1D)$ state of approximately 110 s [4]. This is consistent with collisional quenching of the $O(^1D)$ state by, e.g., vibrational states in ambient N_2 and O_2 at the airglow altitude of about 240 km, as obtained by triangulation of the multi-station image data. The measured decay time can therefore be used when modeling the thermosphere. Particularly, it was found that the experimental results show a slightly slower increase with altitude than modeled values [6]. In addition, it is interesting that following the initial growth phase after HF-on the maximum emission intensity exhibits different temporal evolution in different pump periods, which may be due to natural large scale plasma irregularities in the HF interaction region.

Simultaneously with the airglow measurements the EISCAT-UHF radar was operated to determine several plasma parameter values [5]. The airglow enhancement occurred together with large increases in the electron temperature up to approximately 3500 K, which corresponds to an enhancement of 250% of the unperturbed temperature of about 1000 K. The height of the maximum emission intensity at 6300 Å was 15–20 km above that for the maximum temperature enhancement [6]. The temperature enhancement extended several tens of kilometers below and up to 600 km altitude which was several hundred kilometers above the HF reflection height of approximately 250 km. This asymmetry in altitude extent is consistent with the fact that the energy input from the relatively narrow HF-ionosphere interaction region is transported mainly upward into the diffusion dominated upper F region while in the collision dominated lower F and E regions the energy is instead lost to neutrals [12]. The ion temperature enhancement was up to about 55% of the unperturbed value of approximately 900 K. Since no HF-correlated modulations in the ambient electron density were detected, any large scale density perturbations must have been less than about 6%. For comparison, the enhancement of the electron temperature during daytime experiments is typically a few tens of percent in high latitude experiments [13, 12].

First tomographic estimate of airglow distribution

Multi-station imaging enables triangulation of the emission altitude and, more importantly, tomographic estimates of the airglow volume. The first estimate of the three-dimensional volume emission rate at 6300 Å have been performed [6]. Tomographic inversion of the airglow data obtained by ALIS constitutes an ill-posed problem, with the measurements only from three stations south of the emission region and covering only a limited angular range. Therefore a more constrained method had to be applied to estimate the volume emission rate, which involved the assumption of a model function to describe the spatial variation of the emission. This model function could only depend on a few free parameters which were determined by comparing image projections from the modeled airglow distribution with the original images.

The shape of the $O(^1D)$ excitation was found to vary from prolate along the geomagnetic field to slightly oblate, with typical scale sizes of about 20 km. The mean free path of electrons having an energy of 3.5 eV parallel to the geomagnetic field near 240 km altitude is 5–10 km [5]. The size of the airglow cloud along the geomagnetic field is therefore of the same order or slightly larger than the mean free path of the energetic electrons.

Modeling results

A one-dimensional time-dependent ionosphere-thermosphere model has been used to study the 6300-Å airglow from HF pumping [14, 6]. Input parameters of the model are the neutral composition and temperature, MSIS-90 atmospheric model, the solar ultraviolet flux and precipitating particle flux. The main ionospheric sources of the $O(^1D)$ state that are affected by HF pumping are direct electron impact and dissociative recombination. It was shown that the temperature variation in the dissociative recombination of O_2^+ has to be included [14], which was not done previously [15]. The temporal evolution of the 6300-Å emission in this extended model is inconsistent with the experimental results. Different cases were studied, including assuming the electron distribution to remain Maxwellian and using a heat source that reproduced the electron temperature measurements with the EISCAT-UHF radar, searching for a heat source that reproduces the optical data, as well as assuming an electron source with isotropic flux and uniform energy distribution in the range 2–10 eV. The conclusion is that the ionospheric heating and airglow enhancement are likely to be generated by different mechanisms, implying that the airglow is due to accelerated electrons by plasma turbulence. Particularly, it was found that the electron distribution in the range 2–10 eV needs to be sub-thermal.

Nearly simultaneous images at 6300 Å and 5577 Å

The first nearly simultaneous images of HF-enhanced airglow at 6300 Å and 5577 Å from the F region have been obtained during experiments on 21 February 1999 [16]. The EISCAT-Heating facility was operating at 4.04 MHz and transmitted vertically an effective radiated power of about 73 MW in the cycle 4 min on/4 min off. The airglow was imaged with the ALIS station at Abisko alternatively at 5577 Å and 6300 Å during the same HF pulse. The images at 5577 Å and 6300 Å show almost identical regions of enhanced airglow, which implies that the sources of the two emissions are co-located in the F region. The maximum intensity enhancement at 6300 Å was 40–60 Rayleighs and the maximum enhancement at 5577 Å was 10–20 Rayleighs for the five different HF pulses studied. The intensity ratio of the 5577 Å and 6300 Å emissions of 0.3–0.4 implies that the excitation is caused by a nonthermal electron population. For comparison, previous photometer observations at mid latitudes have given an intensity ratio of 0.05–0.3 [17, 11].

First images at 4278 Å

Experiments performed at EISCAT-Heating in March 2002 have given the first images of emissions at 4278 Å, which is from the 4278A band of the first negative system of N_2^+ and implies that N_2 is ionized by the HF pumping. Previously enhancements at 4278 Å have been observed with a photometer (see the paper by M. Kosch et al. in the present proceedings). The threshold for the emission at 4278Å is about 18 eV and the cross section increases rapidly up to about 100 eV. In the experiments the HF wave was stepped up and down through the third harmonic of the ionospheric electron gyro frequency. The airglow was imaged simultaneously with the Digital All Sky Imager (DASI) (at 6300 Å) operated by M. Kosch at Skibotn and the mobile ALIS station also at Skibotn, Norway. The ALIS station recorded emissions at 5577 Å as the HF frequency was stepped downward through the gyro harmonic and weaker emissions at 4278 Å as the HF frequency was stepped up again.

The dependence of the 4278-Å emission intensity on the pump frequency around the electron gyro harmonic gives input for the theoretical modeling of electron acceleration for HF frequencies near the harmonics. Further, in future experiments it will be important to obtain multi-station images to compare the volume distribution of the emission at 4278 Å with those at, e.g., 6300 Å which require significantly lower electron energies, in order to study the role of the underlying plasma dynamics perpendicular and parallel to the geomagnetic field.

CONCLUSIONS

The experiments on enhanced airglow obtained with the EISCAT-Heating facility and imaged with ALIS in northern Sweden have already given a number of results, which have implications for our understanding of the dissipation of HF-driven plasma turbulence on long time scales as well as the interaction of the ionospheric plasma and the thermosphere. The experimental results indicate that the airglow enhancement is due to electron acceleration in upper hybrid turbulence. This is consistent with the minimum in airglow intensity for HF frequencies near an harmonic of the electron gyro frequency [1] as well as the correlation of the airglow and anomalous heating. Anomalous heating has been associated with anomalous absorption in high latitude experiments, at least during daytime [18, 19], and the anomalous absorption has been attributed to upper hybrid turbulence and the associated formation of density and temperature irregularities [12, 20].

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