An analysis of pump-induced artificial ionospheric ion upwelling at EISCAT

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Abstract

Ion outflow from the high-latitude ionosphere is a well-known phenomenon and an important source of plasma for the magnetosphere. It is also well known that pumping the ionosphere with high-power high-frequency radio waves causes electron heating. On a few occasions, this has been accompanied by artificially-induced ion upwelling. We analyse such a controlled experiment at EISCAT up to 600 km altitude. The pump-enhanced electron temperatures reached up to ~4000 K above 350 km, and ion upwelling reached up to ~300 m/s above 500 km altitude. The pump-induced electron pressure gradient can explain the ion velocity below 450 km. Between 450 and 600 km the electron pressure gradient correlates equally with ion acceleration and ion velocity, which represents the transition altitude to free ion acceleration. The electron gas pressure gradient can explain ion upwelling, at least up to 600 km altitude. In addition, such active experiments open the possibility to estimating the F-layer ion-neutral collision frequency and neutral density with altitude from ground-based observations.

1. Introduction

An important component of magnetospheric plasma is atomic oxygen ions as well as molecular nitrogen and oxygen ions [1], which flow out of the ionosphere and can affect the dynamics of the magnetosphere [2, 3]. Strong field-aligned bulk ion outflows from the topside ionosphere are observed at high latitudes using incoherent scatter radars in the auroral zone and polar cap with typical velocities in the range 100 to 1000 m/s below 1000 km altitude.

Naturally occurring ion outflow can be divided into two categories. Type I were associated with a strong perpendicular electric field resulting in enhanced and anisotropic ion temperatures due to frictional heating, and low plasma density due to a lack of particle precipitation. Type II were associated with auroral arcs and enhanced electron temperature. ~80% (~50%) of ion outflow events were associated with enhanced electron (ion) temperatures. To overcome the downward gravitational force, an upward force must be applied. The upward ambipolar electric field can be increased either by enhancing the electron temperature and/or plasma density gradient. Soft particle precipitation (<500 eV) is clearly associated with ion outflow and is particularly effective at achieving the necessary enhanced pressure gradients in the topside ionosphere [4]. In addition, Joule heating can also enhance the ion upward pressure to overcome gravity. However, electron temperature enhancements appear to be the more effective mechanism for ion outflow from the topside ionosphere.

It is well established that pumping the ionosphere with high-power high-frequency radio waves causes plasma heating. A primary energy exchange mechanism is upper-hybrid resonance. Upper-hybrid resonance acts perpendicular to the magnetic field line and occurs a few km below the pump wave reflection altitude at high latitudes. The temperature enhancements maximise for pump frequencies away from the electron gyro-harmonic frequencies, especially when pumping slightly above a gyro-harmonic frequency, and when pumping parallel to the magnetic field-line direction with electron temperatures reaching up to ~4000 K for night time experiments. More modest ion temperature enhancements may also occur up to ~500K above background. In addition, artificial ion upwelling above 400 km with upward field-aligned velocities up to ~300 m/s have also been reported. One distinguishing feature of the observations of artificial ion upwelling is that the pump on duration was unusually long, i.e. 4 minutes, which may explain why the phenomenon has been reported infrequently. Here we present a new data set from EISCAT, which has been analysed in detail [5].

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2. Experiment and results

The EISCAT facility in Tromsø, northern Norway (69.58° N, 19.22° E), includes a 933 MHz UHF incoherent scatter radar and is co-located with an high-power high-frequency pump facility for artificial heating of the ionospheric plasma operating between 3.85 and 8 MHz.

On 6 October 1998, the Heater was operated in O-mode using a 250 s on, 250 s off cycle with the beam pointing 10^o south using 11 out of the 12 transmitters. Since the beam is ~14^o wide, the field-aligned direction at 12.8^o south is also covered. Between 17:22 and 18:00 UT the pump frequency was 4.54 MHz with an effective radiated power (ERP) of 96 MW. From 18:03 to 18:08 UT, the Heater was re-tuned to 4.04 MHz. From 18:12 to 20:00 UT, the Heater was operated as described above, but at 4.04 MHz with 143 MW ERP. The UHF radar was observing field-aligned from 90 to 600 km using the CP1K code, which consists of a 16-bit alternating code with a 21 μs baud length and 3.15 km range resolution between 89 and 278 km, and a long pulse of 336 μs and 22.5 km range gate separation between 150 and 622.5 km. During this period, it was geomagnetically quiet with Kp = 1^+. Kp did not exceed 2^+ for more than 3 days prior to the experiment. During the period of interest, Bz remained positive, Tromsø was on the equatorward edge of the dusk convection cell and experienced westward plasma convection of <300 m/s.

Figure 1 shows an overview of the data from the EISCAT UHF radar for 17 - 20 UT on 6 October 1998. From top to bottom, the panels show electron density, electron temperature, ion temperature and ion velocity between 100 and 600 km altitude. The data resolution is set to 50 s in order to get a good signal for the analysis and synchronise with the 500 s pump cycle. The data below ~200 km has low signal but does not affect this study. The "noisy data" in each panel below ~350 km correspond to the pump-induced ion-line overshoot phenomenon. This is the well-known pump-induced Langmuir turbulence effect, which is undesirable in this case, and makes normal analysis of the incoherent scatter radar spectrum impossible. Unfortunately, the ion-line enhancement becomes persistent throughout the heater pulse, as was the case here for 18:12 to 19:31 UT, when pumping near an electron gyro-harmonic, in this case the third gyro-harmonic at 4.04 MHz.

Excluding the ion-line overshoot effects below 350 km, the electron density data in figure 1 represents a quiet ionosphere with no structured auroral precipitation. Between 17:00 and 18:10 UT, the critical frequency dropped from ~7.2 to ~3.7 MHz as the sun set, which explains the pump frequency change at 18:12 UT. Between 18:10 and 19:25 UT, the critical frequency ranged between ~3.7 and ~4.1 MHz, thereafter dropping below 3.7 MHz. At times the pump frequency was below the critical frequency, suggesting plasma resonance would not be possible. However, upper-hybrid resonance is possible in an under-dense ionosphere for pump frequencies up to ~0.5 MHz above the critical frequency. Pumping near, or slightly above the critical frequency is advantageous in the F-region because the plasma density gradient is small, giving a long interaction path with the pump wave. In addition, when the plasma density is lower, as is the case towards sunset, then the pumping effect is greater because the same energy is distributed to fewer electrons, assuming other factors such as ERP and pump frequency relative to the electron gyro-harmonic remain the same.

The electron temperature data in figure 1 show large enhancements. Before 18:00 UT these remain below ~3000 K when pumping at 4.54 MHz. The pump cycle immediately after 18:00 UT corresponds to the 4.04 MHz tune-up. Between 18:12 and 19:31 UT electron temperature enhancements up to ~4000 K occur when pumping at 4.04 MHz, possibly the greatest ever observed at EISCAT. The HF reflection altitude of 250 - 300 km, as shown by the ion-line enhancements, corresponds to pumping above the third electron gyro-harmonic (~215 km at 4.04 MHz) where plasma temperature enhancements are maximised. After 19:31 UT the plasma density reduces to the point where upper-hybrid resonance is no longer possible and efficient electron heating ceases, leaving only ohmic heating with small temperature enhancements of a few hundred Kelvin. The field-aligned ion velocity data shows clear upwelling above 350 km, sometimes greater than 250 m/s above 500 km. There is some evidence of ion down-welling during the pump off periods, presumably due to the same ions returning under the force of gravity. This is especially clear after 19:15 UT. There is only weak evidence for the simultaneous down-welling at low altitudes with upwelling at high altitudes. The ion-line overshoot effect masks any ion flow data below ~350 km when the pump is on. However, after pump goes off weak ion down-welling can be observed at ~300 km.

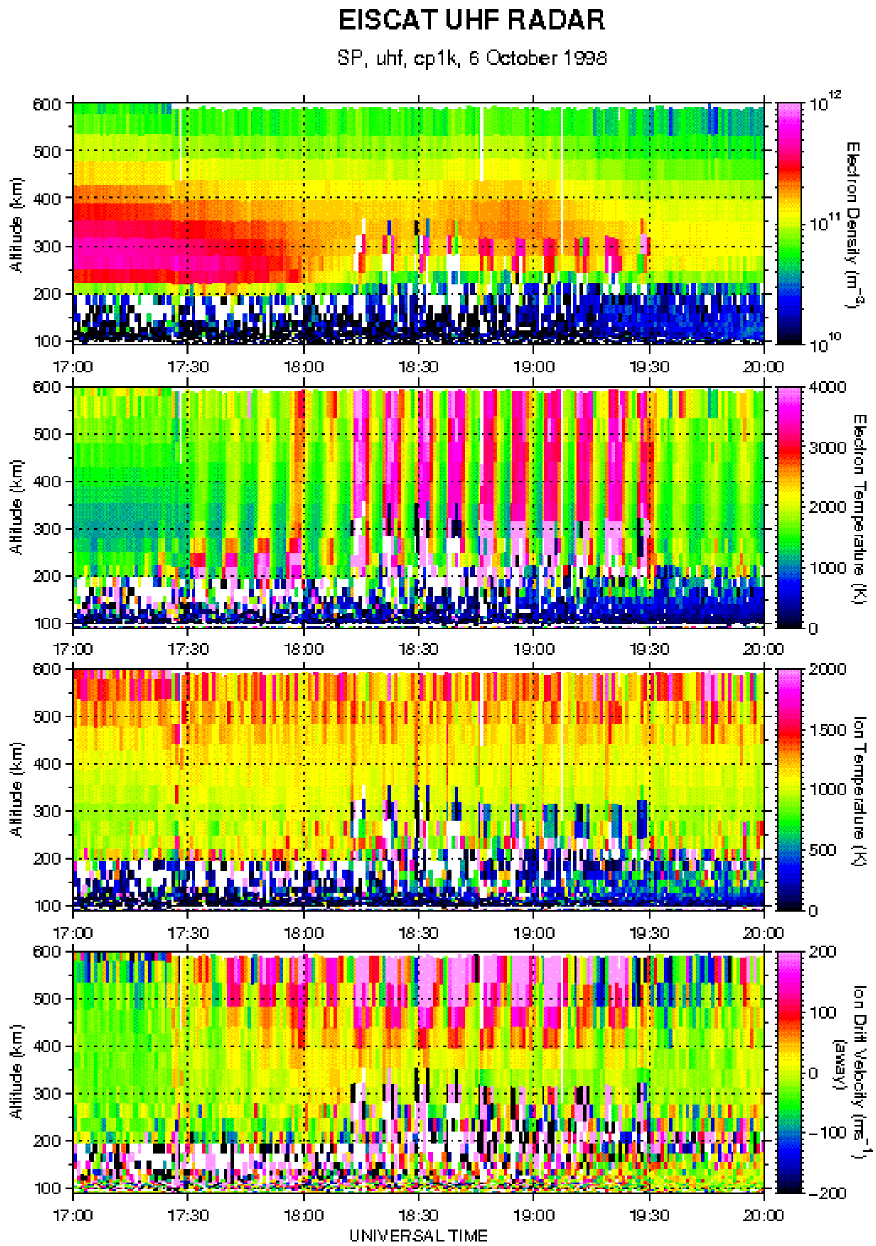

Figure 1. Field-aligned EISCAT UHF radar data for 17 - 20 UT on 6 October 1998. From top to bottom, the panels show electron density, electron temperature, ion temperature and ion velocity between 100 and 600 km altitude. The "noisy data" in each panel below ~350 km correspond to the pump-induced ion-line overshoot phenomenon.

We have analysed the 7 pump cycles between 18:10 and 19:10 UT in more detail, estimating the electron pressure gradient force, because they show clear pump-induced ion upwelling for one pump frequency. The ion temperature is in the range 1000 to 1500 K. The electron temperature is clearly related to the pump cycle with enhancements peaking at ~4000 K at 416 and 461 km and ~4500 K at 506 km altitude from a background of ~1500 K. The field-aligned ion velocity is also clearly correlated to the electron temperature reaching upward velocities of ~75 m/s at

416 km, ~175 m/s at 461 km, and ~300 m/s at 506 km. The increase in ion velocity with altitude is consistent with previous observations. Towards the end of each pump off period there is clear evidence for ion down-welling up to -75 m/s.

At 416 km altitude, the ion velocity is well related to the electron pressure gradient accelerating force, but the ion acceleration is not. At this lower altitude, ion-neutral collisions and the high inertia of the neutral thermosphere prevent the ions from accelerating continuously, so only a constant average velocity is achieved. At 461 km altitude, the relationship between ion velocity and the accelerating force is less clear. At 506 km altitude, the relationship between ion velocity and accelerating force appears to break down. However, there is a relationship between ion acceleration and the accelerating force is apparent. At this higher altitude, the lower neutral density means fewer ion-neutral collisions, so the ions can accelerate under the applied force more freely. It is clear that the ion acceleration starts to approach the accelerating force. It is probably true that a clear relationship between ion acceleration and the electron pressure gradient would become apparent at higher altitudes, but we do not have radar data above 600 km for this experiment. At some altitude, the ion motion would become essentially unrestricted by collisions and the ion acceleration should be given by the accelerating force.

We estimate the ion-neutral collision frequency (ν_{in}) at 416 km altitude as $\nu_{in} = 0.106 \pm 0.034\ s^{-1}$. Assuming $T_i = T_n$ = 1200 K, the neutral density (n_n) is $n_n = 1.29\text{x}10^{14}\ m^{-3}$. The MSISE-90 model predicts a neutral density of $7.11\text{x}10^{13}$ m^{-3}, which is a factor of 1.8× lower compared to our estimate. At 461 km $\nu_{in} = 0.084 \pm 0.036\ s^{-1}$ and $n_n = 1.03\text{x}10^{14}$ m^{-3}. MSISE-90 predicts $n_n = 3.36\text{x}10^{13}\ m^{-3}$, a discrepancy of 3.3×. In both cases, our neutral density estimate is substantially less than MSISE-90, the discrepancy being significantly greater than the root mean square error of the fit. Although our data set is too small to be definitive, the outcome suggests that the neutral density obtained from the MSISE-90 model at high latitudes may need significant correction. A number of ground-based and satellite observations have led to substantial corrections of the MSISE-90 model (up to 100%). Artificial ion upwelling provides a new tool for estimating ν_{in} and n_n in the upper atmosphere as a function of altitude, both of which are not easily obtained by remote measurements.

3. Conclusions

We have analysed pump-induced artificial ion upwelling at EISCAT in some detail [5]. The pump-enhanced electron temperatures reached ~4000 K above 350 km, and ion upwelling reached ~300 m/s above 500 km altitude. The pump-induced electron pressure gradient can explain the ion velocity below 450 km, confirmed by a reasonable deduction of the ion-neutral collision frequency. Above 450 km the electron pressure gradient correlates equally with ion acceleration and ion velocity, which is expected for a decreasing neutral density with increasing altitude. Presumably, above 600 km altitude ion acceleration will be determined by the electron pressure gradient, but this awaits confirmation by obtaining suitable high altitude radar data. However, below 600 km, the electron gas pressure gradient can explain the observed natural ion outflow. In addition, we have demonstrated that this active experiment provides a new method to obtain the ionospheric F-layer ion-neutral collision and hence neutral density as a function of altitude.

4. References

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