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Ionospheric Response to Particle Precipitation within Aurora

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Errata

In Introduction

page 4, line 12 from below: ''auroras'' or ''auroae'' instead of ''aurora'';
page 8, line 4: ''is'' instead of ''are'';
page 8, line 11: add after ''ion outflows'', ''above auroral arcs'';
page 9, line 8 from below: ''interpreted'' instead of ''interpretated''.

In Paper I

page 8, line 4: ''is'' instead of ''are'';
page 17224, line 2: ''km'' instead of ''m'';
page 17227, 2nd column, last sentence: ''the observed luminosity variations measured by an optical camera and a corresponding time sequence of electron density profiles'';
page 17230, 1st column, line 14: ''by'' instead of ''be'';
page 17230, 2nd column, line 8 from below. The sentence starting with: ''If the wave frequency ...'', and the following sentence are simply wrong!

In Paper II

page 729, 1st column, line 23. The two sentences starting with: ''The calculated ambipolar diffusion velocities ...'' can be deleted since the work is done much better in paper III;
page 729, 2nd column, line 4 from below. Add ''assuming steady state and only classical collisions''.

In Paper III

Fig. 6: ''February 20, 1990'' instead of ''November 24, 1989''.

In Paper IV

page 2, line 13 from below: ''electrons'' instead of ''electron'';
page 3, line 9: ''that'' instead of ''hat'';
page 3, line 12: ''current densities'' instead of ''currents'', and ''m^{-2}'' instead of ''m^2'';
page 3, line 13: ''current densities'' instead of ''currents'';
page 3, line 16: ''inferred'' instead of ''[illegible]'';
page 7, line 26: ''interpreted'' instead of ''[illegible]retated'';
page 9, line 17: ''current densities'' instead of ''currents'';
page 9, line 23: ''current densities'' instead of ''currents'';
page 9, line 27: ''current densities'' instead of ''currents'';
page 10, line 1: ''current density'' instead of ''current'';
page 10, line 1: ''current densities'' instead of ''currents'';

page 12, line 13: delete '', which'';
page 12, line 24: ''general'' instead of ''generall'';
page 13, line 12 from below: ''exist'' instead of ''exists'';
Fig. 10, line 2: Comma between Tromsø and Kiruna;
Fig. 10, line 3: ''correspond'' instead of ''corresponds'';
Fig. 10, line 4: ''an'' instead of ''a'';
Fig. 12, line 1: ''plotted'' instead of ''ploted'';
Fig. 13, line 1: ''plotted'' insted of ''ploted'';
Fig. 14, line 1: ''vertically'' instead of ''verticaly''.

In Paper V

page 1, line 3 after the introduction: ''Schunk'' instead of ''Shunk'';
page 2, line 6 after The Model: ''Boltzmann'' instead of Boltzman'';
page 4, last line: ''where'' instead of ''Where'';
page 5, line 10: ''dispersion'' instead of ''dispertion'';
page 5, line 19: ''exceeds'' instead of ''exceed'';
page 5, line 24: ''an excitation'' instead of ''excitation'';
page 10, line 15: ''starts'' instead of ''start'';
page 13, line 11 from below: ''temporal'' instead of ''temporals'';
page 13 line 10 from below: ''turbulence'' instead of ''the turbulences'';
page 14, line 17: ''velocity'' instead of ''velocityi''.

In Paper VI

In author list: ''IZMIRAN'' instead of ''IZMERAN'';
In reference list: Delete references to Foster et al.

In Paper VII

page 1, line 14 after introduction: ''was'' instead of ''were'';
page 2, equations: and indices cannot both be running indecies and specific indices;
page 2, line 10: Equation should read $|1-\chi_s/\varepsilon|$ instead of $|(1-\chi_s)/\varepsilon|$
page 4, line 28 ''agreeing'' instead of ''agree''.

In Paper VIII

Pictures of figures 10 and 11 should change place!

Ionospheric Response to Particle Precipitation within Aurora

by

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ABSTRACT

Wahlund, J-E., 1992. Ionospheric Response to Particle Precipitation within Aurora.

The Aurora is just the visible signature of a large number of processes occurring in a planetary ionosphere as a response to energetic charged particles falling in from the near-empty space far above the planetary atmosphere. This thesis, based on measurements using the EISCAT incoherent scatter radar system in northern Scandinavia, discusses ionospheric response processes and especially a mechanism leading to atmospheric gas escape from a planet.

Sometimes electrons, in the form of pulses with periods between 2–20 seconds, precipitate into the auroral atmosphere and visibly cover the sky with pulsating auroral patches. These pulsating auroras are found to be associated with thin pulsating ionization layers near an altitude of 100 km on top of the broader altitude region of ionization produced by the particle precipitation. In fact, not even monoenergetic and monodirectional precipitating electrons could directly produce the observed thin ionization layers, although particle precipitation is certainly involved in the creation mechanism. The EISCAT measurements give observational constraints that are used to restrict the number of explanations for these thin layers. It is suggested that large-amplitude, broadband electric field fluctuations produced by a beam-plasma discharge instability (BPD) energize ambient ionospheric electrons to energies above the ionization threshold of the neutral atmosphere, thereby increasing the plasma density in a confined layer.

One of the most spectacular events in the high latitude atmosphere on Earth are the "auroral arcs" — dynamic rayed sheets of light. An investigation of the conditions of the ionosphere surrounding auroral arcs shows that strong field-aligned bulk ion outflows appear in the topside ionosphere which account for a large fraction of the escape of atmospheric oxygen from Earth. Four different additional ionospheric responses are closely related to this ion outflow; 1) enhanced electron temperatures of several thousand Kelvin above an altitude of about 250 km, 2) enhanced ionization around an altitude of 200 km corresponding to electron precipitation with energies of a few hundred eV, 3) the occurrence of naturally enhanced ion acoustic fluctuations seen in the radar spectrum, most likely produced by an ion-ion two-stream instability, and 4) upward directed field-aligned currents partly carried by the outflowing ions. From these observations, it is suggested that the energy dissipation into the background plasma through Joule heating, the production of a few hundred eV energetic run-away electrons, and strong ion outflows are partly produced by the simultaneous presence of ion acoustic turbulence and field-aligned currents above auroral arcs.

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Kiruna 1992

This thesis includes a general introduction and the following papers.

I. Observations of thin auroral ionization layers by EISCAT in connection with pulsating aurora.
J-E. Wahlund, H.J. Opgenoorth, and P. Rothwell, *J. Geophys. Res.*, *94*, 17223, 1989.

II. EISCAT observations of strong ion outflows from the F-region ionosphere during auroral activity: preliminary results.
J-E. Wahlund and H.J. Opgenoorth, *Geophys. Res. Lett.*, *16*, 727, 1989.

III. EISCAT observations of topside ionospheric ion outflows during auroral activity: revisited.
J-E. Wahlund, H.J. Opgenoorth, I. Häggström, K.J. Winser, and G.O.L. Jones, *J. Geophys. Res.*, in press, 1992.

IV. Electron energization in the topside auroral ionosphere: on the importance of ion-acoustic turbulence.
J-E. Wahlund, H.J. Opgenoorth, F.R.E. Forme, M.A.L. Persson, I. Häggström, J. Lilensten, submitted to *J. Atmos. Terr. Phys.*, 1992.

V. Effects of current driven instabilities on the ion and electron temperatures in the topside ionosphere.
F.R.E. Forme, J-E. Wahlund, H.J. Opgenoorth, M.A.L. Persson, and E.V. Mishin, submitted to *J. Atmos. Terr. Phys.*, 1992.

VI. Comment on "EISCAT radar observations of enhanced incoherent scatter spectra and their relation to auroral luminosity and field-aligned currents" by P.N. Collis et al.
J-E. Wahlund, H.J. Opgenoorth, and E.V. Mishin, *Geophys. Res. Lett.*, in press, 1992.

VII. Scattering of electromagnetic waves from a plasma: enhanced ion acoustic fluctuations due to ion-ion two-stream instabilities.
J-E. Wahlund, F.R.E. Forme, H.J. Opgenoorth, M.A.L. Persson, E.V. Mishin, and A.S. Volokitin, submitted to *Geophys. Res. Lett.*, 1992.

VIII. On the origin of ion acoustic turbulence in the auroral topside ionosphere.
J-E. Wahlund, M.A.L. Persson, F.R.E. Forme, H.J. Opgenoorth, K. Stasiewicz, and I. Häggström, IRF Scientific Report no. 208, 1992.

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Introduction

"In the thirtieth year, in the fifth day of the fourth month, as I was among the exiles on the banks of the river Chebar, heaven opened and I saw visions from God. ... a stormy wind blew from the north, a great cloud with light around it, a fire from which flashes of lightning darted ... (living creatures appeared) ... between these animals something could be seen like flaming brands or torches, darting between the animals; the fire flashed light, and lightning streaked from the fire ... Over the heads of the animals a sort of vault, gleaming like crystal, arched above their heads ... (a human form appeared) ... And close to and all around him from what seemed his loins upward was what looked like fire, and a light all around like a bow in the clouds on rainy days ... " was told by *Ezekiel* (1:1-28, 593 B.C.) in the Old Testament and is one of the oldest recorded depictions of Aurora Borealis, the Northern Lights. However, it has been suggested [*Siscoe*, 1976] that our earliest record of auroras might even be found in *the serpentine meanders* of Stone Age man. The first to provide a more dispassionate, scientific description of auroras, was Aristotle [384-322 B.C.] in his classical treatise *Meteorologica*, who gave them the name *chasmata*: "*Sometimes on a clear night a number of appearances can be seen taking shape in the sky, such as chasms, trenches and blood-red colors*".

The aurora, as looked upon today, is just the visible signature of a large number of processes occurring in a planetary ionosphere in response to precipitating energetic charged particles from near-empty space far above the atmosphere of a planet. For those planets which have an inherent magnetic field with a near dipole-like configuration, such as Earth, most of the auroral ionospheric response phenomena will be confined to two large-scale oval regions, surrounding the two magnetic poles of the planet. This is so as charged particles tend to move along the magnetic field-lines and since the acceleration regions of the precipitating particles are connected via magnetic field-lines to this, so called, auroral oval. The ultimate main source of the processes which produce the precipitation of energetic particles into a planetary atmosphere is the Sun. The plasma of the solar wind, flowing from the Sun outward through the solar system, distorts the planet's magnetospheric plasma cavity and so triggers the precipitation toward the planetary atmosphere. Understanding the interaction between the solar wind, planetary magnetospheres, ionospheres and atmospheres is the front line of space research today. This thesis will hopefully add to the knowledge about ionospheric response processes within the auroral oval of our planet, and in particular provide more insight to one of the mechanisms leading to atmospheric gas escape from our planet. It will be shown that ionospheric outward fluxes of ions above aurora can become very large and comparable to the worldwide thermal escape flux of electrically neutral compounds from the atmosphere. Therefore, a short discussion on the classical thermal escape mechanism will precede the description of the gas escape processes considered in this thesis.

Planetary atmospheres, as the planets themselves, have their birth in certain physical and chemical events in the primitive solar nebula several thousand million years ago. The original atmospheres of the terrestrial planets (Venus, Earth, Mars) were developed mainly by strong outgassing from the solid planets, with initial compositions connected to processes in the late thermal evolution of the planets themselves. Weaker forms of such outgasing still occur today, for example from volcanos or the evaporation of water from the oceans. Evolutionary processes, such as the escape of gases to space, cometary and meteoritic impacts, atmosphere-hydrosphere-crust interactions, as well as the influence of living organisms, have determined the current composition and structures of the planetary atmospheres. The theory of gravitational escape of thermal gases from planets was developed by *Jeans* [1916]. However, already in 1846 (according to *Chamberlain* [1963]) J. L. Waterstone read an important paper to the Royal Society that revealed for the first time the ideas of atmospheric escape and anticipated much of the subject of the kinetic theory of gases later developed by Clausius and Maxwell. Because of objections by competent, but conservative, referees, the paper itself was not published until nearly half a century later, after Lord Rayleigh located it in the dusty archives of the Royal Society. The basic idea is roughly that if any of the upward-moving molecules in the upper atmosphere do not collide with another molecule, they will in general follow a ballistic path and eventually return to the atmosphere due to gravitational forces. However, if the molecule is energetic enough, i.e. has a velocity greater than the gravitational escape velocity, it will continue out to space and never return. *Spitzer* [1952] derived an expression for the time to reduce atmospheric density to 1/e of its original value by thermal escape. He found that an atmosphere will be lost from a planet in a time less than the age of the solar system provided

$$v_{th,rms} = \sqrt{\frac{3k_{Boltz}T_{exosphere}}{m_{species}}} \geq 0.25 v_{escape}.$$

Since the exospheric temperature on Earth (today) is roughly 1000 K, only hydrogen (H) and maybe helium (He) should have escaped the atmosphere over the time period our planet has existed. The corresponding total escape fluxes can be calculated to be 10^{28}, 10^{20} and 10^{9} particles/s for H, He and atomic oxygen (O) respectively. However, Earth has a substantial reservoir of H in the form of water on the surface, and therefore a lot of H is still encountered in the upper atmosphere today.

In recent years, a large number of observations have shown that the terrestrial ionosphere serves as a significant source of hot plasma to the near Earth space, the Magnetosphere. This implies that upward flows of cold plasma exist and that this plasma at some altitude gains energies much larger than typical ionospheric values [see e.g. reviews by *Horwitz*, 1982; *Moore*, 1984; *Chappell*, 1988]. These plasma outflows include the classical polar wind, the cleft ion fountain, the polar cap fountain, and the auroral ion fountain. Recent measurements with the Millstone Hill incoherent scatter radar also indicate outflow processes of O^+ ions at mid-latitudes (around 55° invariant latitude) [*Yeh and Foster*, 1990], which are associated with energetic ion precipitation from the so called van Allen radiation belts.

The polar wind, first suggested from theoretical arguments by *Banks and Holzer* [1969], is the steady flux of low energy (0.1-2 eV) H^+ and He^+ ions from the polar regions inside the auroral oval. The first observations of these outflows [*Nagai et al.*, 1984], using data from the Dynamics Explorer satellites, revealed that they accounted for the largest part of the light ion escape during so called quiet auroral conditions, with total ion fluxes of about $10\text{-}50 \times 10^{25}$ ions/s.

The cleft ion fountain [e.g. *Lockwood et al.*, 1985], occurring in a small region where the solar wind has direct access to Earth's ionosphere on the sunward side near the auroral oval, provides large fluxes of oxygen ions (O^+) with energies of a few eV to tens of eV. These ion outflows account for a significant fraction of the

O^+ outflows from our planet, and the total fluxes are usually around $1\text{-}5\times10^{25}$ ions/s.

The polar cap fountain, which occurs in similar regions as both the regions described above, provides an outflow of a variety of heavier ion species (like O^+, O^{++}, N^+, N^{++}, N_2^+, NO^+, and O_2^+), and has higher energies (10-100 eV). However, the total escape flux is smaller ($0.2\text{-}2\times10^{25}$ ions/s).

The auroral ion fountains, located in the auroral oval and associated with aurora, are the largest sources for escape of O^+ and heavier ions. These fountains have total fluxes between $1\text{-}10\times10^{25}$ ions/s, and the ions within them exhibit very high energies between 10 eV and 20 keV. The mechanism to energize these ions from thermal energies to several keV is one of the main issues of space research today. A good review of the subject, based on recent measurements from the Swedish satellite Viking at altitudes around 10000 km above the surface of Earth, can be found in a paper by *Lundin and Eliasson* [1991], which describes the very complex observational results obtained from these regions. It is the aim of this thesis to give additional observational constraints near the start altitudes (200-2000 km) of these ion outflows, i.e. in the ionosphere, and investigate the mechanisms for the cause of these ion outflows at these altitudes. It will be shown that at least two types of ion outflows exist in the auroral ionosphere. One type occurs during periods of little energetic particle precipitation, strong perpendicular electric fields and enhanced ion temperatures and can be explained in terms of "normal" thermal outflow due to the increased plasma pressure. The other type, which generally seems to be an order of magnitude stronger and to be present more often, occurs above auroral arcs. This second type of ion outflow cannot be explained by simple thermal processes. Instead, it is shown that complex wave-particle interactions (involving ion acoustic turbulence) are crucial for the development of not only the ion outflows, but also for the energization of electrons within the ionosphere. Since the auroral ion fountains are the major contributor of the heavier ions (such as O^+), the importance of this thesis should be obvious.

Thus, Earth can be envisaged as a multiple fountain which ejects particles from different spatial locations spread around the globe. These particles exhibit a range of masses, from 1 to 32 amu, and a range of energies, from 1 eV to 20 keV. It has been found that the total flux of this global ionospheric outflow is substantial (about 10^{26} s^{-1}). It seems, in the case of Earth, to be typically a few orders of magnitude greater for oxygen escape compared to the "normal" thermal atmospheric escape mentioned above, and thus important for the evolution of the atmospheric oxygen content since the birth of our planet thousands of millions years ago.

Plasma outflows have also been detected on other planets, and especially on Mars where the O^+ outflow of ionospheric origin has been found to be so strong that if present day rates were kept constant it would evacuate the whole atmospheric oxygen content (in the form of CO_2) in less than 100 million years [*Lundin et al.*, 1989, 1990] ! The ion loss from Mars results from both ion pick-up processes, i.e. solar wind momentum transfer to the ionospheric plasma, and ionospheric O^+ beams with energies of up to several keV, possibly from acceleration processes similar to those observed above the Earth's auroral oval. Thus, the processes leading to ion outflows within the auroral oval on Earth might also be active on other planets, which even more illustrates the importance of research in this area.

To achieve new knowledge about ionospheric response processes it is, of course, required that adequate measurement techniques exist. One of the instrumental developments in this respect is the advent of incoherent scatter radars, and this thesis is primarily concerned with measurements made by the EISCAT incoherent scatter radar system in northern Scandinavia. Its location at high latitude makes this radar very suitable for measurements of ionospheric processes in the auroral oval and of ionospheric interactions with the plasma in outer space. The EISCAT system consists of two radars, one operative at UHF (933 MHz) and one at VHF (224 MHz). The UHF system has three receivers, in Tromsø(Norway), Kiruna (Sweden) and Sodankylä (Finland) respectively.

The incoherent scatter technique for ionospheric application uses very powerful (≈2 MW) transmitted radar waves, at frequencies well above the electron plasma frequency, which pass almost unaffected through the ionosphere. A very small fraction of the transmitted radar signal is then scattered by the ionospheric electrons (so called Thomson scattering). The scattered radiation, which contains the averaged physical information from all electrons in a certain volume, is then received on the ground. The scattered radiation from the ions is negligible. However, ions collectively affect the scattering electrons, and the resulting ion acoustic lines in the received radar spectrum are most often used to derive physical parameters, such as the electron and ion temperatures, plasma density, ion composition and the ion-neutral collision frequency. The doppler shift of the ion line gives information on the line of sight ion velocity. Since the EISCAT UHF radar system has three receivers, in Tromsø, Kiruna and Sodankylä respectively, a vector measurement of the ionospheric ion motions is obtained. This can be used to infer the perpendicular electric field. If the electron plasma lines in the incoherent spectrum also are measured, even information of electric currents can be achieved. That is in practice difficult to do, because naturally excited electron plasma lines are generally weak. The spectra of the scattered radiation may also be used for studies of non-Maxwellian plasmas and enhanced collective plasma fluctuations, as described in this thesis. All these parameters may be inferred from the measurements simultaneously, over an altitude interval from 80 km to 1700 km, with a range resolution varying between 300 meters to about 60 km, and a temporal resolution down to a few seconds. Thus, it is a very powerful measurement technique, as can be illustrated by this thesis.

Summary of the Papers Included in the Thesis

Paper I.

Paper I presents EISCAT observations of very thin ionization layers around an altitude of 100 km during periods of pulsating aurora, observed simultaneously by all-sky and narrow angle cameras. These ionization layers, which can be viewed as a response to pulses of precipitating energetic electrons with periods from 2 to 20 seconds, are shown to be thinner than would be expected from collisional energy deposition of even monoenergetic and monodirectional beams of precipitating electrons. Furthermore, the observational characteristics of the thin ionization layers are found to be very similar to those of so called enhanced aurora [*Hallinan et al.*, 1985], which suggests that it is merely another aspect of the same phenomenon. The observations presented by us can be used to rule out some of the proposed mechanisms for the production of enhanced aurora, e.g. a localized layer of metallic ions (so called sporadic E layers) produced from meteoritic ablation in the atmosphere, or strong localized magnetic field-aligned electric fields, or upper boundaries of regions of increased quenching of auroral luminosity. It is instead concluded that the most likely process of creating these thin ionization layers, and associated enhanced aurora, are strong local electric field fluctuations. It is suggested that large-amplitude Langmuir turbulence are produced by a beam-plasma instability which energize the ambient ionospheric electrons to energies above the excitation and ionization thresholds of the neutral atmosphere, thereby producing a confined layer of enhanced auroral emissions and enhanced plasma density. This paper treats a somewhat different aspect of ionospheric response processes than the other papers in the thesis.

Paper II.

Paper II reports the first EISCAT observations of field-aligned ion outflows starting from an altitude of about 300 km. Optical recordings showed that these ion outflows occurred above auroral arcs. Simultaneously, the radar measured precipitating particle ionization and enhanced F-region electron temperatures. These ion outflows are shown to be large (of the order 10^{13} m^{-2} s^{-1}) and could therefore account for a major fraction of O^+ outflows from the atmosphere of planet Earth.

Paper III.

Paper III presents a more thorough investigation of field-aligned ion outflows as seen by the EISCAT radar. The maximum observed fluxes are found to be an order of magnitude larger than for the cases presented in paper II. The new observations presented are from an experiment (called HIALT) specially designed for topside ionospheric studies, with which it is possible to make measurements up to 900 km and 1700 km with the UHF and VHF radar respectively. Two different types of ion outflow can be identified from the large data set. The first type is related to periods of strong perpendicular electric fields, enhanced and anisotropic ion temperatures, and low plasma densities below 300 km, indicating small amounts of auroral precipitation. This type of ion outflow is similar to the ones reported by *Winser et al.* [1988] and can be interpreted in terms of the usual ambipolar thermal expansion mechanism. The second type is found to be related to auroral arcs and enhanced electron temperatures and is of the type presented in paper II. It is shown that additional mechanisms, other than thermal expansion are required to explain the observations. Some possibilities to enhance the field-aligned electric field to required values are discussed, but no final conclusion can be made. Type 2 ion outflows seem to be the more common phenomenon and result in an order of magnitude larger field-aligned ion fluxes.

Paper IV.

Paper IV is an observational follow up paper to two other observational papers, by *Foster et al.* [1988] and *Rietveld et al.* [1991], discussing naturally enhanced ion acoustic spectra measured by incoherent scatter radars. Here, thorough investigation of the surrounding ionospheric conditions during type 2 ion outflows and associated auroral arcs is performed, without discussing the possible ion outflow mechanisms themselves in any detail. It is shown that four different observed physical responses in the ionosphere are closely related to each other; 1) enhanced electron temperatures of several thousand Kelvin above an altitude of about 250 km, 2) enhanced ionization around an altitude of 200 km corresponding to precipitation of electrons with energies of a few hundred eV, 3) type 2 ion outflows, and 4) the occurrence of naturally enhanced ion acoustic lines indicating the presence of ion acoustic turbulence. From the close connection of these observational events, and measurements with experiments on board satellites and rockets reported by others, it is concluded that upward directed small-scale field-aligned currents with strengths between 1-100 μA m^{-2} should be associated with these events. Based on the observed altitude dependence of the field-aligned ion velocities, a crude estimate of the field-aligned electric fields can be made and shown to be in agreement with the current theories of enhanced electrical resistivity in the presence of ion acoustic turbulence. This leads, in turn, to an estimate of the electron heating in the topside ionosphere, and large heat inputs are inferred. It is therefore suggested that the energy dissipation into the background plasma occurs partly through Joule heating produced by the simultaneous presence of ion acoustic turbulence and field-aligned currents, and that this process is a major contributor for the large electron temperature enhancements observed in the auroral active topside ionosphere. Considering that such enhanced resistivity may exist over an altitude region of 1000–10000 km, runaway electrons of energies of a few hundred eV should be produced within the turbulent region as first suggested by *Swift* [1965], which is consistent with the EISCAT observations.

Paper V.

Paper V is a purely theoretical companion paper to paper IV, investigating the possible ionospheric electron and ion heating by three different field-aligned current instabilities. From one dimensional time-dependent calculations it is found that for field-aligned currents with strengths of a few μA m^{-2} the ion acoustic, the electrostatic ion cyclotron, and the Buneman instabilities can occur at altitudes above about 2000 km in the topside ionosphere. It is found that the resulting turbulence affects the transport properties in such a way that the field-aligned electric fields in turn produce greatly enhanced plasma temperatures through Joule heating. The temporal evolutions for the instabilities, as the heating of the electron and ion gases proceed, are investigated and the instabilities are found to be short lived and disappear after a few seconds due to the difference in the ion and electron heating rates. The calculations indicate that low-frequency turbulence is a major contributor in the energy balance of the topside ionospheric thermal plasma.

Paper VI.

Paper VI is a comment on another paper [*Collis et al.*, 1991] on the interpretation of naturally enhanced ion acoustic spectral lines, found in EISCAT data during conditions similar to the type 2 ion outflows discussed in paper 3. The authors of *Collis et al.* [1991] interpretated the enhanced ion acoustic spectra as due to the growth of ion acoustic fluctuations produced near the threshold condition of the electron-ion, field-aligned current driven, ion acoustic instability [*Kindel and Kennel*, 1971; *Rosenbluth and Rostoker*, 1962]. By applying such a method to fit the enhanced spectra, unrealistically large field-aligned currents of several mA m^{-2} had to be inferred. We present theoretical arguments against the possible existence of such large field-aligned currents in the auroral ionosphere. We also question the validity of the analysis method with regard to whether a linear theory can fit enhanced spectra which obviously correspond to a turbulent state of the ion acoustic fluctuations.

Paper VII.

Paper VII is a purely theoretical paper where another explanation for the production of the observed, naturally enhanced, ion acoustic spectral lines is tested and found to better explain such spectra than the method commented on in paper VI. The theory, which we present in paper VII, instead shows that the enhanced ion acoustic fluctuations arise naturally in a plasma unstable to a number of ion-ion two-stream instabilities, and that the observed ionospheric conditions during times of type 2 ion outflows (where these spectra typically can be found) are especially prone for these instabilities to develop. However, only a linear theory is developed and can therefore merely be applicable to weakly unstable plasmas, *near the threshold of the instability.* It is noted that it will become necessary to include non-linear terms in the calculations, as well as to introduce a correct description of the enhanced effective collision frequencies expected during ion acoustic turbulence conditions, to correctly reproduce the measured ion acoustic spectra.

Paper VIII.

Paper VIII presents observations which clearly indicate that the H^+-O^+ two-stream instability, indeed, can produce the observed enhanced ion acoustic fluctuations in the ionosphere. The field-aligned currents for a typical observed event are derived and found to be of the order of 5-50 μA m^{-2}. By using a linear dispersion surface program, which calculates growth rates for different instabilities, together with inferred values of the field-aligned currents, we are able to show that the electron-ion, current driven, ion acoustic instability, cannot be important for ionospheric plasma densities above about 10^9 m^{-3}. We also add a short discussion on the production ion outflows and runaway electrons as effects of ion acoustic turbulence.

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