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Physics of the Aurora

C.-G. Fälthammar
Department of Plasma Physics, Alfvén Laboratory.
Royal Institute of Technology, S-100 44 Stockholm, Sweden.

RESUMEN

La aurora, ya de por sí fascinante por su belleza y la multitud de sus formas, ha resultado aún más fascinante en términos de la Física que se puede aprender de su estudio científico. Observaciones *in situ* de la aurora y de los fenómenos relacionados con ella han sacado a la luz los procesos de la física de plasmas, cuya presencia tiene un profundo impacto en nuestro concepto del espacio que nos rodea. La mayoría de estos procesos están relacionados con procesos de aceleración auroral. Aunque se sabe desde hace tiempo que la aurora es causada por electrones de unos cuantos keV que inciden sobre la atmósfera superior, la forma en que estos electrones obtienen su energía ha sido un asunto crucial y controvertido. Actualmente existe una concordancia casi universal en que los campos eléctricos alineados a los campos magnéticos juegan un papel clave, lo que confirma lo predicho por Hannes Alfvén hace más de tres décadas. Se han reconocido tres mecanismos principales que hacen posible la existencia de tales campos. Es probable que todos ellos operen en la región de aceleración auroral, pero los papeles que cada uno de ellos juega aún no están determinados. También ha quedado claro que existe una intrincada relación entre estos campos y las diversas formas de interacción onda-partícula que involucran campos eléctricos dependientes del tiempo en un amplio rango de frecuencias.

Los campos eléctricos alineados con los campos magnéticos tienen consecuencias importantes sobre el comportamiento de un plasma, no sólo porque energetizan las partículas sino porque afectan también al comportamiento del plasma mismo, mediante la violación de la "condición de campo congelado". Por lo tanto, el entendimiento de estos campos constituye también una base importante para la comprensión de los plasmas cósmicos en general. Las mismas fuerzas que lanzan a los electrones aurorales hacia abajo también lanzan iones positivos hacia arriba, al interior de la magnetosfera. Esta expulsión puede ser tan abundante que en ocasiones una gran parte de la magnetosfera está dominada por plasma de oxígeno proveniente de la propia ionosfera de la Tierra, en vez de estarlo por el plasma de hidrógeno del viento solar. Por razones que apenas empezamos a entender, la expulsión es altamente selectiva. En otras palabras, constituye un mecanismo eficiente de separación química, cuya mera existencia era completamente inesperada hasta hace muy poco tiempo. Un mecanismo similar de separación puede operar en otros plasmas astrofísicos, de modo que la importancia de este descubrimiento podría tener un largo alcance. Alfvén ha enfatizado que las lecciones aprendidas en las regiones accesibles del espacio de plasma requieren un "cambio de paradigma" que afecte a toda la astrofísica, la cosmología y la cosmogonía. La mayoría de estas lecciones han provenido del estudio de los problemas relacionados con la aurora, y es posible que aún surjan más.

PALABRAS CLAVE: campos eléctricos alineados al campo magnético, aurora, aceleración de partículas.

ABSTRACT

The aurora, fascinating by its beauty and its multitude of forms, has turned out to be even more fascinating in terms of the physics to be learned from scientific study of it. *In situ* observations of the aurora and related phenomena have brought to light plasma physical processes, whose existence has a profound impact on our concept of space around us.

Most of these processes are related to the auroral acceleration process. Whereas it has long been known that the aurora is caused by electrons of a few keV energy impinging on the upper atmosphere, the way in which these electrons gain their energy has been a crucial as well as controversial issue. There is now almost universal agreement that magnetic-field aligned electric fields play a key role, in confirmation of a prediction by Hannes Alfvén more than three decades ago. Three main mechanisms that make such fields possible have been recognized. Probably all of them operate in the auroral acceleration region, but their relative roles are still to be determined. It has also become clear that there is an intricate interplay between these fields and various forms of wave-particle interactions involving time-dependent electric fields over a wide range of frequencies.

Magnetic-field aligned electric fields have important consequences for the behaviour of a plasma, not only in terms of its capability to energize charged particles but also for the dynamics of the plasma itself, *e.g.* by violation of the "frozen field condition". Therefore the understanding of such fields also forms an important basis for understanding cosmical plasmas in general.

The same forces that hurl the auroral electrons downwards also expel positive ions upwards into the magnetosphere. This expulsion can be so copious that occasionally large parts of the magnetosphere are dominated by oxygen plasma from the Earth's own ionosphere, rather than by hydrogen plasma from the solar wind. For reasons that we are only beginning to understand, the expulsion is highly selective. In other words, it constitutes an efficient chemical separation mechanism, whose very existence was completely unexpected until recently. As similar separation mechanisms may operate in other astrophysical plasmas, the significance of this discovery could be far-reaching.

It has been emphasized by Alfvén that the lessons learned in accessible regions of the space plasma necessitate a *change of paradigm,* which affects all of astrophysics, cosmology and cosmogony. Most of these lessons have come from study of problems related to the aurora, and there may still be more to come.

KEY WORDS: magnetic-field aligned electic fields, aurora, particle acceleration.

INTRODUCTION

One of the most magnificent among natural phenomena, the aurora, has captivated man's imagination since time immemorial and bred many myths devised to explain its origin in terms comprehensible to the cultural environment concerned.

As a subject of serious scientific study, the aurora has turned out to be both fascinating and rewarding. It is *fascinating* because of its complexity and its rich variety and because it is the result of physical processes in a state of matter that is rare on Earth but is overwhelmingly dominant in our universe. It is *rewarding,* because understanding it requires solving very fundamental physical problems, thereby enhancing our understanding of the universe we live in.

Historical notes

Early efforts by pioneers like Birkeland, Störmer and Alfvén to understand the physics of the aurora led to results of broad significance.

Kristian Birkeland was led by his studies of the aurora to the concept of magnetic-field aligned currents, now often called Birkeland currents. For many years this concept was disregarded, but once the relevant *in situ* measurements were made, the validity of Birkeland's concept was fully confirmed. Not only are the Birkeland currents crucial in the auroral process, but similar, magnetic-field aligned, currents are likely to be important in many other space and astrophysical plasmas.

Carl Störmer pioneered photographic triangulation, which made it possible to determine the altitude distribution of auroral forms. His extensive calculations of particle orbits, although intended to apply to auroral particles, became fundamental to a different branch of space physics, namely that of cosmic ray research. They also proved the existence of trapped orbits in a magnetic dipole field, a discovery whose full significance was realized only after the unexpected discovery of the Earth's radiation belts.

Hannes Alfvén has made a profound as well as far-reaching impact. In developing his theory of the aurora he found it necessary to invent a tool to facilitate the extremely laborious calculations of particle orbits. This led him to the invention of an ingenious perturbation method, and thereby to lay the foundations of the *adiabatic theory of particle motion,* which is now an indispensable part of fundamental plasma physics. By his discovery of a new kind of waves, now called Alfvén waves (and, in passing, the law of frozen-in magnetic field lines) he laid the foundations of *magnetohydrodynamics,* thereby opening a whole new branch of physics.

The aurora - a glimpse of the cosmical plasma

On the Earth the solid liquid and gaseous states dominate the environment, and the fourth state, plasma, is rare. The opposite is true for the universe as a whole, because the cold celestial bodies account for a negligible fraction of the mass of the universe, and virtually all astrophysical processes take place in a plasma environment. The realization of this should, according to Alfvén (1983), lead to a change of paradigm from an "optical universe" to a *plasma universe*.

The nearest visible manifestation of the plasma nature of the universe is the aurora. Already to the naked eye it hints at one of the persistent characteristics of the plasma universe, namely its tendency to form *filamentary structures.*

The aurora may even be partly responsible for the origin of life on Earth, because auroral processes in the upper atmosphere of the primordial Earth may have provided the necessary reactive environment for some crucial chemical syntheses (Arrhenius, 1990).

AURORAL EMISSIONS

The *immediate cause* of the aurora has been known for a long time, namely excitation of upper atmospheric atoms and molecules by energetic charged particles precipitating from space. Electrons (most of which have energy in the 1 - 10 keV range) generally dominate over the ions in terms of number flux by typically a factor 50, but by a more moderate factor (between 6 and 9) in terms of energy flux (Newell *et al.*, 1991).

Although the auroral spectrum is quite complex and consists of a large number of spectral lines and bands, a few lines are especially conspicuous.

The line that usually dominates is the "auroral line" at 5577 A in the yellow-green part of the spectrum, near the wavelength of maximum sensitivity of the human eye. This line in the auroral light was noted already by Ångström. Its identification as a "forbidden" transition in the oxygen atom was achieved by MacLennan in the 1920's. The 5577 A line is usually by far the strongest line in the visible part of the spectrum, but there are much stronger emission lines in the infrared.

Very strong auroras, reaching mid latitudes often have a red colour from the "forbidden" triplet 6300 A, 6364 A and 6391 A in the oxygen atom. Auroras reaching down to low altitude often have a red lower border caused by emissions from nitrogen molecules.

Of the energy carried by the auroral primary electrons only a minor part goes into auroral light emission. Most of it goes into heating the ambient medium (an estimated 50%), dissociation, ionization, excitation of vibrational states, etc. (Rees and Lummerzheim, 1991).

A comprehensive overview of the auroral spectrum can be found in books by Omholt (1971) and Vallance Jones (1974), and a review with references to recent work has been given by Vallance Jones (1991). The excitation and emission processes responsible for the spectrum have recently been reviewed by Rees and Lummerzheim (1991).

AURORAL OVALS

In a statistical sense, occurrence of auroras has maximum probability along two ringshaped regions around the magnetic poles of the Earth. These are the *auroral zones.* By definition these are stationary in time and in geographical coordinates (except on time scales long enough for the geomagnetic field to undergo large-scale change).

From a physics point of view the more interesting concept is that of the *auroral ovals,* which represent the actual global distribution of auroras at a given time. These are also ring-shaped, nearly circular, regions around the magnetic poles, but more excentric relative to these than the auroral zones. They are not defined in geographical coordinates but can be considered as fixed in inertial space coordinates, while the Earth rotates underneath them.

The size and shape of the auroral ovals, and hence of the "polar caps" enclosed by them, depend strongly on the properties of the solar wind. Particularly important in this context is the interplanetary magnetic field, *IMF* (see *e.g.* Akasofu and Roederer, 1984) and notably its southward component, B_z. This component plays a key role for the power input to the magnetosphere, as was early on demonstrated in a dramatic way by Burton *et al.* (1975). Later studies have sought to clarify in detail what combination of solar wind parameters has the strongest correlation with magnetospheric and auroral activity. One such combination is the epsilon parameter introduced by Perreault and Akasofu (1978), cf. also Akasofu (1991). A consensus has, however, not been reached yet. The azimuthal component, B_y, of the IMF also influences the auroral ovals, for a review see Nakai (1987). For a recent review of factors that control the auroral ovals, see Siscoe (1991).

The most drastic changes of the auroral oval are those that take place during magnetic substorms, and the typical features of which (rapid equatorward expansion followed by slow recovery) were described already in the classic work by Akasofu (1964). Examples of oval response to individual severe magnetic storms were reported by Meng (1984).

CONNECTION TO THE MAGNETOSPHERE

It is customary and uncontroversial to compare the discrete auroras to TV pictures projected onto the Earth's atmosphere by beams of primary electrons produced by complex plasma processes in the magnetosphere above. But when it comes to the question *how* the various elements of the auroral ovals connect to magnetospheric regions, there is still wide and open disagreement.

One reason for this difficulty is the fact that tracing of auroral magnetic field lines is subject to great uncertainty. Extensive measurements of magnetospheric magnetic fields for many years have provided an impressive data base on which quite sophisticated quantitative magnetic models have been based (see *e.g.* Tsyganenko, 1987, and references therein). While such models can give a good description of the average character of the magnetic field vector at a given location under given conditions, field line tracing over long distances remains uncertain because of integrated errors. This is so already in a static case, because auroral currents, too small in latitudinal scale to be included in global models, can cause substantial deviations, as shown for example by Lui and Krimigis (1984). The difficulties escalate when the dynamic time variations of the aurora have to be taken into account.

One view, advocated by Lyons (1991), is that the region of discrete nightside auroras is mapped along the plasma sheet boundary layer to the vicinity of the border between open and closed magnetic field lines. This would also be the location from which magnetospheric substorms start. There are, however, strong indications that magnetospheric substorm breakup takes place closer to the Earth, so that the substorm current wedge and the associated discrete auroras form well inside the region of closed magnetic field lines. This view is taken in near-Earth models of magnetic substorms (see *e.g.* Rothwell *et al.*, 1991). Arguments for the view that nightside discrete auroral forms map to regions within the central plasma sheet have recently been summarized by Galperin and Feldstein (1991).

According to several authors (Murphree *et al.*, 1981; Evans, 1985; Meng and Lundin, 1986) the midday section of the auroral oval exhibits a persistent auroral activity that is more or less independent of activity in the nightside oval. Thus the midday auroral region does not seem to be a mere extension of the nightside oval (Akasofu and Kan, 1980; Meng and Lundin, 1986).

The dayside discrete auroras have been interpreted in terms of impulsive injections into the magnetosphere of magnetosheath plasma (Eastman *et al.*, 1976; Bythrow *et al.*, 1981; Meng and Lundin, 1986). Such injections, proposed by Lemaire *et al.* (1979) and Heikkila (1982) (for a review see Lemaire and Roth, 1991) have also been invoked as causes of a reverse (dusk to down) electric field in the magnetospheric equatorial regions and an agent for transfer of momentum from the solar wind to the interior of the magnetosphere (Heikkila and Winningham, 1971; Heikkila, 1984; Lundin and Dubinin, 1985; Woch and Lundin, 1991).

The èxistence of such a dusk-to-dawn electric field near the magnetopause has been verified by satellite measurements (Mozer, 1984), but its significance remains controversial (Heikkila, 1986). A remaining mystery is how the magnetic-field aligned electric fields can be supported, which are needed to decouple the intruding plasma clouds at the passage through the magnetopause (by violating the "frozen-in field condition"). If this concept of dayside discrete auroras is correct, they are intimately related to one of the key magnetospheric plasma phenomenon still to be clarified, namely the entry of plasma into the magnetosphere.

Once the plasma clouds are inside the region of closed field lines, the magnetic mirrors will allow them to sustain magnetic-field aligned electric fields in which auroral primaries can be accelerated. Stasiewicz (1985) has derived expressions for the resulting electric fields.

AURORAL CURRENT SYSTEM

One of the very first results of scientific study of the aurora was the discovery by Hiorter and Celsius in 1741 that aurora is closely related with magnetic disturbances and hence with electric currents. A mathematically elegant method of representing magnetic disturbances from electric currents in space was introduced by Chapman (1927), who used an *equivalent current system* confined to a spherical shell (representing the ionosphere) and thus consisting of horizontal currents only. But the convenience of using such a representation contributed to the neglect for many years of the fact that the real auroral current system is three-dimensional and contains also magnetic field aligned currents, as already earlier realized by Birkeland (1913). In a historical review, Dessler (1984) has illustrated how deeply rooted the concept of two-dimensional current systems was: even when magnetic signatures of Birkeland currents were directly measured in space they were first misinterpreted in terms of standing Alfvén waves.

It is now well established that the electrojets are fed by Birkeland currents as schematically illustrated in Fig. 1. The *large scale* distribution of the incoming and outgoing Birkeland currents has been extensively mapped. A typical pattern is shown in Fig. 1. According to a now well established nomenclature, the inner and outer current systems in Fig. 2 are called the Region 1 and Region 2 currents respectively. During conditions of northward IMF an additional system, the NBZ current system (Iijima *et al.*, 1984) develops poleward of the Region 1 and 2 system. For an extensive review, see Potemra (1988).

The *fine structure* of auroral currents is still not well known. Part of the reason is that there is no method of directly measuring electric currents in space. In practice they have to be inferred from sequential single point measurements of the magnetic field along a spacecraft orbit, and this requires assumptions that may or may not be fulfilled. Systematic multipoint measurements, as in the forthcoming Cluster project, will greatly improve our knowledge in this respect.

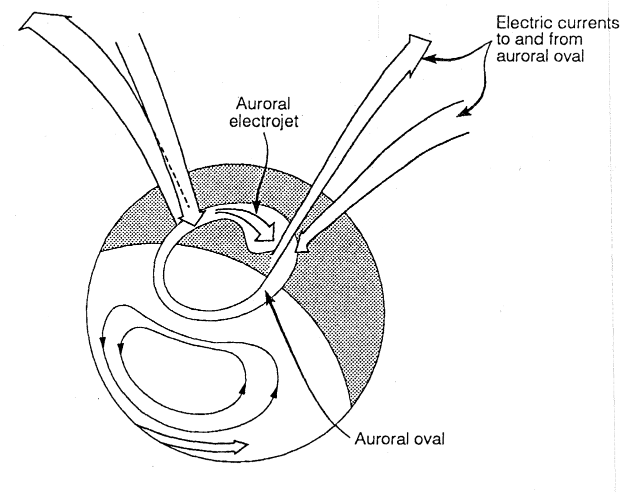


Fig. 1. Schematic representation of the auroral electrojet system and Birkeland currents feeding it (Lanzerotti, 1988).

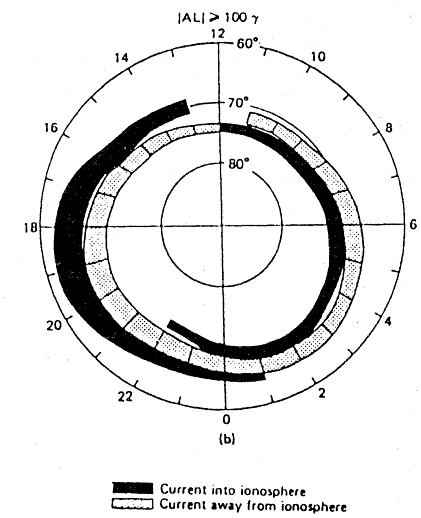


Fig. 2. Summary of the distribution of Birkeland currents during magnetically active periods (Iijima, 1991).

ACCELERATION PROCESSES

A crucial problem in auroral physics is how the auroral primaries are accelerated to their observed energy. This is also a problem of general interest, since a remarkable capability of accelerating charged particles is an outstanding and general characteristic of space and astrophysical plasmas. This capability is all the more remarkable because the acceleration has to take place in a medium devoid of insulators, an absolute prerequisite in man-made accelerators.

In bold defiance of prevailing theoretical convictions at the time, Alfvén (1958) proposed that auroral primaries are accelerated in electrostatic potential drops above the ionosphere, but at that time few dared to take him seriously. Yet, as soon as *in situ* measurements of the electrons that cause the aurora were made, indications were found that Alfvén's idea was indeed right. Thus McIlwain (1960), Albert (1967) and Evans (1968) observed electron distribution functions indicative of electrostatic acceleration and interpreted them accordingly.

Gradually, more and more evidence has accumulated, and there is now almost complete consensus that magnetic-field aligned electric fields do play a key role in the auroral acceleration process, but also that complementary non-adiabatic processes, including various types of wave-particle interaction, are important.

The observational evidence invoked in favour of magnetic-field aligned electric fields include:

¤ Precipitating auroral electrons with a velocity space distribution as if accelerated through a potential drop.

¤ Widened electron loss cones.

¤ Upgoing beams of ions with a distribution function as after passage through a potential drop.

¤ Artificial ion beams injected upward from the ionosphere and observed to undergo sudden acceleration along the magnetic field.

¤ Artificial electron beams injected upwards and reflected in a way consistent with a potential barrier above (although alternative interpretations may not be excluded).

¤ Comparisons of electric fields measured at high and low altitude, which show that the spatial distributions differ in a way consistent with a magnetic-field aligned electric field in the intervening altitude range.

¤ Electric field measurements revealing the existence of numerous small scale electric double layers, which together may account for potential drops of several kV.

¤ Direct measurement of magnetic-field aligned components associated with strong localized auroral electric fields.

Based on the combined evidence (for a review, see *e.g.* Fälthammar, 1983) there is now almost total consensus that the auroral acceleration involves combinations of electrostatic acceleration with nonadiabatic, diffusive processes. But even so, a full explanation of all observed features of the auroral particle distributions is still not at hand.

A dissenting view voiced first by Bryant (1976), Whalen and Daly (1979) and later in a number of papers by these authors, advocates that magnetic-field aligned (dc) electric fields should not be needed at all in the auroral acceleration process. In a recent paper (where references can also be found to previous work) Bryant *et al.* (1991) claim that stochastic acceleration of electrons by electrostatic waves of the lower hybrid type, powered by ion streams incident from the outer magnetosphere, can explain many features of the auroral electron distribution, such as:

¤ A bulge, plateau or peak in the energy distribution.

¤ Magnetic field alignment at energies below the peak.

¤ An invariant low-energy region.

¤ A steeply falling edge above the peak.

¤ A double peak.

¤ Electron conics.

¤ An upward beam.

¤ Counterstreaming electrons.

¤ A horseshoe-like distribution.

¤ Modulations of the field aligned current and energy flux.

Such results are not really in conflict with the consensus view, according to which the auroral acceleration depends on *both* magnetic-field aligned electric fields and stochastic processes and that, even so, we have not yet found a combination that can account for everything. What *is* in conflict with the consensus, and with hard evidence, is the credo that in the end everything can be explained by stochastic processes only, and that magnetic-field aligned electric fields do not play any role.

An important extension of the theory of dc electric field acceleration was introduced by Hultqvist (1988) and Hultqvist *et al.* (1988) by showing that simultaneous acceleration of electrons and ions can result from a magnetic-field aligned electric field with low frequency fluctuations superposed on a dc level, as further discussed by Block and Fälthammar (1990).

For a recent review of auroral acceleration, see Lundin and Eliasson (1991).

MAGNETIC-FIELD ALIGNED ELECTRIC FIELDS

The presence of magnetic-field aligned electric fields in the auroral acceleration region proves that such fields can, indeed, exist in collisionless space plasma, and this has important implications in a much wider context than just auroral physics. There are two main reasons for this. First, such fields are a supremely efficient means of accelerating charged particles (and efficient charged-particle acceleration is one of the outstanding characteristics of cosmical plasmas). Second, existence of such fields (impossible according to classical plasma theory) is a necessary condition for violating the "frozen-field condition" and thus has a potentially profound impact on the dynamics of collisionless plasmas.

The evidence for magnetic-field aligned electric fields in the auroral acceleration region is now so extensive (see *e.g.* Fälthammar, 1983; Block and Fälthammar, 1991), that an account cannot be included here, beyond the short list given above and a couple of examples.

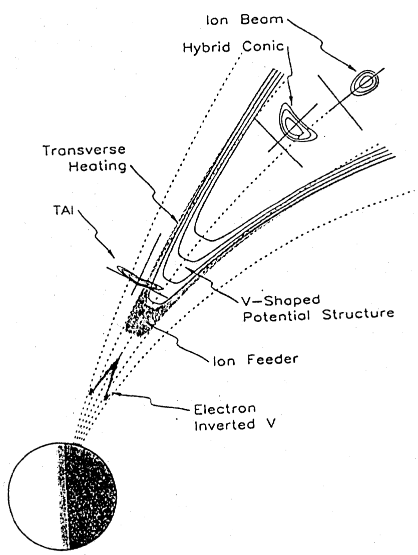


Fig. 3. Consensus concept of the auroral acceleration region (Shelley and Collin, 1991).

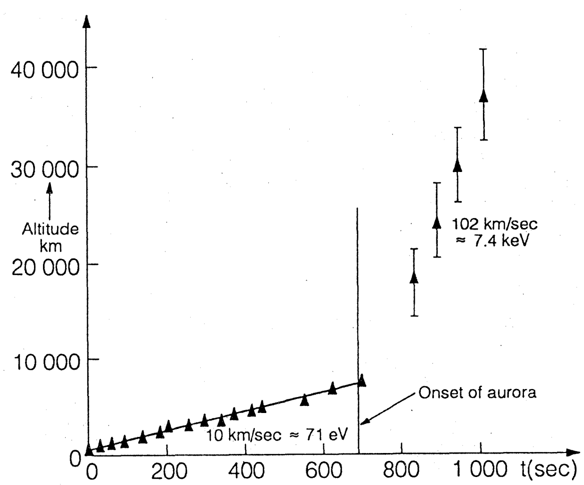


Fig. 4. Trace of the tip of a Ba+ jet emitted from a rocket payload. The sudden change of slope implies a velocity change corresponding to an energy increase of 7.4 keV (Haerendel *et al.*, 1976).

The first example is the classical, and still standing, interpretation of "inverted V" precipitation in terms of electrostatic acceleration (Fig. 3). The other is the result of an active rocket experiment (Fig. 4), where an artificial ion beam is suddenly accelerated upward along the geomagnetic field line at the onset of an aurora on the same field line. No other reasonable explanation has been found than the acceleration in a dc electric potential of 7.4 kV.

Given the existence of magnetic-field aligned electric fields, there remains the question how they are possible, *i.e.* why - in the absence of collisions - they are not "short-circuited" by electrons moving freely along the magnetic field lines. The answer to this question must be some mechanism that can balance the momentum imparted to the electrons by the magnetic-field aligned electric field. As shown by Fälthammar (1978), the possibilities are few:

Origin of force	Resulting phenomenon
AC magnetic field	-
AC electric field	Anomalous resistivity
DC magnetic field	Mirror-supported electric field
Charge carrier inertia	Electric double layer

Anomalous resistivity

Anomalous resistivity is sometimes invoked as a possible mechanism for supporting magnetic-fields above the aurora. There are, however, difficulties with this concept. For one thing it requires excessive levels of rms electric field (Shawhan *et al.*, 1978). For another, it implies a local heating rate incompatible with observations (Block and Fälthammar, 1976).

Magnetic-mirror supported electric fields

Magnetic-mirror supported electric fields are of two main types. The first, which depends on differential anisotropy of trapped particles and can exist even without a net current, was proposed by Alfvén and Fälthammar (1963). The other, which requires an electric current out of a magnetic mirror, was analyzed by Knight (1973) and has been further generalized by later authors, *e.g.* Fridman and Lemaire (1980). Applied to the auroral acceleration region it exhibits some interesting features illustrated in Fig. 5.

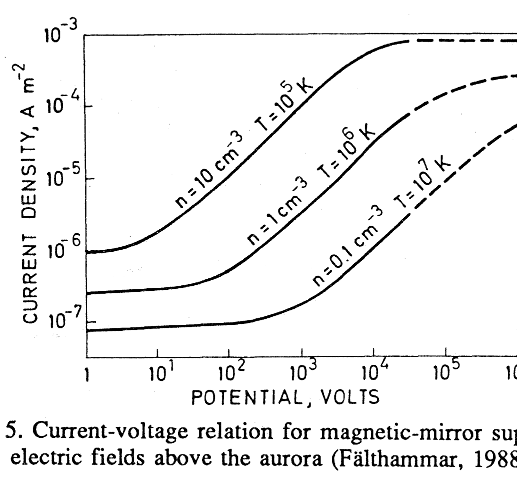


Fig. 5. Current-voltage relation for magnetic-mirror supported electric fields above the aurora (Fälthammar, 1988).

(1) A small but finite current can be drawn with negligible voltage.

(2) A saturation current exists that cannot be exceeded however high voltage is imposed.

(3) A middle region of considerable extent (about 3 powers of ten in voltage and current) exists, where the current density is directly proportional to the voltage.

For conditions typical of auroral flux tubes, the slope in the linear regime corresponds to a conductance of 3 ($\mu A/m^2$)/kV. On the other hand there exists no local relation between current density and electric field, *i.e.* the concept of conductivity does not apply.

A corollary of the current-voltage relation is a corresponding relation between acceleration voltage and energy flux, which is quadratic in the region of linear conductance. That relation has been beautifully confirmed, for example in the rocket experiments by Lundin and Sandahl (1978) and the satellite experiments by Menietti and Burch (1981). Viking results reported by Brüning *et al.* (1990) have shown examples where the saturation region is reached in the interior of dayside auroral arcs.

Electric double layers

The electric double layer is a phenomenon well-known from laboratory experiments and mercury rectifiers. It was also this phenomenon that Alfvén (1958) suggested to be responsible for auroral acceleration.

Electric double layers are of two kinds, *weak* double layers with potential drops comparable to the voltage equivalent of the ambient alectron thermal energy, and *strong* double layers with potentials much greater than that. The strong double layers have a thickness of only some tens of Debye lengths, and the weak double layers even less.

From particle measurements that reveal the presence of magnetic-field aligned electric fields it is very difficult to determine their spatial distribution, *i.e.* whether they are concentrated to double layers or not (Greenspan *et al.*, 1981; Burch (1991). On the other hand, the flanks of the potential structures associated with magnetic-field aligned electric fields (cf. Fig. 3) are frequently observed as "electrostatic shocks" (Mozer *et al.*, 1977). An example from the Swedish satellite Viking is shown in Fig. 6. Although such measurements allow determination of the potential below the satellite they still do not reveal the potential distribution along the magnetic field, *i.e.* whether it is double-layer like or not.

On the other hand, *weak* electric double layers occur profusely, together with soliton-like structures, and moving rapidly upward along the magnetic field (5 - > 50 km/s) they are easily observed. First seen with the S3-3 satellite (Temerin *et al.*, 1982; Mozer and Temerin, 1983)

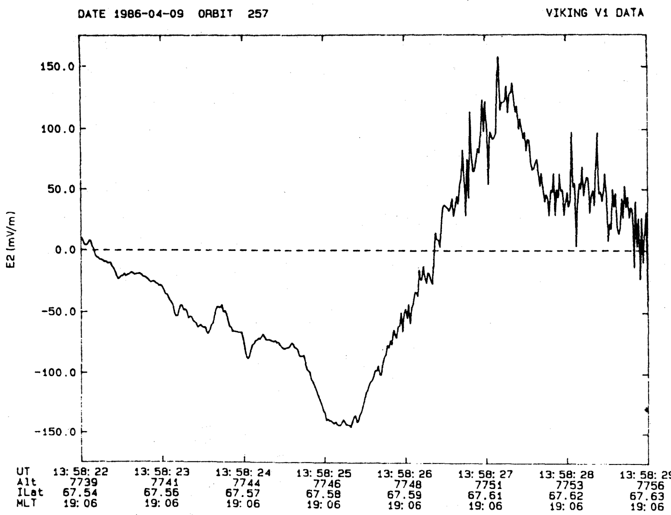


Fig. 6. Close-up view of electrostatic shock observed with the Viking satellite (Fälthammar *et al.*, 1987).

they have been studied in detail with the Viking satellite (Boström *et al.*, 1988). Although each of them has a potential drop of less than 1 V, they are so numerous that they may account for a total potential drop of several kV.

ION BEAMS AND CONICS

The auroral acceleration region does not only produce precipitation, of many electrons, into the ionosphere. It also ejects ions upward into the magnetosphere. The upward ion fluxes are of two kinds, *beams* and *conics.*

Beams

Upward-moving ion beams are by necessity created by the same magnetic-field aligned electric fields that hurl auroral primary electrons downward. Comparisons of measurements on one and the same satellite of ion beam energy on one hand and widened electron loss cones on the other (both of which are due to the electric potential drop below the satellite) show a generally good agreement (Reiff *et al.*, 1988; Block and Fälthammar, 1991). (In the comparison account has to be taken of the fact that part of the directed ion energy becomes thermalized in passage.) As can be expected, ion beams occur preferentially in the evening sector where the inverted-V precipitation ascribed to magnetic-field aligned electric fields are most common, and preferentially at high altitude, above 5000 km (Shelley and Collin, 1991). They usually have a high correlation with upward Birkeland currents.

Conics

The ion *conics* are named for their distribution in velocity space, which is characterized by an off-axis maximum around a symmetry axis parallel to the magnetic field. They are generated by transverse acceleration followed by expulsion by the magnetic mirror force, which transforms some of the energy residing in velocity transverse to the magnetic field into energy of magnetic-field aligned velocity. Transverse ion acceleration is a common occurrance at all altitudes throughout the aurora oval, with some preference for the morning side.

The exact mechanism by which the transverse energization occurs is still a controversial issue. Proposed accelerating agents include electrostatic ion cyclotron waves (Ungstrup *et al.*, 1979; Klumpar, 1979; Rönnmark and André, 1991), electromagnetic ion cyclotron waves (Chang *et al.*, 1986), lower hybrid waves (Chang and Coppi, 1981), broad band noise (André *et al.*, 1990), non-linear interaction with waves below the gyrofrequency (Temerin and Roth, 1986), double cyclotron absorption and oblique electrostatic shocks (Lennartsson, 1980; Borovsky, 1984; Greenspan, 1984). An interesting recent possibility has been proposed by Lundin and Hultqvist (1989) who on the basis of the electric field measured with the Viking satellite (Block *et al.*, 1987) found that in the auroral acceleration region the space and time variations of the electric field are strong enough to extract cold ions from the ionosphere by transverse acceleration.

Hybrid conics

Hybrid conics also occupy conical regions in velocity space, but with the apex of the conic at a finite upward parallel velocity. A common interpretation of these is, of course, transverse acceleration combined with electrostatic parallel acceleration. Hybrid conic distributions have, however, also been simulated by purely stochastic acceleration (Temerin, 1986). Chang (1986) and Retterer *et al.* (1987) used a model of ion cyclotron resonance with broadband electromagnetic turbulence to numerically reproduce hybrid conics.

At high altitude above the nightside oval magnetic-field aligned post-acceleration of conics may make them too narrow to be resolved, and they may therefore be taken for beams.

Whereas O^+ dominates the ion outflow, H^+ and He^+ are observed as well. The multi-component character of the ionospheric plasma has to be taken into account in the analysis of the transverse heating (see *e.g.* Ashour-Abdalla *et al.*, 1987, 1988). A recent review of auroral ion acceleration has been given by Shelley and Collin (1991), who have compiled the following data on ion outflow.

As can be noted in Table 1 (from Collin *et al.*, 1984), the outflow of ions is enhanced during magnetically disturbed times. The total outflow during disturbed times has been estimated at 10^{26} ions per second and about a third of that during quiet times (Chappell, 1987).

AURORAL WAVES

In space plasma a great variety of wave modes are possible. The two main categories are electromagnetic and electrostatic waves, the latter characterized by curl **E** = 0.

Table 1

The estimated terrestrial ion outflow in the energy range 0.5 to 16 keV for O^+ and H^+ during magnetic storms and quiet times.

		Range	Mean
Quiet time			
	H^+	0.7 - 1.4 x 10^{25} s^{-1}	1.1 x 10^{25} s^{-1}
	O^+	0.15 - 0.4 x 10^{25} s^{-1}	0.27 x 10^{25} s^{-1}
	Total	0.85 - 1.8 x 10^{25} s^{-1}	1.3 x 10^{25} s^{-1}
	O^+/H^+	0.1 - 0.4	0.25
Storm time			
	H^+	1.5 - 4.5 x 10^{25} s^{-1}	3.0 x 10^{25} s^{-1}
	O^+	3.5 - 5.0 x 10^{25} s^{-1}	4.2 x 10^{25} s^{-1}
	Total	5.0 - 9.5 x 10^{25} s^{-1}	7.2 x 10^{25} s^{-1}
	O^+/H^+	0.7 - 2.1	1.4

The range indicates the uncertainty of the estimate resulting from both counting statistics and uncertainties in the identification of the newly outflowing ions.

The frequency ranges of the six most important *electromagnetic* modes are summarized in Fig. 7a. The characteristic frequencies of *electrostatic* modes that can exist on auroral field lines are summarized in Fig. 7b.

The most important waves in the auroral region are

Electromagnetic	Electrostatic
Auroral kilometric radiation	Upper hybrid waves
Auroral hiss	Electrostatic electron cyclotron waves
ELF noise bands	Lower hybrid waves
Low frequency electric and magnetic noise	Electrostatic ion cyclotron waves
Alfvén waves	Broadband electrostatic noise

The frequency regimes concerned are shown in Fig. 7. Even a brief review of the many modes would be beyond the scope of this presentation, and only a few comments will be given. For a systematic discussion, see for example Gurnett (1991).

Auroral kilometric radiation

The auroral kilometric radiation, AKR, is the highest-frequency radiation generated in the auroral region. The typical frequency range is 50 - 400 kHz. Because of the intervening dense plasma regions, it cannot propagate to the Earth's surface. Therefore it was unknown until satellite measurements became available. On the other hand, it radiates freely into space, making the Earth a strong radio source, which emits 10^7 - 10^8 W, occasionally as much as 10^9 W. This radiation is primarily generated in the right-hand extraordinary mode (cf. Fig. 7) and only a small part, about 2%, in the left-hand ordinary mode.

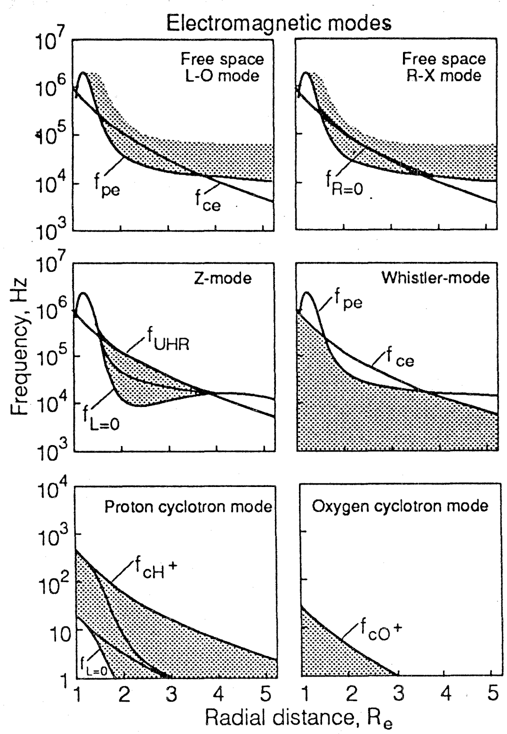
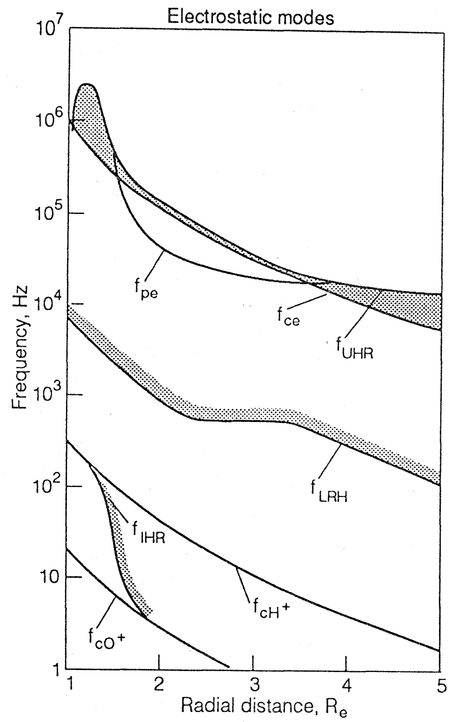


Fig. 7. a. Frequency ranges of the six most important electromagnetic wave modes in the auroral ionosphere. (After Gurnett, 1991.)



b. Characteristic frequencies of electrostatic wave modes on auroral field lines. (After Gurnett, 1991).

Many theories have been proposed to explain the AKR. It is generally believed that it is due to a cyclotron maser mechanism. The free energy source for these waves has been proposed to be the loss cone in the auroral electron distribution. According to new results, based on data from the Viking satellite, the energy source seems to be the loss cone distribution of an electron population trapped by a magnetic mirror below and an electric potential barrier above (Louarn *et al.*, 1990). This result fits in a very satisfactory way into the general picture of the auroral acceleration region.

Low frequency electric and magnetic field noise

On auroral magnetic field lines strong fluctuations of electric and magnetic fields are observed. Some of these are purely electrostatic, others contain magnetic as well as electric components.

When magnetic components are observed, they are usually strongly correlated with the electric components. Such correlation can arise in two ways.

1) If the magnetic fields derive from Birkeland currents, they will be associated with electric fields, due to the ionospheric closure currents, with such a direction that the Poynting vector is directed downward. The ratio of electric to magnetic field variations will be given by $1/\mu_0\Sigma_P$, where Σ_P is the height-integrated Pedersen conductivity in the ionosphere below.

2) If the magnetic fields are due to Alfvén waves, they will also be associated with electric fields. In this case, the ratio is determined by the local Alfvén velocity, V_A, but they also depend on whether the waves are propagating or standing.

As a result there are two competing interpretations of low frequency electric and magnetic fluctuations: one ascribing them to stationary *Birkeland currents*, the other to propagating or standing *Alfvén waves*. The distinction between these two interpretations is difficult for at least two reasons.

1) The values of $1/\mu_0\Sigma_P$ and V_A are rather similar, so that observed correlations are often compatible with either interpretation.

2) It is likely that both stationary structures and Alfvén waves occur. For example, Alfvén waves are the natural intermediaries in the transient process of setting up a quasi-stationary structure. Analysis of the phase relation between electric and magnetic field may help make the distinction.

Alfvén waves

In the acceleration region above auroras the plasma density is often extremely low, and the Alfvén velocity correspondingly high. The Viking satellite often encountered regions where the Alfvén velocity was as high as 20 000 km/s or more. In such regions the B/E ratio is extremely small (namely $1/V_A$) and Alfvén waves have magnetic field components too weak to be detected. On the other hand, the electric field detector on the Viking satellite easily recorded these Alfvén waves by their electric fields, and thereby opened a whole now parameter range of Alvén waves to direct observation (Fälthammar *et al.*, 1987).

AURORAL ELECTRODYNAMICS

In understanding the global electrodynamics of the aurora it has always been a handicap that satellites make only sequential one-point measurements, and that the repetition rate, limited by the orbital period of 90 minutes or more, can be too slow compared to the time scales of change.

An important tool for overcoming this difficulty is the development of global models of auroral electrodynamics, where the local measurements by one or more satellites are combined with remote sensing data such as ultraviolet pictures of the whole auroral zone and appropriate ground based data, using a realistic electrodynamic model of the ionosphere. Particularly successful models of this kind have been developed by Marklund *et al.* (1987, 1988) and Richmond and Kamide (1988). These allow determination of "instantaneous" distributions of electric fields, currents, etc. Fig. 8 shows an example, where the "instantaneous" electrostatic equipotentials calculated from the Marklund model are superimposed on an image of the northern auroral distribution from the UV camera on the Viking satellite, in this case what is called a theta aurora.

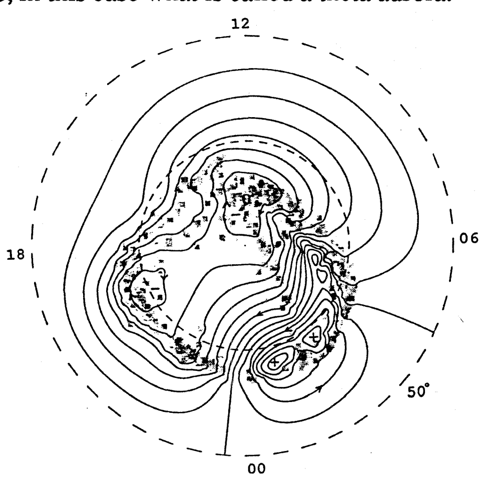


Fig. 8. Electric equipotential lines determined from the Marklund-Blomberg model superimposed on the auroral oval as determined by the Viking UV imager (curtesy of G. Marklund).

CHEMICAL SEPARATION

As a consequence of the previously mentioned profuse outflow of ionospheric ions, large parts of the magnetosphere become populated mainly with plasma of terrestrial, rather than solar, origin. The concept of a closed loop of plasma exchange between the magnetosphere and ionosphere was proposed by Block and Fälthammar (1969) and by Axford (1970). It became a very real possibility when Shelley *et al.* (1972) discovered the ionospheric outflows, and Chappell (1987) even argued that the ionosphere by itself is a fully adequate source of magnetospheric plasma. As also ions of unquestionable solar wind origin are observed (Krimigis, 1991), the question is not whether both sources contribute, but in what proportion. This is still an open issue.

As the upper parts of the ionosphere are dominated by hydrogen and helium ions, it is remarkable that oxygen ions are usually the dominating component where terrestrial plasma populates the magnetosphere. This is a manifestation of selectivity in the transport and acceleration processes involved. Hultqvist (1983) showed that the ions subject to acceleration must originate at ionospheric levels where the composition is very different from that of the ion outflows, *i.e.* the process of upward transport has to be selective. Furthermore, the acceleration process itself may be highly selective.

Whatever the actual transport and acceleration processes involved are, the fact remains that magnetospheric plasma of ionospheric origin has a very different composition than the (relevant layers of the) ionosphere itself. This means that in the Earth's ionosphere-magnetosphere system there exists an efficient chemical separation mechanism, which was completely unexpected and is not fully explained even today. This is a lesson that shold be kept in mind when considering abundance ratios in other cosmical plasmas. They, too, may practice their own chemical separation, and abundances in observable surface layers may be deceitful witnesses of what is hidden below.

CONCLUDING REMARKS

The Earth's environment in space, as we now know it, is distinctly different from what was expected before the advent of *in situ* measurements. The reason for this metamorphosis is that the behaviour of the space plasma is dominated by plasma physical processes that were previously in some cases disregarded, in other cases altogether unknown. Most of these processes are directly or indirectly involved in the physics of the aurora. Plasma processes must be expected to be similarly important in other cosmical environments, as these are virtually without exception in the plasma state. What has already been learned, and what remains to be learned in the study of the aurora provides a better understanding of such plasma processes and thereby a safer basis for the understanding of our plasma universe in its present state (astrophysics) as well as how it evolved to that state (cosmology).

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C.-G. Fälthammar,

Department of Plasma Physics, Alfvén Laboratory,
Royal Institute of Technology, S-100 44 Stockholm, Sweden.