# Observations of Auroral Zone Processes by the Viking Satellite [and Discussion]

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# Observations of auroral zone processes by the *Viking* satellite

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[Plate 1]

The scientific results of the *Viking* project obtained up to the spring of 1988 are reviewed. During solar minimum conditions, when *Viking* was operated, the dayside auroral oval has been found to be the most active part, except during strong substorms and storms. A number of new auroral morphological features have been seen with the imaging experiment onboard *Viking*. Large-amplitude slow fluctuations of the electric field heat the ionospheric plasma and pump up the magnetic moment of the ionospheric ions so that they may leave the ionosphere. These fluctuations also accelerate ionospheric electrons upwards along the magnetic field lines. The importance of the acceleration of auroral electrons into the atmosphere by magnetic field-aligned potential differences has been confirmed. The first satellite-borne plasma wave interferometer on *Viking* has made it possible to determine a number of characteristics of the 'weak' double layers, seen first by the *S*3-3 satellite. A large number of these along the magnetic field lines produce large electric potential differences. Many new results concerning wave–particle interactions have been obtained, of which a few are presented here.

## Introduction

The results presented in this report have been obtained by many different members of the *Viking* scientific team, comprising more than 40 members from nine countries and led by six principal investigators for onboard measurements. These were:

L. Block, Sweden, electric field measurements;
T. Potemra, U.S.A., magnetic field measurements;
R. Lundin, Sweden, particle measurements;
G. Gustafsson, Sweden, low-frequency plasma waves;
A. Bahnsen, Denmark, high-frequency plasma waves;
S. Murphree, Canada, imaging experiment.

There was also a substantial coordinated suborbital measurement programme. Results from that are reported by H. Opgenoorth (this Symposium). For information about the *Viking* satellite and the experiments onboard, see, for example, Hultqvist (1987*a*).

In at least five areas of space physics, results from *Viking* have had a major impact: the global distribution of magnetosphere–ionosphere interactions; the auroral morphology and substorm dynamics; the heating and expulsion of ionospheric plasma into the magnetosphere; the field-aligned acceleration of auroral electrons into the atmosphere; and wave generation. This report contains brief summaries of the scientific contributions to these five areas as of the spring of 1988. There are certainly additional areas where *Viking* has contributed and will contribute significantly, but those have not been included here because in the author's judgement it is still too early for a summary.

## GLOBAL DISTRIBUTION OF MAGNETOSPHERE–IONOSPHERE INTERACTIONS

The imaging experiment on *Viking* (Anger *et al.* 1987*a*) has for the first time made the daytime aurora almost as accessible for observations as the nighttime aurora. The *Viking* imager results have demonstrated that the dayside part of the auroral oval, in periods around the minimum of the solar cycle when *Viking* was in operation, is generally more active than the nightside oval, except during larger substorms and storms (Hultqvist & Lundin 1987). The relative importance of the dayside oval for the magnetosphere–ionosphere interactions is greater than previously appreciated. It is, of course, nothing new that the polar cusp is a region of more or less continuous penetration of magnetosheath plasma down to ionospheric altitudes, but that the dayside part of the auroral oval is generally more active in terms of energetic particle acceleration and precipitation than the nightside part in solar minimum years does not appear to have been realized before *Viking*. The energies of the accelerated particles are, however, generally somewhat lower than found in the nightside auroral oval during active periods.

*Viking* spent a large fraction of its measurement time at medium altitudes (5000–13500 km) in the polar cusp and cleft regions. It has therefore been possible to study these regions in somewhat greater detail than has been available before for solar minimum conditions. The cusp 'proper' is a limited central region near noon in the dayside oval (Lundin 1988*b*; Kremser & Lundin 1989; Hultqvist & Lundin 1987). There the magnetosheath plasma penetrates generally more or less unchanged down to the upper ionosphere. The distribution is relatively smooth over the cross section of the cusp proper. In the cleft region, i.e. outside the cusp proper in the dayside auroral oval, the fluxes are lower but generally much more structured in most parameters. This is illustrated in figure 1, plate 1, which shows all sorts of structures in the distributions of both ions and electrons at an altitude of 13000 km in the morning sector of the cleft.

## AURORAL MORPHOLOGY AND SUBSTORM DYNAMICS

As the imaging experiment on *Viking* had a better resolution in time and space and a better contrast on the dayside of the Earth than earlier ones, it is not surprising that it has provided us with new knowledge about the dayside aurora. The Canadian experiment's team, with first C. Anger and later S. Murphree as principal investigators, have reported several new results and others are in preparation for publication. Here we can only list some of these results with references.

1. The polar cap arcs frequently constitute the boundary between closed field lines on one side and within the arc and open field lines (the polar cap) on the other side. Sometimes, however, the field lines appear to be open on both sides of it with the polar cap arc thus representing a bifurcation of the magnetospheric lobe (Murphree, personal communication 1988). In such cases, the polar cap arc has been found to join the dayside oval at roughly a right angle. Such polar cap arcs seem to appear mainly in away sectors of the solar wind and when $B_z > 0$.

2. Large-scale curls are seen also in the dayside aurora, indicating that velocity shear and the Kelvin–Helmholtz instability also operate on the dayside (Murphree, personal communication 1988).

3. Polar cap arcs, connected with the dayside auroral oval at both ends and shaped as the

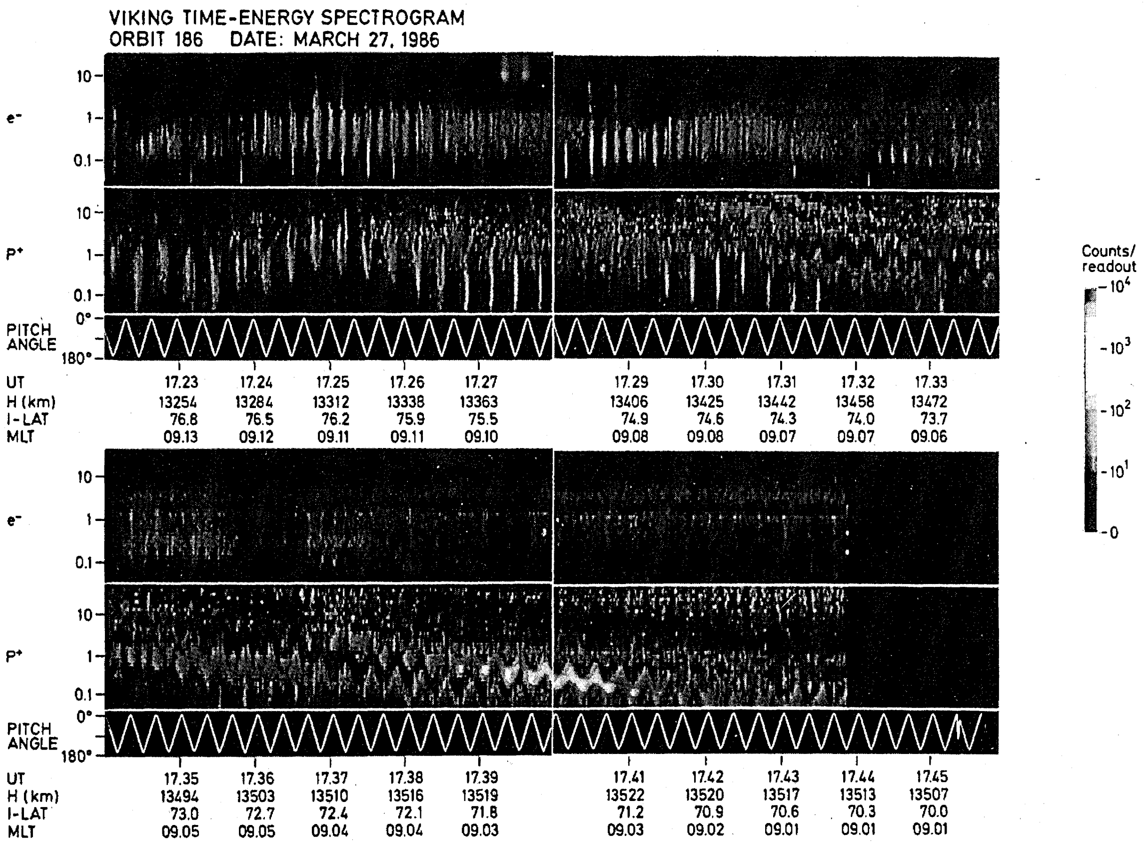

FIGURE 1. Energy–time spectrogram for ions and electrons obtained in the cleft region of the dayside oval (orbit 186). Each spectrogram displays counts accumulated against energy in 32 energy steps within 0.6 s, corresponding to a pitch angle resolution of 5°. The lower panel displays the pitch angle against time (0° corresponds to downcoming particles). H is height, I-LAT is invariant latitude, MLT is magnetic local time.

flow lines of the convection in the polar cap, have been observed (Murphree, personal communication 1988). These observations indicate that velocity shear in the convection motion may be of importance for arc formation in the polar cap.

The *Viking* imager has also provided new insights about the nightside aurora, which is perhaps more remarkable as the nightside aurora has been studied for quite a long time.

4. The substorm expansion in the midnight region is primarily directed eastward and westward along the poleward arc of the quiet auroral oval. A bulge may develop either immediately or later (Anger *et al.* 1987*b*; Rostoker *et al.* 1987).

5. There is generally no westward motion of auroral forms associated with westward travelling surges (Anger *et al.* 1987*b*).

6. In the pre-midnight sector the most common direction of motion is eastward (Shepherd *et al.* 1987).

7. The aurora on both the nightside and the dayside of the Earth often contains 'hot spots' which come and go within minutes. There may be many such spots appearing like pearls on a string, with disturbances between spots of order 1.0–1.5 h on the dayside and less than 1 h on the nightside. There are indications that they are spiral-shaped folds, most likely caused by the Kelvin–Helmholtz instability (Lui *et al.* 1987; Murphree and Vo & Venkatasan, personal communication 1988).

## HEATING AND EXPULSION OF IONOSPHERIC PLASMA INTO THE MAGNETOSPHERE

The electric field and low-frequency plasma wave experiments on *Viking* have demonstrated the frequent occurrence of very low-frequency fluctuations of large amplitudes in the electric field. This is illustrated by figures 2 and 3. Figure 2 shows the time series observation of the electric field experiment for two components, $E_1$ being along the projection of the magnetic field lines on to the spin plane of *Viking* and $E_2$ in the same plane but perpendicular to $E_1$. The angle between the magnetic field lines and the spin plane was 6° in the period shown. As can be seen, the perpendicular amplitude of the fluctuations ($E_2$) reached several hundred millivolts per metre and $E_1$ tens of millivolts per metre. The period with the most intense electric field turbulence in figure 2 is identical with the period with elevated ion conics and strictly field-aligned low-energy upward electron beams in figure 1.

A power density spectrum of the low-frequency variations of the perpendicular electric field component is shown in figure 3 for a time in the middle of the period with strong turbulence in figure 2. The spectrum peaks at or below 1 Hz and is more or less monotonically decreasing with increasing frequency. The power density in figure 3 at 1 Hz is at least three orders of magnitude larger than that found in the period before the turbulence in figure 2. The magnetic field measurements showed no observable variations corresponding to those seen in the electric field. The fluctuations in the electric field are therefore likely to be electrostatic.

The importance of these intense very low-frequency fluctuations of the electric field for the magnetosphere–ionosphere interaction seems not to have been fully realized before. It appears that some of the more important new results from the *Viking* project are associated with these fluctuations. They are intense enough and slow enough compared with the ion gyroperiods to start up fast $\boldsymbol{E}\times\boldsymbol{B}$ drift of the plasma (Lundin 1988*a*). An amplitude of the order of 100 mV m$^{-1}$ corresponds to an $\boldsymbol{E}\times\boldsymbol{B}$ drift speed of the order of 100 km s$^{-1}$ in the region near apogee of the *Viking* orbit, where the measurements shown in figures 1–3 were made. When the

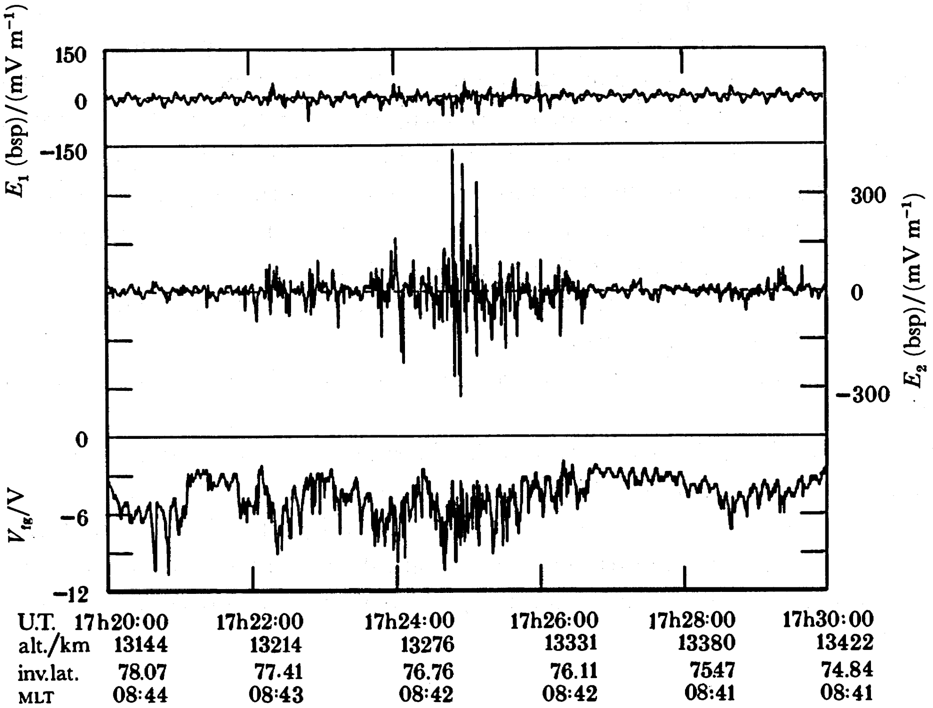

FIGURE 2. Two components of the electric field, $E_1$ and $E_2$ in a coordinate system (bsp), which has axis 1 along the projection of the magnetic field on the spin plane and axis 2 also in the spin plane but perpendicular to the magnetic field projection (positive towards dusk), for a ten-minute period in orbit 186 (27 March 1986). The lowest frame shows the 'floating ground' potential, $V_{fg}$, which is approximately equal in magnitude to the satellite potential relative to the plasma and opposite in sign. It shows mainly density variations (decreasing density corresponds to more negative $V_{fg}$). Only every 32nd data point is included (courtesy of L. P. Block & P. A. Lindqvist). (U.T. is universal time, MLT is magnetic local time.)

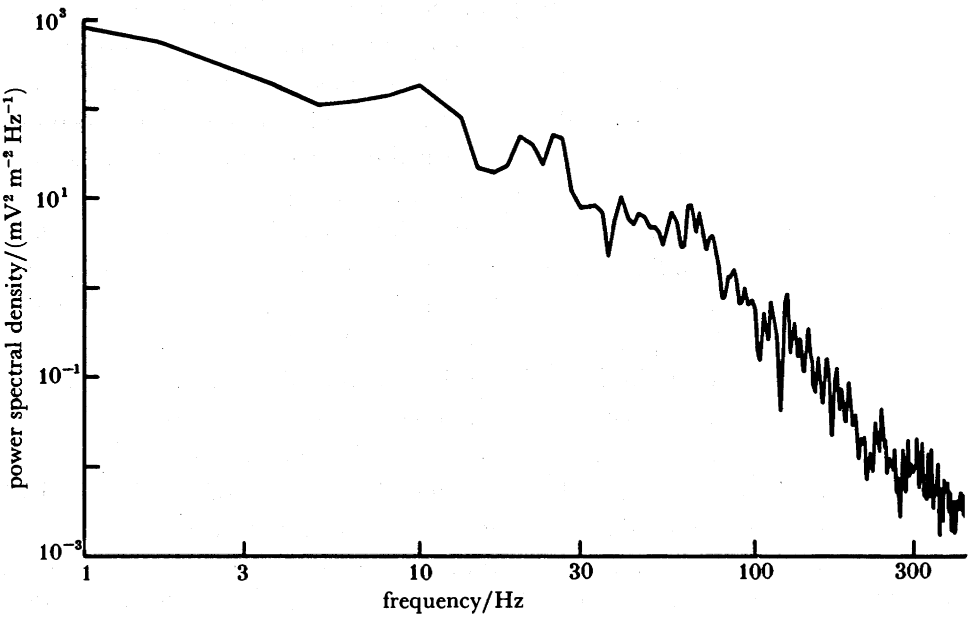

FIGURE 3. Power spectral density (root mean square (r.m.s.)) of one electric wave field component ($\Delta E_y$) roughly perpendicular to the magnetic field direction in a region with strong low-frequency electric field turbulence during *Viking* orbit 186 (17h24:49, 27 March 1986; five spectra averaged, proton's gyrofrequency is 30 Hz; boom angle is 107.4°; courtesy of G. Gustafsson & H. Koskinen).

field changes amplitude and direction, part of the drift velocity is transferred into increased gyration velocity for a portion of the charged-particle populations. The effect of the turbulence is therefore a perpendicular heating of the ions and an associated increase of their magnetic moments which, with the amplitudes observed, leads to an escape of the ions upward along the magnetic field lines (Lundin 1988*a*).

As the $\boldsymbol{E} \times \boldsymbol{B}$ velocity is the same for all plasma constituents in a stationary state, the electric field turbulence obviously favours the heavy ions in terms of energy increase. The *Viking* observations do not show 16 times higher energy for $O^+$ than for $H^+$ but rather about twice as high an energy along the field lines for $O^+$ as for $H^+$ and some four times higher perpendicular (thermal) energy for $O^+$ than for $H^+$. This may be partly because of some 'non-stationary' effects, which affect $O^+$ more than $H^+$ because of the 16 times lower gyration frequency of $O^+$, and partly because of acceleration of the ions along the field lines by parallel electric fields, which give the same energy increase to all ions irrespective of mass (Lundin 1988*a*). Figure 4 shows observational results from *Viking* of the energies of $O^+$ and $H^+$ compared with what one would expect from a combination of field-aligned and perpendicular acceleration of the plasma.

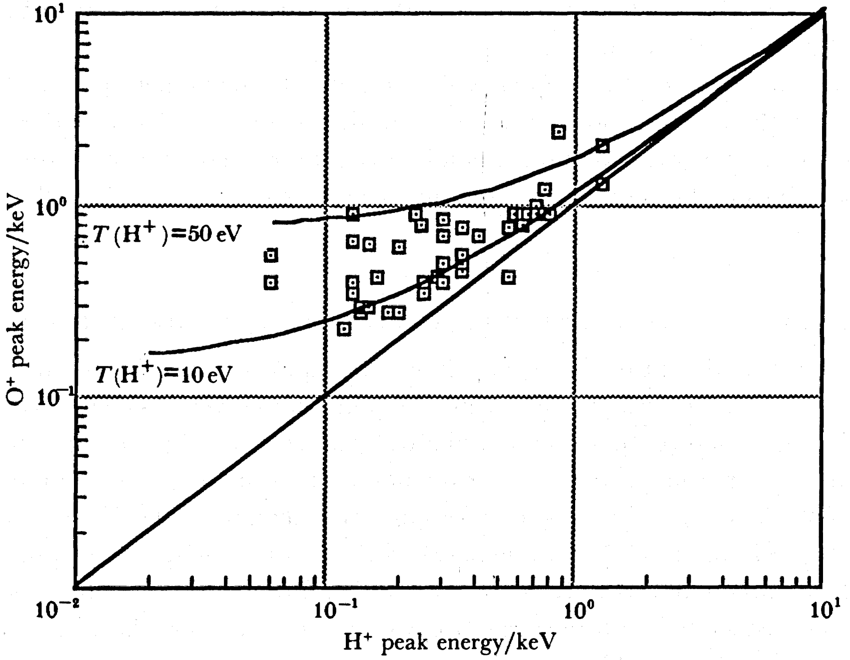

FIGURE 4. Scatter plot of $O^+$ peak energy $H^+$ peak energy for upward flowing ion beams observed during a number of *Viking* passes through the auroral oval. The straight diagonal line corresponds to acceleration of ions in a parallel electric field. By adding a transverse acceleration which give equal velocities to all ion species, the curved lines are obtained for two different transverse velocities corresponding to 10 eV and 50 eV for protons, respectively (after Lundin 1988).

In figure 1 an example of simultaneous observations of field-aligned upward flowing ions (at the minimum energy of the ion conics) and electrons can be seen from about 17h24 U.T. to 17h26:30 U.T. As mentioned earlier, this period coincides with the period of intense electric field fluctuations shown in figure 2. The $E_1$ component of the electric field in figure 2 indicates the existence of a magnetic field-aligned component of the electric field. As there was an angle of some 6° between the spin plane and the magnetic field direction, the data in figure 2 do not definitely prove the existence of an $E_{\parallel}$, considering the large perpendicular components present. Such a proof is, however, provided by the very narrow field-aligned electron beams observed.

The simultaneous observations with a spinning satellite of field-aligned electrons and ions, flowing in the same direction along the field lines, may be understood in terms of electrostatic acceleration of both the electrons and the ions (Hultqvist *et al.* 1987; Hultqvist 1987*b*). The field fluctuations are slow enough for the electrons to be accelerated upward when $E$ points downward and to disappear out of the height-limited (thousands of kilometres) acceleration region before $E$ changes direction. The ions experience the fluctuations of $E$ as an irregular non-resonant wave field and are not very much affected by them. They mainly feel the upward-pointing direct-current component of $E$, which is much smaller than the amplitude of the fluctuations. *Viking*, which was near the upper edge of the acceleration region when the data in figures 1–3 were taken, therefore saw within each spin period both upcoming field-aligned electrons and ions. Electrons were of course also accelerated downward in the acceleration region, but they were not seen by *Viking*. As the cold plasma density decreases rapidly with altitude, one expects the number of upward electrons to be larger than the number of downward accelerated ones. The average current would therefore be downward directed, as shown by the magnetic field data.

It thus appears that the very low-frequency fluctuations of the magnetospheric electric field play a major role in the heating and 'pumping' up of the magnetic moment of the ionospheric ions so they can escape the gravitational field and move into the magnetosphere and also in the extraction of both ions and electrons from the uppermost ionosphere by parallel electric field acceleration.

## FIELD-ALIGNED ACCELERATION OF ELECTRONS INTO THE ATMOSPHERE

The electric field experiment on *Viking* has shown that the U-shaped potential structures in the acceleration region associated with electron precipitation in inverted-V events are made up of several small-scale structures, possibly in a hierarchy of scales. It appears that the U-shaped equipotential surfaces are shaky, trembling or oscillatory on a small scale but rather steady on a large scale (Block 1987). An example of an intermediate scale U-shaped potential distribution is shown in figure 5. The angle between the measurement plane (spin plane) and the magnetic field direction was only 4°. $E_{\parallel}$ was of the order of 10 mV m$^{-1}$ and the total potential difference associated with the structure was about 1 kV over a horizontal distance of 30–40 km at the *Viking* altitude. This is obviously an example that provides strong evidence for the importance of field-aligned quasi-static potential differences for the acceleration of auroral electrons.

*Viking* carried the first satellite-borne electric field interferometer. By means of it some new characteristics of solitary rarefaction structures occurring at altitudes of 1–2 $R_E$[†] have been determined. Figure 6 shows examples of such solitary rarefaction waves as observed with $\Delta n/n$ (where $n$ is the local electron density) probes on *Viking* (after Bostrom *et al.* 1987; Gustafsson *et al.* 1988). Note the time delay between the signals on probe 1 above the spacecraft and on probe 2 below it. From data of the kind shown in figure 6 it has been possible for the first time to determine the size (of the order of 100 m both along and perpendicular to $\boldsymbol{B}$), velocity

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[†] $R_E = 6.37 \times 10^6$ m.

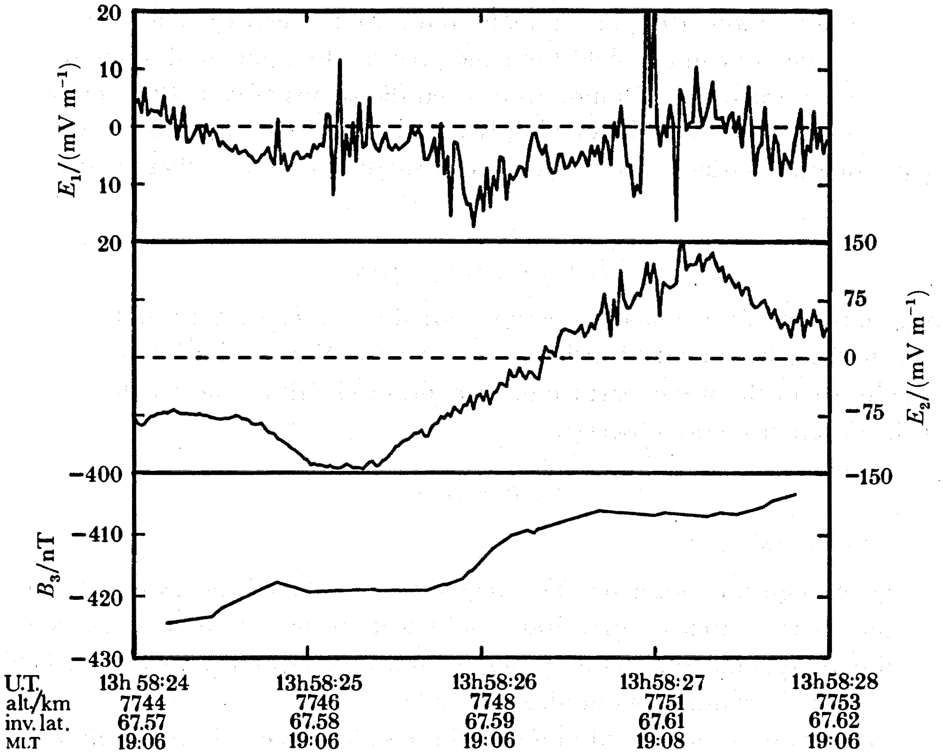

FIGURE 5. Electric and magnetic field variations during a *Viking* pass (orbit 257, 9 April 1986) through a U-shaped potential distribution over an auroral arc. $E_1$ and $E_2$ are defined in the caption of figure 2. $B_3$ is the westward magnetic field component, perpendicular to the main magnetic field. An upward parallel electric field of about 17 $\mathrm{mV\ m^{-1}}$ is collocated with the maximum $B_3$ variation, corresponding to Birkeland current density of 50 $\mu\mathrm{A\ m^{-2}}$ in the ionosphere (after Block 1987).

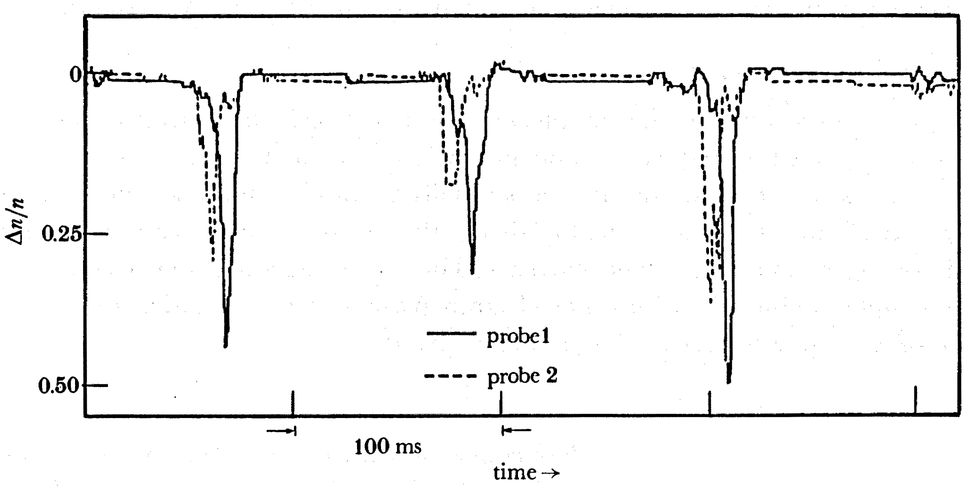

FIGURE 6. Waveform data from two $\Delta n/n$ probes displaying solitary rarefaction waves. The time delay between the two signals corresponds to an upward motion of the wave (after Gustafsson *et al.* 1988).

(upward, 5 to more than 50 $\mathrm{km\ s^{-1}}$), plasma density depletion (up to 50%) and potential change (of order 1V) of these solitary waves. They appear to be identical with so-called weak double layers, first observed with the *S*3-3 satellite (Temerin *et al.* 1982; Mozer & Temerin 1983). The *Viking* data show that they frequently occur in regions with upward-propagating ion beams and downward-accelerated electrons, i.e. within the acceleration region. Structures of this kind are seen in about 10% of the *Viking* data. Many such weak and variable double layers may occur along a magnetic field tube and give rise to a potential difference along the magnetic field lines of the order of hundreds or even thousands of volts (Bostrom *et al.* 1987). Such a scenario is consistent with the previously mentioned observation (Block 1987) that the U-shaped equipotential surfaces are varying on a small scale but rather steady on a large scale.

## WAVE GENERATION

A very large number of wave modes are represented in the *Viking* wave data. Some of those modes appear to have been studied little or never before. We summarize below very briefly some new results about the wave–particle interaction mechanisms and we do not even try to describe all the different modes observed.

### *Electron waves*

#### *Auroral kilometric radiation* (AKR)

*Viking* passed through the AKR generation region in some 36 of approximately 1400 passes and showed that there is a close correlation, on a scale of tens of kilometres, between AKR generation and both upgoing ion beams of energies and strong quasi-static electric fields below the satellite (Bahnsen, personal communication 1988).

AKR has been found to be generated in one and the same place for tens of minutes or more, thus being a highly stationary phenomenon, like the quiet aurora (Bahnsen, personal communication 1988).

*Viking* has not found any clear relation between electron density depletions and AKR generation (Bahnsen, personal communication 1988). Some of the more favoured theories require a plasma depletion in the generation region (see, for example, Wu 1985).

#### *Broadband electrostatic noise* (BEN)

BEN has been observed in the frequency band between the electron plasma and gyrofrequencies, i.e. in the frequency band just below that of the AKR. It seems not to be propagating (i.e. is electrostatic) and it occurs usually in, or close to, AKR sources. Erlandson *et al.* (1987) have found that BEN occurs together with upward electron beams and large-scale downward-flowing region 1 Birkeland currents. They have suggested that electron acoustic waves may couple nonlinearly with other electron plasma waves, resulting in the observed distribution of wave power over a wide frequency band.

#### *Auroral hiss*

Auroral hiss also generally occurs in close connection with AKR. *Viking* measurements have demonstrated that the intensity of auroral hiss is often very high, even higher than that of AKR. The electric field amplitude may amount to a few hundred millivolts per metre (Bahnsen *et al.* 1987; Pottelette *et al.* 1989), which is higher than reported before. The hiss occurs in bursts of short duration, typically a few seconds, corresponding to a spatial extent along the satellite track of the order of 10 km. The energetic auroral electrons are most likely generating the waves, but to reach the high observed intensities the waves probably have to be trapped inside small-scale enhanced density structures (Pottelette *et al.* 1989).

### *Ion waves*

#### *Electrostatic hydrogen cyclotron* (EHC) *waves*

The *Viking* measurements have demonstrated that there is no one-to-one relation between the occurrence of upward-moving ion beams and the occurrence of EHC waves. Such a relation is expected if the ion beams contain the free energy for the wave generation, which appears most likely. *Viking* measurements have shown that the characteristics of the ion beams may be quite stable during periods of tens of minutes, whereas the waves may appear and disappear within seconds (Andre *et al.* 1987). The EHC waves show no phase difference over the distance between the *Viking* probes (80 m), so their wavelength is much larger than 80 m. Their wave vector is generally a few degrees off perpendicularity. Andre *et al.* (1987) have shown that the variability of the waves in the presence of ion beams is most likely due to a varying content of low-energy electrons in the plasma.

#### *Ion cyclotron harmonic* (ICH) *waves*

Figure 7 shows an example of a spectrogram of IHC waves, sometimes also called ion Bernstein waves. Only a few examples of such wave emissions were known before *Viking* and they seemed to have somewhat different characteristics.

The IHC waves are found mainly near higher harmonics and at several harmonics at the same time. The harmonic number may vary within seconds. The emission frequency is generally slightly above the harmonics of the proton gyrofrequency. The amplitude is low, *ca.* 1 mV $m^{-1}$ or lower. These waves are not associated with ion beams or conics, but free energy appears to be available generally in the loss cone of the hot ion population (Koskinen *et al.* 1987).

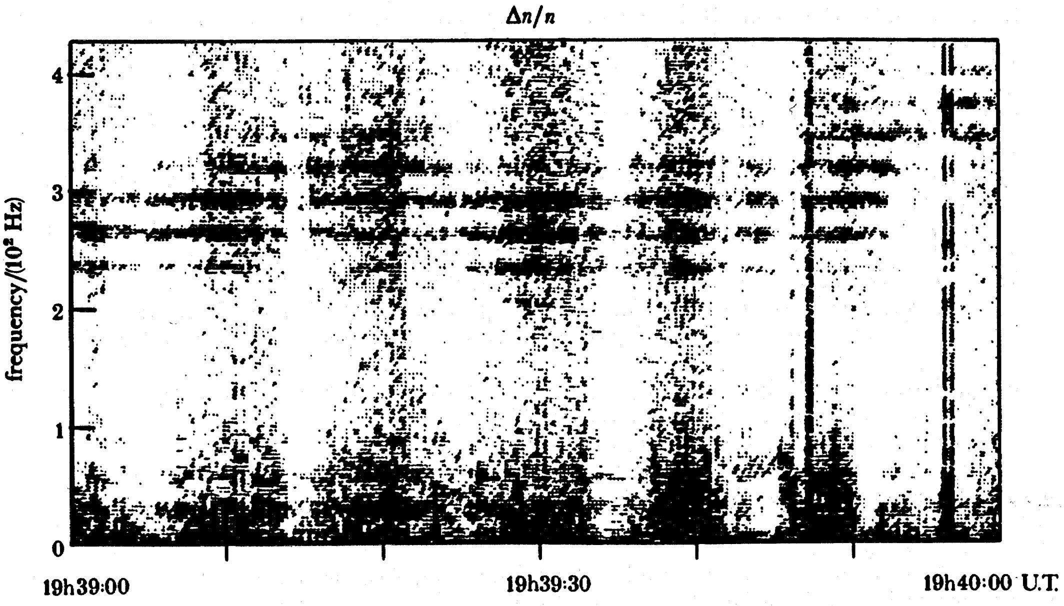

FIGURE 7. The dynamic spectrum of ion Bernstein waves at high harmonics measured by *Viking* (V4L waveform data for $\Delta n/n$ probes, orbit 159, 22 March 1986; after Koskinen *et al.* 1987).

### *Intense ion waves in regions of depleted plasma density*

Ion waves with frequencies slightly above the proton's gyrofrequency and with amplitudes as high as 50 mV $m^{-1}$ have been observed with *Viking* in the evening auroral oval, where the plasma is often depleted. There are often strong harmonics of these waves at frequencies that are multiples of the fundamental frequency and the harmonics are thus not separated by the proton's cyclotron frequency. The electric field vector is strictly perpendicular. The generation of these waves seems to be dependent on the inhomogeneity of the plasma in the depleted region. The mechanism is likely to be nonlinear because of the high field intensities (Gustafsson *et al.* 1988).

## CONCLUDING REMARKS

The analysis of the *Viking* database will probably peak in 1988 and 1989, but it will continue for many years. A complete review of the scientific outcome of the *Viking* project will therefore have to wait for several years. It seems, however, possible to now conclude (in the spring of 1988) that *Viking* has already delivered at least as much as we had expected from it.

The author is grateful to many members of the *Viking* scientific team who have provided him with their 'latest', still unpublished, results. He alone is responsible for the selection of the scientific results presented and for possible mistakes. The *Viking* project owes its success to the combined efforts of the entire scientific team, Swedish Space Corporation, Saab Space Corporation and the Swedish Board for Space Activities.

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## *Discussion*

P. J. Christiansen (*University of Sussex, U.K.*). I have two questions and one comment.

1. Is there a magnetic component associated with the strong low-frequency fluctuations that Professor Hultqvist describes?

2. What is the relation of the fundamental of the strong harmonic wave to the local gyrofrequency?

3. My comment concerns the strength of the pearl aurora. If the generator is an extended region of Kelvin–Helmholtz instability there will be regions of high vorticity, one per wavelength which could drive downward electron currents. Is it possible that the pearl spacing is related to this?

B. Hultqvist.

1. We were not able to see any magnetic fluctuations above the sensitivity limit of the magnetometer.

2. The fundamental frequency had a value of *ca.* 65 Hz and $f_{\mathrm{CH}^+}$ was *ca.* 50 Hz.

3. As far as I know, that is the line of thought of the observers (J. S. Murphree, personal communication, 1988).

D. Jones (*Space Plasma Physics Group, British Antarctic Survey, Cambridge, U.K.*). I was most interested in the statement that auroral kilometric radiation (AKR) not only has its source in regions of plasma depletion, but also sources in regions where there is no such depletion. The cyclotron maser theory for AKR production has predicted that if the source lies in a region of plasma depletion, such that the ratio of electron plasma frequency to electron gyrofrequency is of the order of 0.1, then the radiation should be in the $x$-mode. However, as the ratio increases, 0-mode radiation can also be produced and may possibly dominate. I am aware that some effort has been expended in determining the polarization of AKR observed by *Viking*. Do the results confirm these predictions of the cyclotron maser theory?

B. Hultqvist. I am sorry that I cannot answer that question. I have to refer Dr Jones to the experimenters (A. Bahnsen & E. Ungstrup).

M. Lockwood (*Rutherford Appleton Laboratory, Didcot, U.K.*). The pumping of ionospheric ions in the cleft by electric fields of frequencies below the gyrofrequency is of particular interest to me, and I have two questions. How does Professor Hultqvist know that these are not spatial structures and that this is not a gyro–radial effect? Secondly, to extract $O^+$ ions with the fluxes which are observed in the 'cleft ion fountain', these fluctuations would be required at very low altitudes in the topside auroral ionosphere. Does he have observations at low altitudes or is this an effect which pumps up ion energies, but which works in association with a second lower-altitude extraction mechanism?

B. Hultqvist. The amplitude of the fluctuations of the electric field is so high that the corresponding $(\boldsymbol{E}\times\boldsymbol{B})/B^2$ speed is much higher than the satellite's speed. Therefore it is unlikely that the variations are due to the motion of the satellite through a spatial structure.

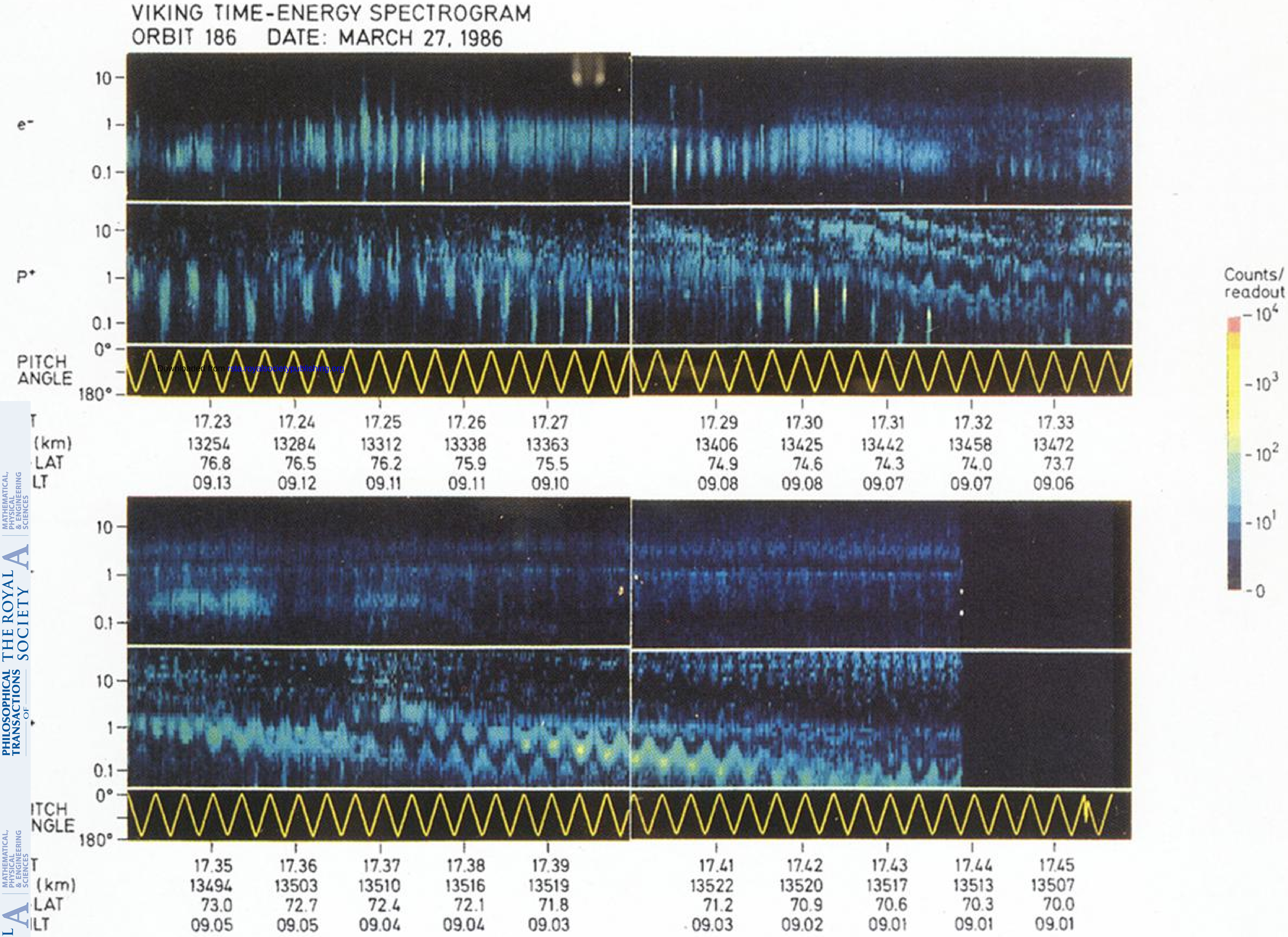
We have no measurements below *ca.* 3000 km so we do not really know how far down the fluctuations reach; but we do not know of any reason that they should not reach down to the upper ionosphere.

T. E. Moore (*NASA Marshall Space Flight Center, Huntsville, Alabama, U.S.A*). I would like to question the value quoted in answer to M. Lockwood's question for the low-frequency wave amplitudes observed from *Viking* (100 km $s^{-1}$). I am familiar with other observations of strong and narrow convection features with localized velocities of order 10 km $s^{-1}$, which, given the large rates of shear bounding them, could certainly give rise to fluctuations with comparable amplitudes. 100 km $s^{-1}$ seems startlingly large. Is there any way to reconcile these numbers? The 10 km $s^{-1}$ values come from altitudes of roughly 1 $R_E$.

B. Hultqvist. The 100 km $s^{-1}$ value is the order of magnitude of the $(\boldsymbol{E}\times\boldsymbol{B})/B^2$ velocity at the altitude of *Viking* for an electric field of order 100 mV $m^{-1}$. It may not reach this velocity, but still the order of magnitude should not be very different.

M. Saunders (*Blackett Laboratory, Imperial College, London, U.K.*). Professor Hultqvist demonstrated the need for high time-resolution measurements for a complete understanding. Has the auroral imager seen evidence for time-dependent reconnection phenomena such as flux transfer events within the cusp region?

B. Hultqvist. I know only of a study that is underway and has in its working title the words 'flux transfer events' (by R. Lundin & T. Potemra).



IGURE 1. Energy–time spectrogram for ions and electrons obtained in the cleft region of the dayside oval (orbit 186). Each spectrogram displays counts accumulated against energy in 32 energy steps within 0.6 s, corresponding to a pitch angle resolution of 5°. The lower panel displays the pitch angle against time (0° corresponds to downcoming particles). H is height, I-LAT is invariant latitude, MLT is magnetic local time.