PARALLEL ELECTRIC FIELDS ACCELERATING IONS AND ELECTRONS IN THE SAME DIRECTION*

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Abstract. In this contribution we present Viking observations of electrons and positive ions which move upward along the magnetic field lines with energies of the same order of magnitude. We propose that both ions and electrons are accelerated by an electric field which has low-frequency temporal variations such that the ions experience an average electrostatic potential drop along the magnetic field lines whereas the upward streaming electrons are accelerated in periods of downward pointing electric field which is quasi-static for the electrons and forces them to beam out of the field region before the field changes direction.

1. Introduction

The first ideas about the aurora being the result of an electrical discharge around the Earth, and thus about electric fields playing a major role, date back to Lomonosov and Canton in the eighteenth century. However, Alfvén seems to have been the first to specify the role of the electric field and to introduce an electric field component along the magnetic field lines – generally called ‘parallel electric fields’ for brevity – as a major source of acceleration of the auroral energetic particles. He did this in his Theory of Magnetic Storms, I, II, III in 1939 and 1940. Later he extended his arguments in favour of the importance of parallel electric fields in space around the Earth on the basis of experience from laboratory experiments (Alfvén, 1955, 1958) and electrostatic double layers were also proposed to be of importance in space (see Alfvén, 1972).

Chapman and several of his collaborators were critical of Alfvén’s ‘electric field theory’ of aurora and magnetic storms. Cowling (1942) wrote a special paper objecting to it. A common argument against the theory was that the conductivity along the magnetic field lines in an above the ionosphere is so high that any space charges and associated parallel electric fields will be eliminated very effectively. Chapman (1969) maintained this criticism of the role of parallel electric fields in aurora. The parallel electric field concept was thus dismissed as being contrary to generally accepted theories and it was only the direct measurements in space in the 1960s and 1970s that finally changed the situation completely. In the U.S.A. Review and Quadrennial Report to the IUGG in 1979 Stern (1979) states that “in the period 1975–1978… it became increasingly evident that the condition $E_\parallel = 0$… is often grossly violated in the magnetosphere. It would be only fair to say that the period marked a transition from general scepticism concerning the role of $E_\parallel$ in the magnetosphere to the acceptance of $E_\parallel$ as an essential ingredient in such phenomena as discrete auroras...”.

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Among the many observational results that paved the way for the general acceptance of the importance of parallel electric fields, some were of special importance in breaking the resistance. When Evans (1974) eliminated the problem that the existence of an intense low-energy tail of the observed peaked electron spectra constituted, one big stumbling block disappeared. The S3-3 satellite, launched in 1976 gave many new results which supported the importance of a parallel electric field component in accelerating ions out of the upper ionosphere (Shelley et al., 1976) and in driving Birkeland currents (e.g., Potemra, 1979). S3-3 also provided direct electric field observations strongly suggesting the existence of electric fields with $E_\parallel \neq 0$ above the auroral oval (Mozer et al., 1977).

That the existence of parallel electric fields now is proved beyond reasonable doubt, does not, of course, mean that field aligned acceleration is the only important acceleration process. The observations - also by means of S3-3 - of ions accelerated primarily transverse to the magnetic field lines - so called ion conics - were reported first by Sharp et al. (1977). The ion conics are sometimes 'elevated' so that the lowest energy ions are magnetic field aligned (Klumpar et al., 1984; Horwitz, 1986; Temerin, 1986). The existence of upward accelerated electron beams on the same field lines along which ion conics occur has been mentioned by several authors (Sharp et al., 1980; Klumpar and Heikkila, 1982; Collin et al., 1982; Lin et al., 1982; Burch et al., 1983; Kintner and Gorney, 1984). Here we will demonstrate the simultaneous observations by means of the Swedish satellite Viking of upward moving electrons and ions of similar parallel energy. This appears at first sight difficult to understand in terms of parallel electric field acceleration. In this brief contribution in honour of Hannes Alfvén we will outline how a parallel electric field can accelerate both ions and electrons upward along the magnetic field lines above the auroral zone ionosphere. The present report is only a preliminary one. A study using all available data from Viking is under way.

2. Observations

The Viking data to be discussed below are shown in Figure 1. It contains two colour spectrograms showing the counts per readout from three of the 11 spectrometers in the particle experiment on Viking. For a description of the experiment see Sandahl et al. (1985). The electron data were obtained with an electrostatic analyser covering an energy range of 0.01–40 keV and a field of view of $5^\circ \times 5^\circ$. With the satellite in cartwheel mode the spectrograph covered, in the period of interest, all pitch angles except $6^\circ$ around the field line with an angular resolution of $\sim 5^\circ$. The 100 km mirroring loss cone had a width of $11–12^\circ$ at the satellite. The ion data are from two electrostatic analysers covering the energy ranges 0.04–1.2 keV and 1.2–40 keV, respectively. Their angular resolutions were $4^\circ$ and $6^\circ$. The pitch angles at which the measurements were made are shown in the bottom panel (0° means downward moving particles and 180° upward moving). The energy scales are given along the lefthand vertical edge and below the panels are shown universal time, UT, satellite altitude, H, invariant latitude, I-LAT, and magnetic local time, MLT.
Fig. 1. Energy-time spectrograms for electrons and positive ions obtained from the particle experiment on Viking. Each spectrogram displays counts accumulated in 32 energy bins during 0.6 s, corresponding to a pitch angle resolution of 5°. The lower panel shows the pitch angle of the observations versus time. The position of the satellite is given by altitude (H), invariant latitude (I-LAT), and magnetic local time (MLT).

The data shown in Figure 1 are interesting for this study because it shows in the period 17:24–17:26 UT strongly elevated ion conics together with upward moving electron beams, some of them quite narrow in angular width. The “elevation” of the conics reaches almost 1 keV in the middle of the period mentioned. The ion fluxes along the magnetic field lines at ~1 keV in the conics where of the order of $6 \times 10^5 \text{ (cm}^2 \text{s sr keV)}^{-1}$, whereas the upward electron flux reached more than $10^9 \text{ (cm}^2 \text{s sr keV)}^{-1}$ below 1 keV in the most intense beams and more than $10^8 \text{ (cm}^2 \text{s sr keV)}^{-1}$ at 1 keV. Data from ion mass spectrometers on Viking show that the ions in Figure 1 were mainly hydrogen ions.

These observations appear to be the first reported of ions and electrons moving upward along auroral zone magnetic field lines. They were obtained in a fairly quiet period a few hours after a series of substorms. AE was <100 nT, $K_p$ was 3- and Dst = −37 nT. There are many other examples of this kind in the Viking data base, but they will be reported in a later study.
3. Discussion

Klumpar and Heikkila (1982) reported observations from the ISIS-2 spacecraft at quite low altitudes of narrow upward moving electron beams with very soft energy spectra. The peak flux was below 100 eV and sometimes even below 10 eV. In a few cases they saw also perpendicularly accelerated ions, which they suggested had been accelerated above the altitude range with a parallel electric field. Since the observations were made in the upper ionosphere the potential drop had to be achieved over a narrow altitude range and thus $E_z$ had to be so high that runaway electrons are produced (according to Dreicer, 1959, 1960). They did not report field aligned ion fluxes. Collin et al. (1982), Lin et al. (1982), Burch et al. (1983), and Kintner and Gorney (1984) also observed upward electron beams together with ion conics but did not report any field aligned ions.

Klumpar et al. (1984) were the first to report 'elevated' ion conics, i.e., ion distributions which are field aligned at low energies and conical at higher energies (ion bowl distributions according to Horwitz (1986)). They interpreted the distributions in terms of both perpendicular and parallel (later, at greater altitudes) acceleration of the ions. Horwitz (1986) showed that bowl-shaped distributions can also be formed by transverse heating in a region of finite horizontal extent, followed by essentially adiabatic convective flow to the observation location. Temerin (1986) found that the ion bowl distribution – or the 'elevated' ion conics as they are called above – can be understood in terms of only perpendicular acceleration, provided the perpendicular heating occurs in a broad altitude range below the satellite and provided the 'elevation' is not too large. Gorney et al. (1985) discussed a possible trapping of ion conics in downward parallel electric fields. None of these authors dealt with simultaneous observations of 'elevated' conics (ion bowl distributions) and upward moving electron beams. The observations shown in Figure 1, therefore, appear to be the first reported. None of the explanations proposed by the different above-mentioned authors appears to be able to explain the data in Figure 1 for the following reasons: With the mechanism of Klumpar et al. (1984) no upgoing electrons would be seen by Viking. The presence of a downward electrical potential fall of a magnitude of several hundred eV, which accelerates the beam electrons upward, would eliminate or strongly reduce the 'elevation' of ion conics formed in the ways suggested by Horwitz (1986) and Temerin (1986). The upward narrow electron beams occur only together with the 'elevated' ion conics in Figure 1 and as these narrow electron beams very clearly indicate the existence of a downward directed parallel electric field in this period (but not before or after) we would expect that the bottom of the conics would be at lower energies in the period 17:24–17:26 than before or after, rather than at higher energies as has been observed. According to Horwitz' (1986) mechanism the plasma convection would be in opposite directions before and after ~17:25 UT which hardly seems reasonable. In addition, electric field measurements indicate (personal communication by Block and Lindqvist and by Gustafsson and Koskinen) that there existed in the period of elevated ion conics very strong broadbanded low-frequency turbulence but not before or after, indicating that Viking was on field lines which passed the transverse heating region, in which case Horwitz' mechanism is not in agreement with the particle observations. Even without a downward potential drop the observed large elevation of the conics at the center of the region (0.7–0.8 keV) may
be more than Temerin's mechanism can produce (Temerin, personal communication) and with a downward potential drop of a few hundred eV it is even more unlikely that his mechanism can give rise to the observed distributions.

We propose the following model for the production of coincident upward flow of ions and electrons. The parallel electric field has a broad variation spectrum superimposed on an upward directed DC field. A very strong low frequency electric field turbulence was observed together with the elevated ion beams, as mentioned above. The effect of the electric field variations on an ion moving through the region largely averages out, so that the upward moving ions mainly increase their parallel kinetic energy with the potential change along the magnetic field lines. The variation spectrum of the parallel electric field is supposed to have the largest amplitudes at such frequencies that the electric field is effectively quasi-static for the electrons, but not for the ions. When these quasi-static parallel field components point downward the electrons are accelerated upwards to such high velocities that they leave the region with an electric field before the parallel field component switches direction. It is illuminating that an electron that has been accelerated through a potential increase of 100 V will pass a distance of 600 km along the field line in the next 100 ms, whereas a proton will only go 14 km in the next 100 ms after it has achieved the energy 100 eV.

Thus, whereas the ions are on the average accelerated only by the average potential change, which is directed upward, the upgoing electrons are accelerated also by larger but short lived downward directed fields, which are quasi-static for the electrons but not for the ions. The satellite only sees upward moving electrons when it is above the acceleration region and it cannot resolve the temporal variations in the electron flux.

Bryant et al. (1978) discussed possible consequences of a fluctuating electrostatic field in a different context of acceleration of primary auroral electrons.

The data shown in this brief report certainly do not prove the correctness of the proposed mechanism, which is speculative at the present state, put forward because no other proposed mechanism seems to be able to explain the observations. An investigation, in which data from all relevant experiments on Viking will be used, is under way.

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References


