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FAST observations of the solar illumination dependence of upflowing electron beams in the auroral zone

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[1] Electron beams accelerated upward out of the ionosphere are commonly observed in the auroral acceleration region. We present a statistical study of their distribution in magnetic local time, invariant latitude, and altitude, and its dependence on whether the ionospheric foot point of the satellite is illuminated or dark. The occurrence probability maximizes at ~12% near 70° invariant latitude (ILAT) and midnight when the ionosphere is in darkness, and at ~1% near ~78° ILAT from ~0600 to 1300 magnetic local time (MLT) when the ionosphere is illuminated. When the ionosphere is in darkness, there is approximately an order of magnitude increase in the probability from ~1000 to ~4000 km in almost all local time sectors. When the ionosphere is sunlit, the rapid increase begins at a higher altitude, ~2500 km. The probability also increases with solar zenith angle, with the increase being slower and occurring at a higher solar zenith angle at lower altitudes. These observations are consistent with a scale-height and density-dependent mechanism for the parallel potential in the downward current region. More than 90% of the observed upflowing electron beams have characteristic energies between ~50 and ~300 eV. The statistical results suggest that there are many more beams with durations of <5 s (latitude widths of <0.2°) and with lower energies. *INDEX TERMS:* 2407 Ionosphere: Auroral ionosphere (2704); 2704 Magnetospheric Physics: Auroral phenomena (2407); 7807 Space Plasma Physics: Charged particle motion and acceleration; 2479 Ionosphere: Solar radiation and cosmic ray effects; 2712 Magnetospheric Physics: Electric fields (2411); *KEYWORDS:* upflowing electron beams, downward current region, solar illumination

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1. Introduction

[2] Auroral scientists have long been interested in the question of whether there are auroras in daylight. It is only recently, with the advent of in situ observations of the electrons that produce the discrete aurora and remote observations of auroral emissions at ultraviolet wavelengths, that the question could be observationally addressed. Statistical studies of the accelerated electrons [*Newell et al.*, 1996], of upflowing ion beams [*Collin et al.*, 1998], and of UV emissions [*Liou et al.*, 2001] have indicated that discrete auroras are less frequent when the ionosphere is illuminated by the Sun. Two different explanations have been proposed for the solar illumination effect on primary auroral acceleration. *Newell et al.* [1996] and subsequently a number of other authors [e.g., *Liou et al.*, 1997, 2001; *Shue et al.*, 2001; *Petrinic et al.*, 2000] concluded that ionospheric conductivity, i.e., auroral feedback [*Atkinson*, 1970; *Lysak*, 1991], controlled the acceleration. Others, including *Mozer and Hull* [2001], *Ergun et al.* [2002], *Johnson et al.* [2003], and M. Temerin et al. (The low-altitude extent of the auroral acceleration region in the upward current region as determined by upwardly accelerated ion beams, unpublished manuscript, 2001; hereinafter referred to as unpublished manuscript, 2001) suggested that the dominant effect was the altitude distribution of the plasma within and above the ionosphere. The physical mechanism invoked was based on the Knight relation [*Knight*, 1973] for the parallel potential drop necessary to allow low-density plasma sheet electrons to carry a given upward field-aligned current into an increasing magnetic field and on requirements of quasi-neutrality [*Stern*, 1981]. Another density-dependent mechanism was discussed by *Lysak and Hudson* [1979], who suggested that the parallel potential would occur in the altitude region where the electron drift maximizes for a given field-aligned current and density distribution.

[3] Discrete auroras occur in the upward field-aligned current region. With their high time resolution plasma measurements, FAST and Freja have provided a new understanding of the auroral acceleration region that includes reversed acceleration in the downward current region, in addition to the usual discrete auroral acceleration

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associated with upward field-aligned currents [see, e.g., *Paschmann et al.*, 2003]. The processes associated with the downward current region, such as diverging electrostatic shocks and upflowing electron beams, have been called the ''inverse'' aurora [*Carlson et al.*, 1998a] and have also been associated with black aurora [*Marklund et al.*, 1997]. Recent FAST evidence, including comparisons between the potential drop across the perpendicular electric field structures bounding the electron beams and the electron beam energy [*Carlson et al.*, 1998a] and direct measurement of a downward parallel electric field and associated electron beam [*Andersson et al.*, 2002], suggests that upflowing electron beams are often accelerated by quasi-static parallel electric fields below the satellite altitude. Earlier ISIS and DE studies [*Klumpar and Heikkila*, 1982; *Burch et al.*, 1983] suggested that upflowing electron beams, accelerated by parallel electric fields, might often carry the current in the downward current region. A statistical study of FAST data [*Peria et al.*, 2000] has shown that this is correct. *Marklund et al.* [2001] have suggested that the time evolution of the magnitude of the parallel electric field in the downward current region may depend on the change in the *E* and *F* region density associated with supporting the current.

[4] Preliminary investigations of the effect of solar illumination on the ''inverse'' aurora indicated that this acceleration process is also suppressed by sunlight. *Karlsson and Marklund* [1996] and *Marklund et al.* [1997] examined the occurrence of small scale size, large-amplitude electric fields perpendicular to the geomagnetic field. They showed that these electric fields were more common and had larger amplitudes when the ionosphere was dark. FAST studies of upflowing electron beams [*Carlson et al.*, 1998b; *Elphic et al.*, 2000; *Peria et al.*, 2000] indicated that upward acceleration of electrons by parallel electric fields does not occur at altitudes of <4000 km when the ionosphere is sunlit. Results reported at higher altitudes by *Burch et al.* [1983] near DE 1 apogee (~20,000 km altitude) and by *Collin et al.* [1982] from S3-3 (up to 8000 km) provide hints that the parallel potential is smaller in magnitude and moves to higher altitudes when the ionosphere is sunlit. Utilizing plasma data obtained close to the equinox and noon magnetic local time (i.e., sunlit), *Burch et al.* [1983] found that upflowing electron beams (UFE) were common and had distributions consistent with acceleration in a parallel potential the order of 10 V near ~6000 km altitude. *Collin et al.* [1982] concluded that UFE were rarely observed below 5000 km and usually had energies below ~400 eV. *Carlson et al.* [1998b] suggested that the very similar occurrence frequencies and seasonal dependence of upflowing ion beams (in the upward current region) and upflowing electron beams (in the downward current region) indicated that both phenomena were controlled by the ion scale height.

[5] Although these studies have very clearly shown a strong seasonal (or solar illumination) dependence in the occurrence of upflowing electrons, they have not provided a complete statistical study of the altitude, magnetic local time, and magnetic latitude distribution of UFE occurrence and energy for illuminated and nonilluminated conditions. In this paper we discuss the results of such a study. The data set and methodology are described in section 2; the statistical results are presented in section 3; and comparisons with previous studies and conclusions are discussed in section 4. Note that the enhanced EUV associated with solar maximum has effects similar to those produced by solar illumination. A study in progress will address solar cycle dependence of UFE.

2. Data Sets and Methodology

[6] The FAST satellite [*Carlson et al.*, 1998a] is in a polar orbit with apogee of ~4300 km and perigee of ~400 km and obtains data in all local time sectors due to the precession of its orbital plane. The data utilized herein were obtained from a study of approximately 3 years of electron data from September 1996 through June 1999. The orbital dynamics results in fairly uniform coverage in altitude, magnetic local time, and latitude. The electron measurements were made by the electron electrostatic analyzers (EESA) [*Carlson et al.*, 2001]. The common data format (CDF) summary files of flux versus pitch angle (5-s spin period resolution) were analyzed for the occurrence of peaks in the electron flux parallel (or antiparallel) to the magnetic field, flowing away from the Earth. Note that each pitch angle bin is ~11°. The algorithm checks each time step (spin period) for a beam signature in the pitch angle flux data, both around 0° and 180°. The CDF files contain two pitch angle files, one for energies from 100 to 1 keV and one for energies >1 keV. If a beam was found in both energy ranges, the one with the peak flux was selected for the statistics. For the statistical plots related to characteristic energy, beams found in adjacent spin periods were combined. The characteristic energy was defined to be the energy at peak energy flux from the upgoing electron energy spectrum, which includes energies down to 50 eV. For this reason, an electron beam identified in the 100 eV to 1 keV pitch angle file can have a characteristic energy as low as 50 eV. In addition to the characteristics of the electron beams and their location in invariant latitude, magnetic local time, and latitude, the database includes the solar zenith angle at the 100 km altitude foot point of the satellite. In the plots shown in our figures, the occurrence probability is defined to be the number of spin periods with a beam normalized by the number of spin periods the satellite sampled, in the specific ILAT-MLT-altitude bin.

[7] The total number of spin periods that are dark (illuminated) is ~2.6 million (~1.3 million). There were ~3200 beams (or ~5200 spin periods with a beam) when the ionosphere was illuminated, and ~15,400 (or ~32,000 spin periods with a beam) when the ionosphere was dark. When the ionosphere is dark (illuminated), a beam lasts 1.9 (1.4) spin periods on average. Most UFE had a latitudinal width of <0.2°. Approximately 30% (17%) had a latitudinal width of 0.2°–0.5° in darkness (sunlight). In the plots shown in our figures, the occurrence probability is defined to be the number of spin periods containing a beam (within a given MLT-ALT-ILAT-solar illumination box) divided by the total number of spin period samples in that box. Note that boxes are summed over different parameters in each of the plots.

3. Statistical Results

[8] To determine the effect of solar illumination on upflowing electron beams (UFE), the database was divided

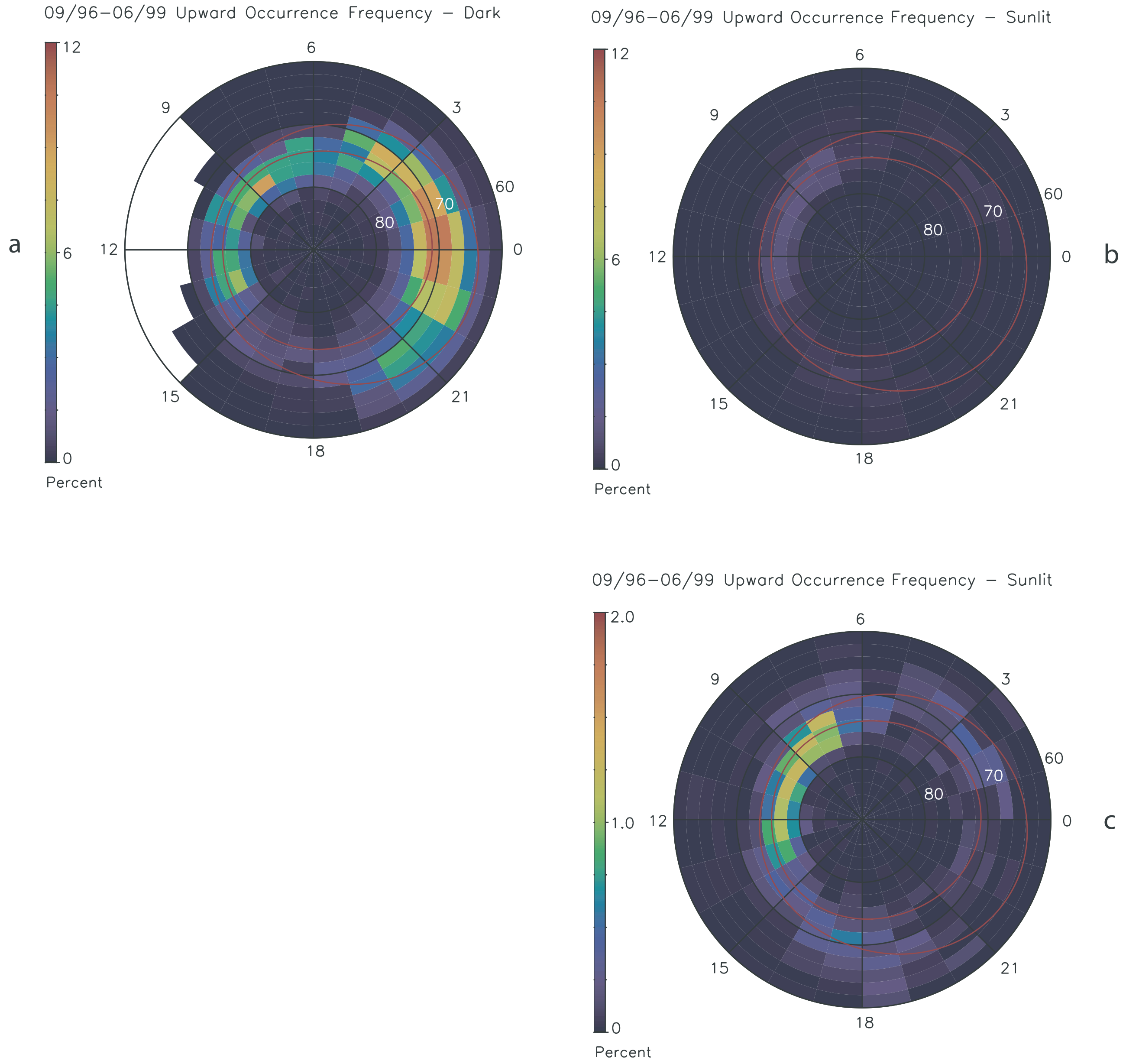

Figure 1. The occurrence probability of upflowing electron beams (UFE) versus magnetic local time and invariant latitude, for a dark ionosphere (solar zenith angle (SZA) > 101°) (Figure 1a) and for an illuminated ionosphere (SZA < 99°) (Figure 1b) (same scale as Figure 1a) and in Figure 1c (different scale). The nominal location of the auroral zone is shown in red.

into periods when the solar illumination angle at the 100 km altitude foot point of the satellite was <99° (sunlit) or >101° (darkness). Figure 1 plots the occurrence probability of UFE versus magnetic local time and invariant latitude (summed over altitude) for a dark ionosphere in Figure 1a and for an illuminated ionosphere in Figure 1b (same scale as Figure 1a) and in Figure 1c (expanded scale). The nominal location of the auroral zone is shown in red. In Figure 1a the probability maximizes at ~12% in the bins at 71° ILAT from ~2300 to 0100 MLT. There are less intense maxima from ~0800 to 0900 MLT and from 1300 to 1400 MLT at ~77° ILAT. Although similar features are visible in Figures 1b and 1c, the probabilities are much lower and the local time peak shifts. When the ionosphere is illuminated, the UFE probability peaks at ~1.2% in the morning, from ~0700 to 1300 MLT at ~77°. Under sunlit conditions, UFE are more frequently observed in the morning than near midnight, whereas under dark condition, the opposite holds true. Under all solar illumination conditions, UFE are uncommon near dawn and dusk.

[9] The occurrence probability for solar zenith angles (SZA) far from sunset or sunrise is shown in Figure 2, in which "dark" events have SZA > 110° and "sunlit" events have SZA < 85° (note these are the limits utilized by *Newell et al.* [1996]). The highest occurrence probability in darkness (~14% at 70° ILAT) is slightly larger than in Figure 1. In sunlight, the peak probability is still on the dayside but is much smaller than seen in Figure 1. Because the solar zenith

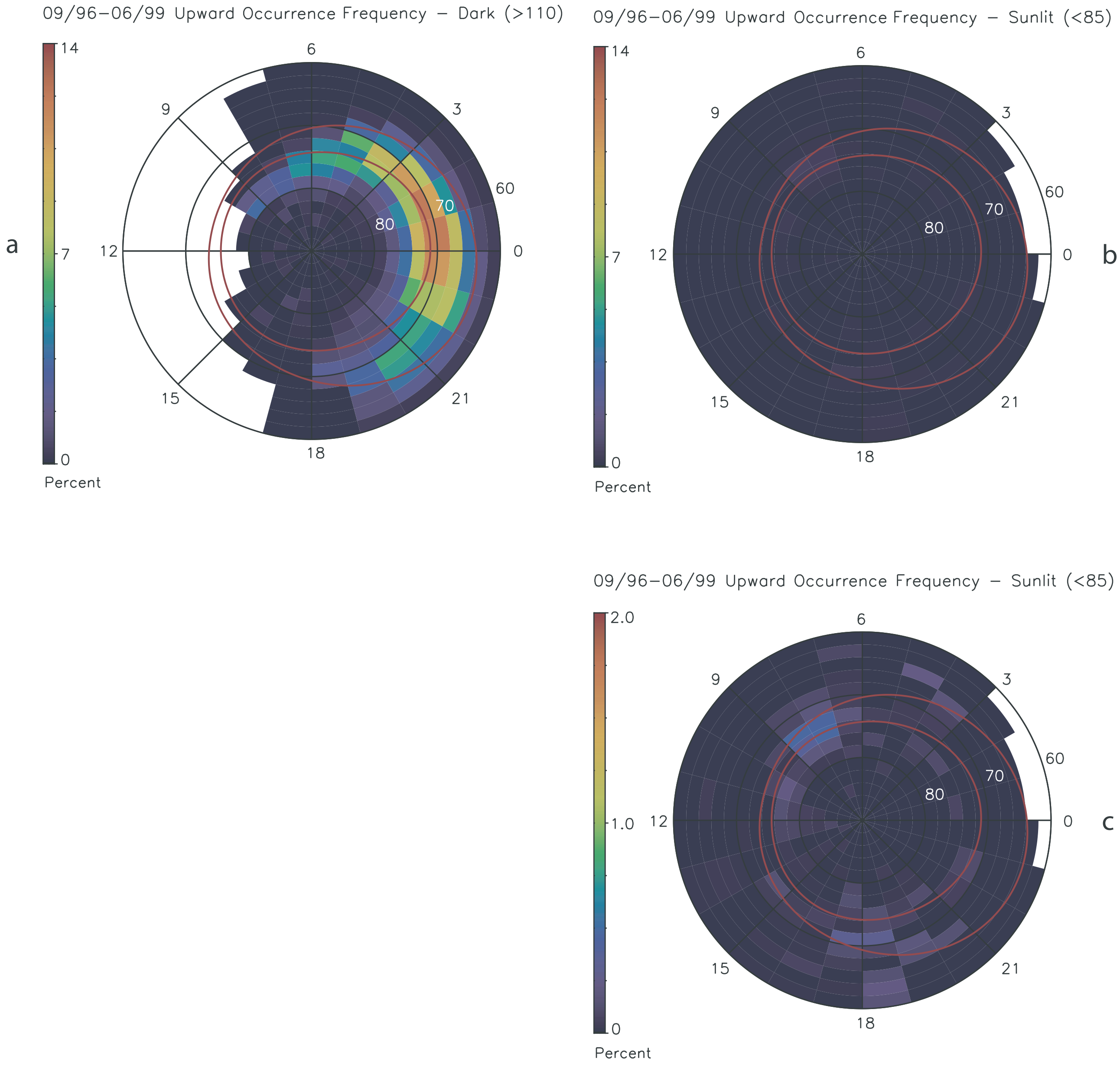

Figure 2. The occurrence probability of upflowing electron beams versus magnetic local time and invariant latitude, for SZA > 110° (Figure 2a) and SZA < 85° (Figure 2b) (same scale as Figure 2a) and in Figure 2c (different scale).

angle is directly related to the length of time the ionosphere has been in darkness (or in sunlight), the differences between Figure 1 and Figure 2 can be interpreted as a UFE dependence on the length of time the ionosphere has been in darkness (or in sunlight). The fact that the occurrence of UFE near noon in sunlight is much smaller for SZA < 85° than for SZA < 99° suggests that most of the events observed in this local time sector in Figure 1 occurred just after sunrise, when the ionosphere density distribution had not yet reached daytime values.

[10] The solar zenith angle dependence is shown another way in Figure 3: the occurrence probability for UFE versus solar zenith angle for three different altitude bins. In the highest altitude bin (3000–4000 km) the probability begins to increase rapidly at ~95°. In the lowest altitude bin the rise is slower until ~105°. The peak probability is lower at lower altitudes for all SZA. The dependence on SZA for nightside (2100–0300) and dayside (0800–1400) UFE can be compared over the range of SZA from ~70° to 105° where the coverage is similar (~10^4 spin periods) (not shown). In the highest altitude bin the rapid increase in occurrence probability begins at ~80° on the dayside, ~15° lower than on the nightside. The observed altitude dependence of the variation of UFE occurrence with solar zenith angle (hours in darkness) is consistent with a density-dependent acceleration mechanism.

[11] Occurrence statistics have also been determined on a "per auroral zone crossing" basis, in two different ways: (1) the average number of beams per auroral zone crossing, and (2) the percentage of crossings containing at least one

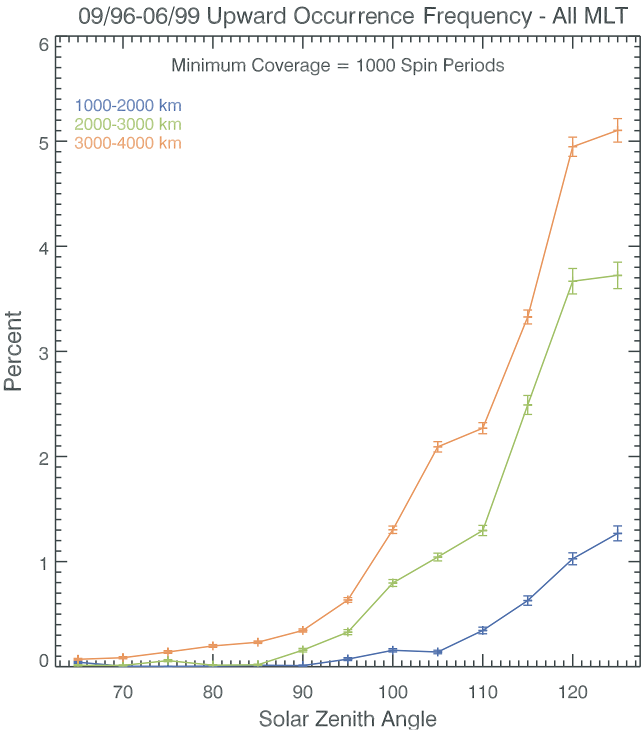

Figure 3. The occurrence probability for upflowing electron beams (UFE) between 2200 and 0100 MLT versus solar zenith angle (SZA) for three different altitude bins.

electron beam. On average, there are two electron beams observed per dark auroral zone crossing and 0.5 beams per illuminated crossing. When 3-hour MLT sectors are examined (without regard to illumination), ~1.1 beams per crossing are observed from 2100 to 0300 MLT and ~0.6 from 0900 to 1200 MLT, and the minimum is 0.3 from 1500 to 1800 MLT. On average, 0.5 (0.3) dark (illuminated) crossings contain an electron beam.

[12] The altitude dependence of UFE is examined as a function of magnetic local time in Figure 4 and as a function of energy in Figure 5. The altitude bins are 500 km wide and data points are plotted at the center of the bin. Error bars shown are just the square root of the number of UFE. Figure 4 shows the occurrence probability versus altitude for eight color-coded MLT bins for events in darkness (Figure 4a) and in sunlight (Figure 4b). When the ionosphere is in darkness, there is approximately an order of magnitude linear increase in the probability from 1000 to 4000 km in almost all local time sectors (except the 1200–1800 and 0300–0600 MLT sectors). When the ionosphere is sunlit, the probability is smaller and the increase with altitude is slower, and there is a suggestion that the increase begins at higher altitude (2000–2500 km).

[13] A plot of the occurrence versus altitude for six color-coded energy bins (Figure 5) shows the energy dependence of the occurrence of UFE. Note that there are so few UFE with energies above 1 keV that the lines corresponding to the three highest energy bins are close to the x-axis. The probability of observing a UFE increases dramatically with altitude (by more than a factor of 10). In darkness, the increase with altitude for energies <100 eV is linear over the full altitude range and has a steepening in the slope at ~2000 km for energies of ~100 eV to 1 keV. In sunlight, the slope increases at an altitude of ~2500 km for energies of ~100 to ~300 eV and at ~3500 km for 300 eV to 1 keV. The observed energy/altitude dependence suggests that there may be many more lower energy beams. Approximately 85% (95%) of the observed UFE in darkness (sunlight) have energies between ~50 and 100 eV, and ~11% (3%) have energies between 100 and 300 eV.

[14] In addition to the altitude dependence shown in Figure 5, the average characteristic energy depends on magnetic local time. The highest average energies are observed on the nightside (between ~1800 and ~0300 MLT), and the lowest energies are observed between ~0900 and 1500 MLT. This trend is clearest when the ionosphere is dark.

4. Discussion and Conclusions

[15] The observations described above show that the occurrence probability of upflowing electron beams in the auroral zone is strongly dependent on solar illumination. This is consistent with the earlier, more limited, studies of UFE utilizing FAST data [*Carlson et al.*, 1998b; *Elphic et al.*, 2000; *Peria et al.*, 2000], which showed that the occurrence probability of UFE was largest in darkness (or winter) and at high altitudes. The results are also consistent with the statistical study of electric fields observed by Freja [*Karlsson and Marklund*, 1996; *Marklund et al.*, 1997], which covered an altitude range of 1400 to 1770 km in the Northern Hemisphere and 750 to 1000 km in the Southern Hemisphere (compare with our lowest bin at 750–1250 km and the next bin at 1250–1750 km). Although such diverging fields may often be associated with the occurrence of downward parallel electric fields below the satellite altitude (and thus upward acceleration of electrons), they may also be associated with parallel fields above the satellite altitude, particularly in the case of the events with smaller magnitudes (100–200 mV/m). The Freja results therefore are likely to be a mixture of cases with potential below the satellite and potential only above the satellite altitude. In addition to their finding that the large electric fields were less common when the ionosphere was sunlit, *Marklund et al.* [1997] also found that the large-amplitude fields were rarely seen in their low-altitude passes. Given the differences between the two data sets (FAST UFE and Freja electric fields), the agreement is quite good. The results are also in general agreement with results from satellites at other altitudes, including DE 1, ISIS, and S3-3. Because most UFE are short duration, the higher time resolution FAST data (with simultaneous sampling of all pitch angles) are required to perform the complete statistical study needed to unravel the altitude, MLT, ILAT dependence of UFE, and of the associated parallel electric fields in the downward current region.

[16] At altitudes below ~4000 km, parallel potential drops greater than ~100 V are observed approximately 12% of the time near 70° ILAT and midnight when the ionsophere is in darkness and ~1% of the time for sunlit conditions. On the basis of the short duration of most beams, we can infer that the latitudinal size of the region of parallel potential was usually narrow (<0.2° in invariant latitude). Because the database utilized herein was restricted

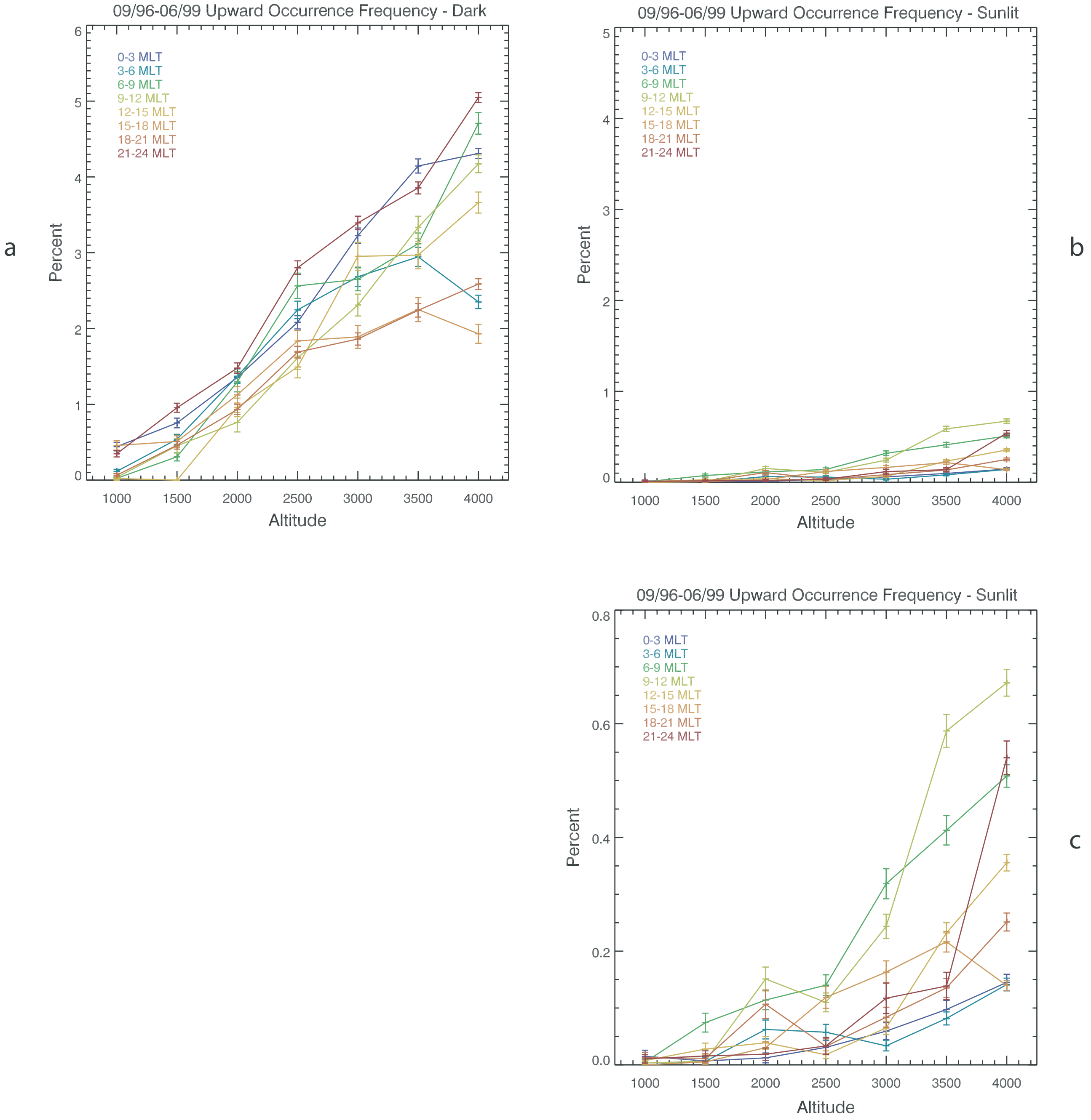

Figure 4. The occurrence probability versus altitude for eight color-coded magnetic local time (MLT) bins for events in darkness (Figure 4a) and in sunlight (Figure 4b).

to beams with energies greater than or equal to ~50–100 eV, the occurrence probability of parallel potentials less than 100 V could not be examined. The observed statistics, however, suggest that potential drops of this magnitude are common in the downward current region.

[17] There is more than an order of magnitude increase in probability of observing a UFE from 1000 to 4000 km. The parallel electric field in the downward current region can extend below 1000 km in darkness and 1500 km in sunlight. At all altitudes, most UFE have energies of <~300 eV. Above 4000 km altitude, ~15% have a higher energy. The MLT dependence is different under sunlit conditions than in darkness. Parallel electric fields are relatively more common on the dayside for sunlit conditions and on the nightside in darkness.

[18] There are only a few models that have explicitly examined the downward current region and the size of the expected parallel potential drop. *Chiu et al.* [1981] developed a kinetic model of the current-voltage relationship for the entire auroral circuit, including both the upward and downward current regions. They concluded that the potential drop in the downward current region was a few hundred volts, much less than the kilovolts observed in the upward current region. Their estimate is consistent with our observations. *Temerin and Carlson* [1998] presented an electrostatic model of the parallel potential drop in downward

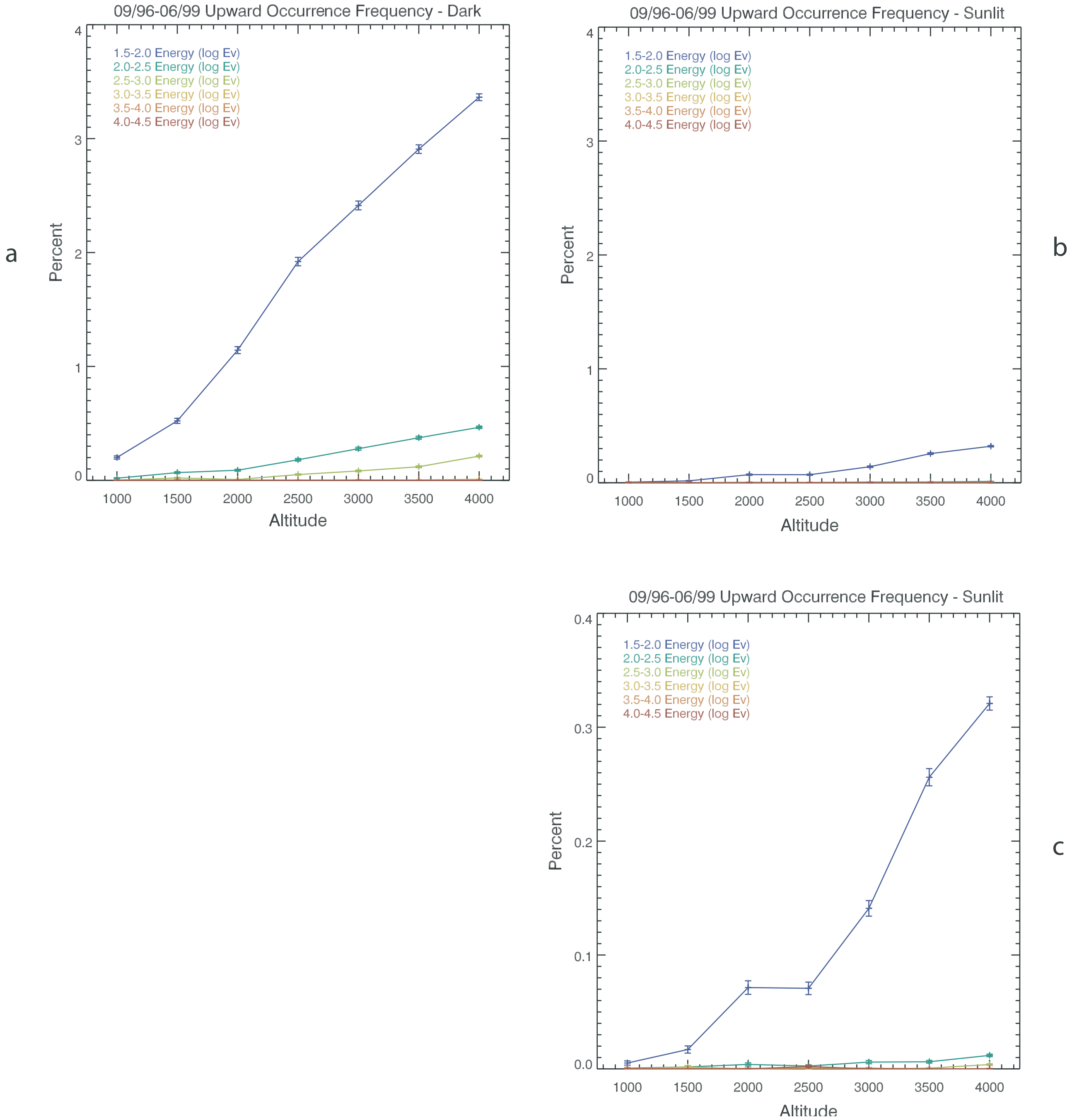

Figure 5. The occurrence probability versus altitude for five color-coded energy bins for events in darkness (Figure 5a) and in sunlight (Figure 5b).

current regions in which the ion density distribution is the controlling factor. It did not explicitly include solar illumination effects. For typical plasma sheet electron parameters, the required potential drop obtained by using this model is ~1 kV. On the basis of UFE statistics presented herein, the typical potential drop is only a few hundred volts. This implies that additional physics, such as wave-particle interactions, must be included to adequately model the downward current region, as discussed by *Temerin and Carlson* [1998]. Several researchers have taken a different approach to modeling the downward current region by including wave effects and observed ion heating in a kinetic treatment [*Gorney et al.*, 1985; *Jasperse*, 1998; *Jasperse and Grossbard*, 2000]. In a statistical study of FAST data in the downward current region, *Lynch et al.* [2002] have shown a good correlation between the measured ionospheric ion density and the parallel electric field inferred from the ion distributions using the method of *Jasperse and Grossbard* [2000]. Our results on UFE provide additional compelling evidence that it is the ionospheric density that controls the parallel electric field in downward currents.

[19] It is interesting to compare the statistical results on UFE with those obtained for the primary auroral acceleration in the upward current region, where downflowing

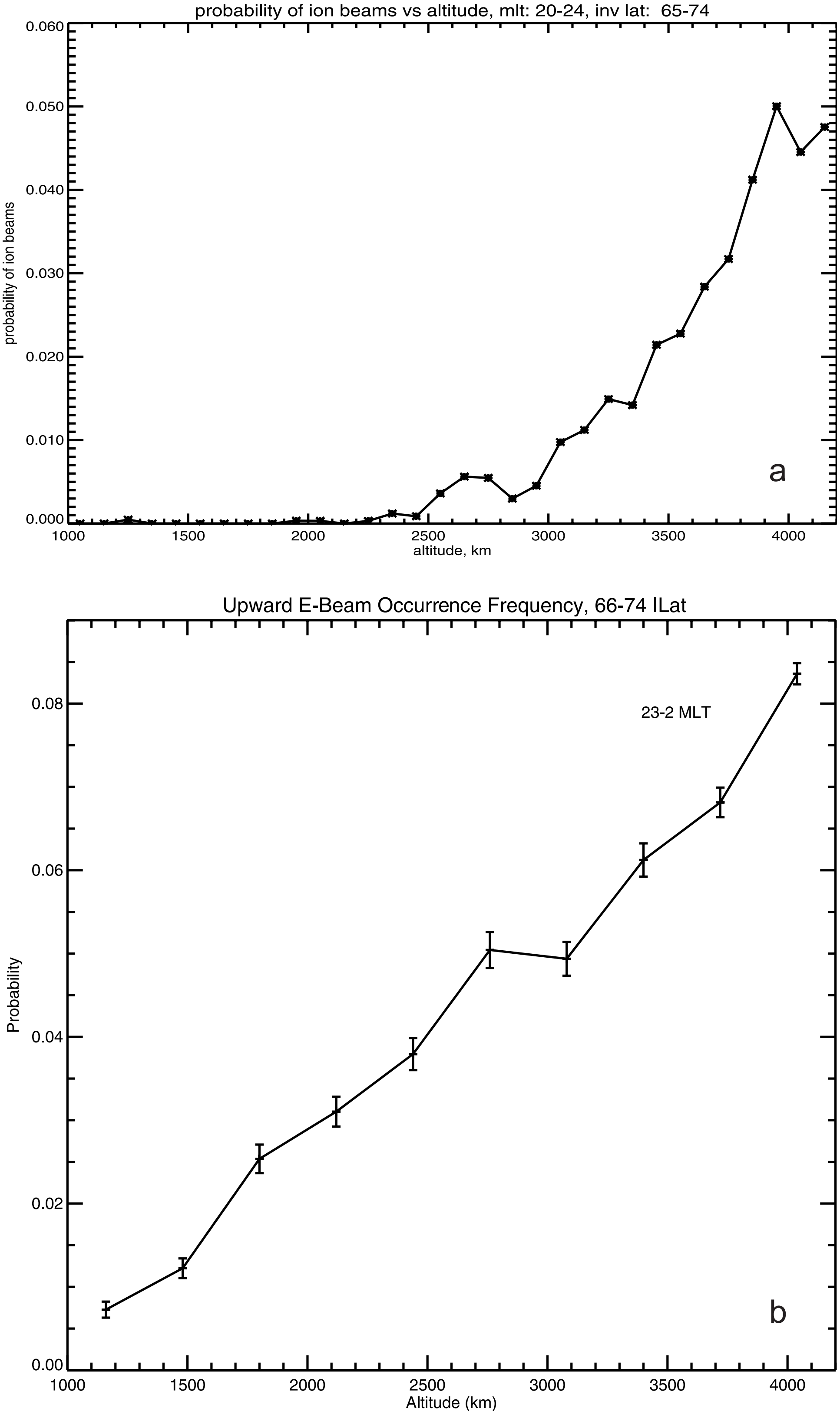

Figure 6. The altitude distribution of upflowing ion beams (UFI) in darkness at 2000–2400 MLT (M. Temerin et al., unpublished manuscript, 2001) (Figure 6a) and the altitude distribution of UFE in darkness at 2200–0200 MLT (Figure 6b).

electrons and upflowing ion beams are accelerated by the upward parallel electric field. Utilizing DMSP observations, *Newell et al.* [1996] showed that downflowing auroral electron beams that carried an energy flux >5 ergs/cm^2 s occurred ~3 times more often in darkness than in sunlight. This is smaller than the factor of ~10 effect observed for UFE. Comparison of the altitude distribution of upflowing ion beams (UFI) in darkness at 2000–2400 MLT (M. Temerin et al., unpublished manuscript 2001) with UFE (Figure 6) indicates that, on average, the parallel potential extends to lower altitudes in the downward current region than in the upward current region. The probability of observing a parallel potential drop increases much more rapidly with altitude in the upward current region than in regions of downward current [see also *Marklund et al.*, 1997]. M. Temerin et al. (unpublished manuscript, 2001) argued that the exponential increase in the occurrence was consistent with most ion beams being accelerated close to the satellite altitude (i.e., a confined region of electric field). For UFE, the increase is linear, consistent with a uniform electric field. In addition, the characteristic energy of UFI is larger than that of UFE, implying that the potential drop at altitudes below 4000 km is usually larger in the upward current region. Both upflowing ion beams and upflowing electron beams are controlled by the time that the foot point has been in sunlight (solar zenith angle).

[20] Although solar illumination effects in the upward and downward current region have many similarities, the boundary conditions that govern the development of the parallel potential drop at low altitudes is quite different. In both regions the need to carry a specific field-aligned current and requirement of quasi-neutrality determines the necessary potential distribution (*Knight* [1973], *Stern* [1981], *Temerin and Carlson* [1998], and references therein). In the upward current region, these requirements result in the existence of a double layer at low altitudes for a wide range of ionospheric and plasma sheet parameters [*Stern*, 1981; *Ergun et al.*, 2002] due to the need to contain the ionospheric electrons and accelerate the ionospheric ions to neutralize the plasma sheet electrons in the auroral cavity. In the downward current region, quasi-neutrality can be maintained with a potential drop that is more uniformly distributed in altitude because of the feedback between the strong perpendicular ion heating, combined with the mirror force, and the parallel electric field. This is consistent with the results presented herein that show a linear increase with altitude in the occurrence of UFE and a decrease in the occurrence of UFE when the ionosphere is illuminated.

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References

Andersson, L., et al. (2002), Characteristics of parallel electric fields in the downward current region of the aurora, *Phys. Plasmas*, *9*, 3600.

Burch, J., P. Reiff, and M. Sugiura (1983), Upward electron beams measured by DE-1: A primary source of dayside region 1 Birkeland currents, *Geophys Res. Lett.*, *10*, 753.

Carlson, C. W., R. F. Pfaff, and J. G. Watzin (1998a), The Fast Auroral Snapshot (FAST) mission, *Geophys Res. Lett.*, *25*, 2013.

Carlson, C., et al. (1998b), FAST observations in the downward auroral current region: Energetic up-going electron beams, parallel electric fields, and ion heating, *Geophys. Res. Lett.*, *25*, 2017.

Carlson, C., J. P. McFadden, P. Turin, D. W. Curtis, and A. Magoncelli (2001), The Electron and Ion Plasma Experiment for FAST, *Space Sci. Rev.*, *98*, 33.

Chiu, Y. T., A. L. Newman, and J. M. Cornwall (1981), On the structure and mapping of auroral electrostatic potentials, *J. Geophys. Res.*, *86*, 10,029.

Collin, H., R. Sharp, and E. Shelley (1982), The occurrence and characteristics of electron beams over the polar regions, *J. Geophys. Res.*, *87*, 7504.

Collin, H. L., et al. (1998), The seasonal variation of auroral ion beams, *Geophys. Res. Lett.*, *25*, 4017.

Elphic, R., et al. (2000), FAST observations of upward accelerated electron beams and the downward field-aligned current region, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani et al., p. 173, AGU, Washington, D. C.

Ergun, R. E., L. Andersson, D. Main, Y.-J. Su, D. L. Newman, M. V. Goldman, C. W. Carlson, J. P. McFadden, and F. S. Mozer (2002), Parallel electric fields in the upward current region of the aurora: Numerical solutions, *Phys. Plasmas*, *9*, 3695.

Gorney, D., Y. Chiu, and D. Croley Jr. (1985), Trapping of ion conics by downward parallel electric fields, *J. Geophys. Res.*, *90*, 4205.

Jasperse, J. (1998), Ion heating, electron acceleration, and the self-consistent parallel electric field in downward current regions, *Geophys Res. Lett.*, *25*, 3485.

Jasperse, J., and N. Grossbard (2000), The Alfven-Falthammar formula for the parallel electric field and its analogue in downward auroral current regions, *IEEE Trans. Plasma Sci.*, *28*, 1874.

Johnson, M. T., J. R. Wygant, C. Cattell, and F. S. Mozer (2003), Seasonal variations along auroral field lines: Measurements from the Polar spacecraft, *Geophys. Res. Lett.*, *30*(6), 1344, doi:10.1029/2002GL015866.

Karlsson, T., and G. Marklund (1996), A statistical study of intense low-altitude electric fields observed by Freja, *Geophys Res. Lett.*, *23*, 1005.

Klumpar, D., and W. Heikkila (1982), Electrons in the ionospheric source cone: Evidence for runaway electrons as carriers of downward Birkeland currents, *Geophys Res. Lett.*, *9*, 2873.

Knight, S. (1973), Parallel electric fields, *Planet. Space Sci.*, *21*, 741.

Liou, K., et al. (1997), Synoptic auroral distribution: A survey using Polar ultraviolet imagery, *J. Geophys. Res.*, *102*, 27,197.

Liou, K., P. T. Newell, and C.-I. Meng (2001), Seasonal effects on auroral particle acceleration and precipitation, *J. Geophys. Res.*, *106*, 5531.

Lynch, K., J. Bonnell, C. W. Carlson, and W. Peria (2002), Return current region aurora: $E_{\|}$, j_z, particle energization, and broadband ELF wave activity, *J. Geophys. Res.*, *107*(A7), 1115, doi:10.1029/2001JA900134.

Lysak, R. (1991), Feedback instability of the ionospheric resonant cavity, *J. Geophys. Res.*, *96*, 1553.

Lysak, R. L., and M. K. Hudson (1979), Coherent anomalous resistivity in the region of electrostatic shocks, *Geophys. Res. Lett.*, *6*, 661.

Marklund, G., T. Karlsson, and J. Clemmons (1997), On low-altitude particle acceleration and intense electric fields and their relationship to black aurora, *J. Geophys. Res.*, *102*, 17,509.

Mozer, F. S., and A. Hull (2001), Origin and geometry of upward parallel electric fields in the auroral acceleration region, *J. Geophys. Res.*, *106*, 5763.

Newell, P., C.-I. Meng, and K. Lyons (1996), Suppression of discrete aurorae by sunlight, *Nature*, *381*, 766.

Paschmann, G., S. Halaand, and R. Treumann (Eds.) (2003), *Auroral Plasma Physics*, *ISSI Space Sci. Ser.*, vol. 15, Kluwer Acad., Norwell, Mass.

Peria, W., C. Carlson, R. Ergun, J. McFadden, J. Bonnell, R. Elphic, and R. Strangeway (2000), Characteristics of field-aligned currents near the auroral acceleration region: FAST observations, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani, p. 181, AGU, Washington, D. C.

Shue, J.-H., P. T. Newell, K. Liou, and C.-I. Meng (2001), The quantitative relationship between auroral brightness and EUV Pedersen conductance, *J. Geophys. Res.*, *106*, 5883.

Stern, D. P. (1981), One-dimensional models of quasi-neutral parallel electric fields, *J. Geophys. Res.*, *86*, 5839.

Temerin, M., and C. Carlson (1998), Current-voltage relationship in the downward current region, *Geophys. Res. Lett.*, *25*, 2365.

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