FAST observations of the solar illumination dependence of downgoing auroral electron beams: Relationship to electron energy flux

C. Cattell,[1] J. Dombeck,[1] C. Carlson,[2] and J. McFadden[2]

Received 25 July 2005; revised 3 September 2005; accepted 18 November 2005; published 15 February 2006.

[1] The dependence of the occurrence frequency of downgoing auroral electron beams on solar illumination, as a function of energy flux, has been examined utilizing data from the FAST satellite. Solar illumination has almost no effect on the occurrence frequency of electron beams with energy flux less than or equal to a few erg/cm^{2}s; however, the ratio of the occurrence frequency in darkness to that in sunlight increases with the energy flux carried by the beam. For an energy flux >5 ergs/cm^{2}s, the ratio is ~2 to 2.5, consistent with the results of Newell et al. (1996b). The characteristic energy of dayside beams is less than that on the nightside by a factor of ~2. Both on the dayside and nightside, the characteristic energy of the electron beams increases with the energy flux carried by the beam and the energy is somewhat dependent on solar illumination, ~50% (20%) higher in darkness for dusk (morning) beams. Although there are fewer very intense aurora in sunlight, the very intense aurora that occur have characteristic energies comparable to those in darkness. These results are consistent with a density and scale height dependent mechanism for parallel potential drops in the auroral acceleration region.

Citation: Cattell, C., J. Dombeck, C. Carlson, and J. McFadden (2006), FAST observations of the solar illumination dependence of downgoing auroral electron beams: Relationship to electron energy flux, *J. Geophys. Res.*, *111*, A02201, doi:10.1029/2005JA011337.

1. Introduction

[2] The effect of solar illumination on the aurora has been examined utilizing measurements of auroral electron beams [*Newell et al.*, 1996b], ultraviolet auroral emissions [*Liou et al.*, 1997, 2001; *Shue et al.*, 2001], x-ray emissions [*Petrinic et al.*, 2000], auroral kilometric radiation [*Kumamoto and Oya*, 1998] and upflowing ion beams [*Collin et al.*, 1998; *Temerin*, 1999]. Since *Newell et al.* [1996b] first characterized the solar illumination dependence of the occurrence frequency of accelerated electrons that produce intense arcs by using DMSP data at 800 km altitude, many other studies have examined related questions. *Liou et al.* [1997] showed a similar seasonal dependence in Polar UVI images, which has subsequently been examined in more detail by *Liou et al.* [2001] and *Shue et al.* [2001]. The occurrence of upflowing ions from dusk to midnight observed by Polar [*Collin et al.*, 1998] was also suppressed during summer. In a study of upflowing ions using FAST data, *Temerin* [1999] showed that the altitude where the parallel potential occurred was strongly dependent on solar illumination (solar zenith angle) and was usually above 2000 km, and that the beams were most energetic in the pre-midnight local time sector. *Kumamoto and Oya* [1998] showed that auroral kilometric radiation was suppressed in the summer hemisphere compared to the winter and that the effect was most pronounced for higher frequencies, consistent with the decrease in the occurrence of energetic auroral electron beams and an increase in their acceleration altitude. *Petrinic et al.* [2000] found that x-ray emissions were more probable in darkness than in sunlight. *Morooka and Mukai* [2003], in a study of seasonal effects on the altitude of auroral acceleration utilizing both electron and ion observations, found that the altitude increased in summer. Note that studies that are sectored by season include changes due to the earth's dipole tilt in addition to illumination effects [*Russell and McPherron*, 1973; *Lyatsky et al.*, 2001].

[3] Most of the above studies concluded that the solar illumination dependence of auroral electron beams was due to the larger pre-existing ionospheric conductivity in sunlight compared to darkness via the ionospheric feedback mechanism [*Lysak*, 1991] for producing the parallel potential. In an MHD simulation of the feedback instability with different conductivities in the northern (winter) and southern (summer) ionosphere, *Pokhotelov et al.* [2002] found that the electron energy flux was larger into the winter auroral zone than the summer one. Note that possible effects due to the different altitude distribution of density in the two hemispheres was not included. Solar illumination also affects the ionospheric density and scale height. *Johnson et al.* [2001], using Polar data, showed that there is a large-scale density cavity in the auroral zone near 1 R_e altitude and its depth depends very strongly on the solar illumination. The average plasma density for illuminated conditions (~20–40/cm^3) is a factor of ~5 larger than for dark conditions (~5–10/cm^3). In darkness, the lowest average density is ~a few tenths/cm^3. This is consistent with the

[1]School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota, USA.
[2]Space Sciences Laboratory, University of California, Berkeley, California, USA.

0148-0227/06/2005JA011337$09.00

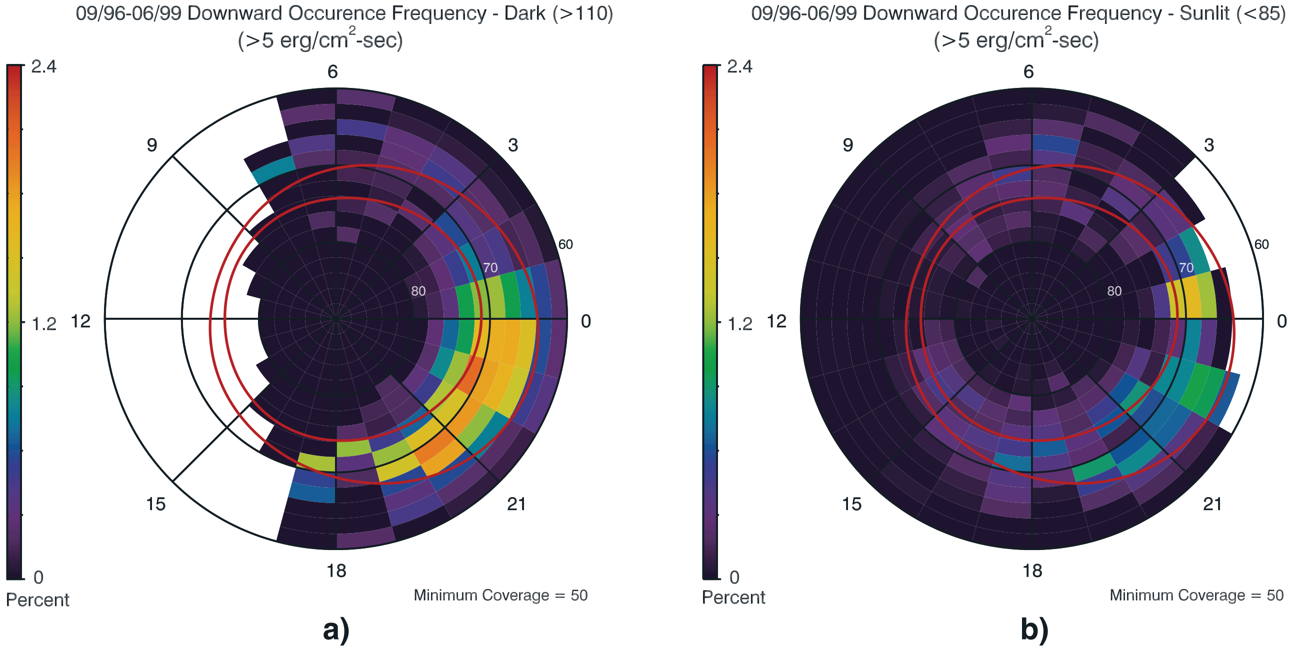

Figure 1. The occurrence probability of downgoing electrons beams with an energy flux >5 ergs/cm^{2}s, and for solar zenith angles (SZA) of >110° ('very sunlit') and <85° ('very dark'). The average location of the auroral oval is shown in red.

FAST observations in ion beam regions [*Strangeway et al.*, 1998; *McFadden et al.*, 1999a, 1999b]. Low densities occur in the same regions and have similar illumination dependence as auroral electrons and upflowing ions, so an alternate explanation for the illumination-dependence of aurora is the density distribution. This conclusion was in several recent studies, including *Johnson et al.* [2003], who showed a strong correlation between the occurrence of large perpendicular electric fields and low density in the upward current region and *Hull et al.* [2003], who showed a similar dependence for parallel electric fields. The particle studies of *Temerin* [1999] and *Morooka and Mukai* [2003] also concluded that parallel electric field in the upward current region was controlled by local plasma density. Similar conclusions were reached by *Lynch et al.* [2002] and *Cattell et al.* [2004] for acceleration in the downward current region.

[4] In this study, we examine the dependence of downgoing auroral electron beams on solar illumination, utilizing three years of electron data from the EESA instrument [*Carlson et al.*, 2002] on the FAST satellite. FAST [*Carlson et al.*, 1998] 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 and apogee. The database, described in *Cattell et al.* [2004], is obtained from the CDF files, which have a 5 second (spin period) resolution and 44 energy bins, and is restricted to beams with energies greater than 50 eV. An additional more restrictive beam algorithm was developed to check the results for this study. In addition to the requirement that the pitch angle distribution be peaked along the magnetic field, the algorithm required that the energy distribution fall off from the energy peak more steeply than three times the rate for a Maxwellian. The algorithm just examined the drop from the peak flux energy bin to the next highest energy bin. This is because if the distribution is Maxwellian and the peak is between two energy bins the resulting drop from the peak will be even lower. Note that some actual beams may be discarded. Although fewer beams were obtained by the more stringent method, there were no significant differences in the results. The figures shown in this paper utilize the more stringent algorithm for identifying beams. The statistical results are presented in section 2. A discussion of the results and their possible significance and relationship to previous studies and models for the auroral potential drop in the upward current region are presented in section 3. Conclusions are presented in section 4.

2. Statistical Results

[5] To study the effects of solar illumination on the downward acceleration of auroral electron beams, the occurrence frequency of downgoing beams with different energy fluxes has been examined. Figure 1 presents the results for downgoing electron beams with an energy flux >5 ergs/cm^{2}s, and for solar zenith angles (SZA) of >110° ('sunlit') and <85° ('dark'). Regions that are white had fewer than 50 spin periods of data meeting the SZA criterion. The average location of the auroral oval is shown in red. These limits on SZA and energy flux were chosen for comparison with *Newell et al.* [1996b], and similar results are obtained. The occurrence of these 'intense' aurora is suppressed in sunlight by a factor of ~2–2.5 (compared to ~3 found by Newell et al.).

[6] Figure 2 shows the occurrence probability for four energy flux values with less restrictive limits on SZA: Figure 2a (dark) and Figure 2b (sunlit) are for all electron beams with energy flux >0.25 erg/cm^{2}s; Figures 2c and 2d are for events with energy flux of 0.5–1.5 erg/cm^{2}s; Figures 2e and 2f are for events with energy flux of 2.5–

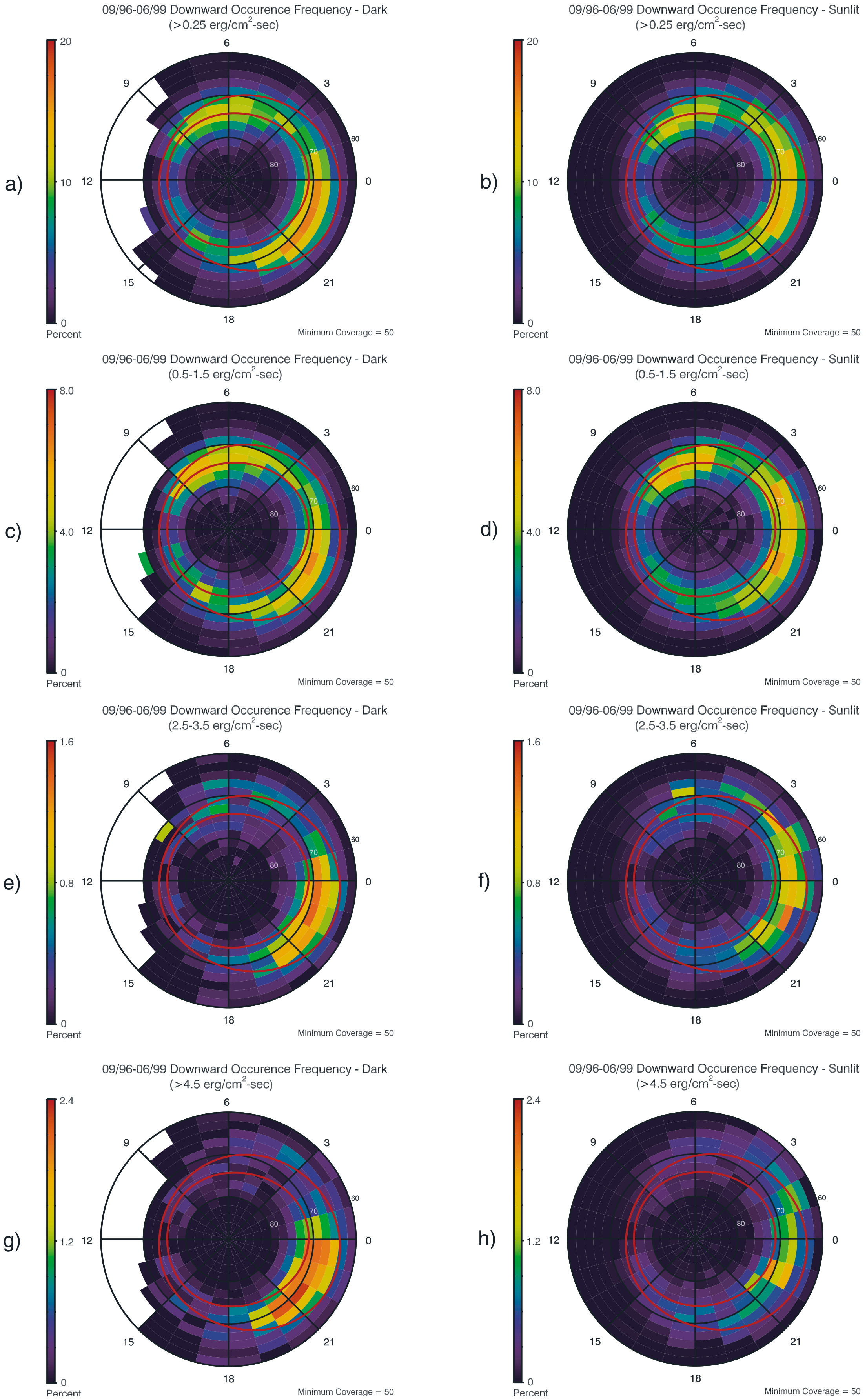
09/96-06/99 Downward Occurence Frequency - Dark
(>0.25 erg/cm^2-sec)
09/96-06/99 Downward Occurence Frequency - Sunlit
(>0.25 erg/cm^2-sec)
a)
b)
09/96-06/99 Downward Occurence Frequency - Dark
(0.5-1.5 erg/cm^2-sec)
09/96-06/99 Downward Occurence Frequency - Sunlit
(0.5-1.5 erg/cm^2-sec)
c)
d)
09/96-06/99 Downward Occurence Frequency - Dark
(2.5-3.5 erg/cm^2-sec)
09/96-06/99 Downward Occurence Frequency - Sunlit
(2.5-3.5 erg/cm^2-sec)
e)
f)
09/96-06/99 Downward Occurence Frequency - Dark
(>4.5 erg/cm^2-sec)
09/96-06/99 Downward Occurence Frequency - Sunlit
(>4.5 erg/cm^2-sec)
g)
h)
Percent
Minimum Coverage = 50
6
3
0
21
18
15
12
9
60
70
80

Figure 2

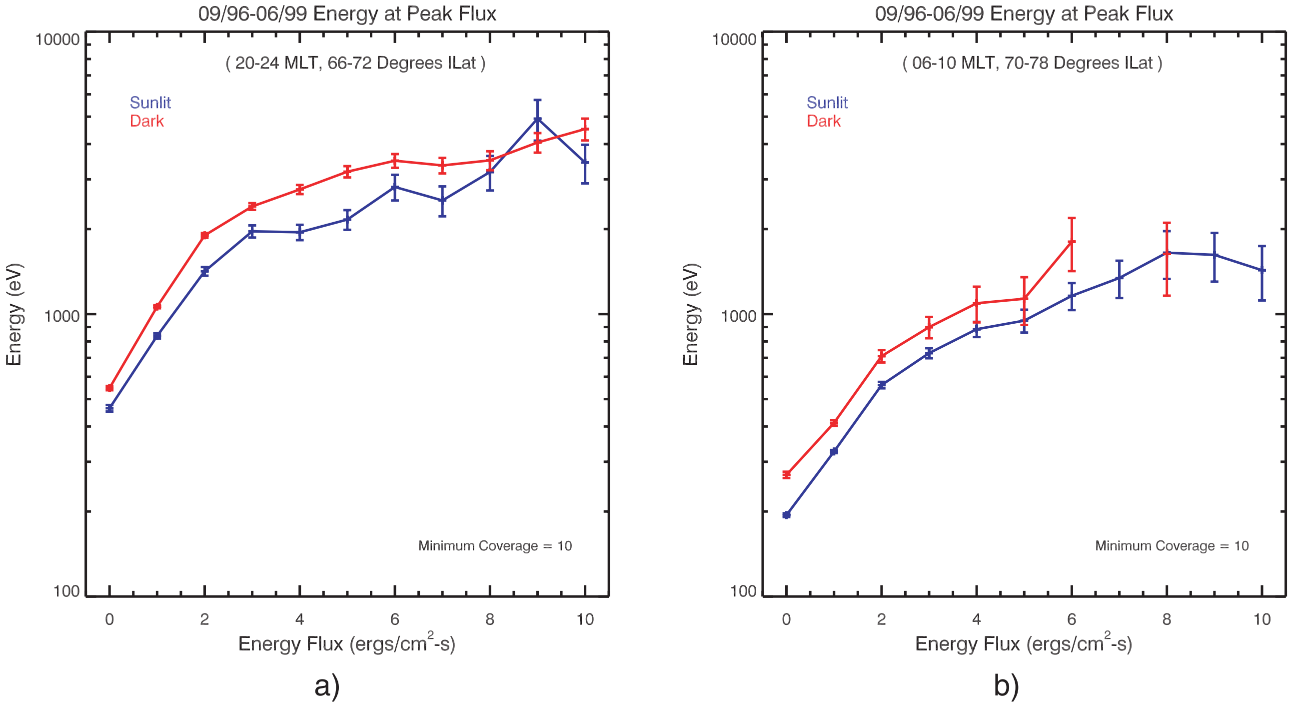

Figure 3. The characteristic energy is plotted versus energy flux for sunlit (blue) and dark (red) beams, (a) averaged over 20–24 MLT and 66–72 ILAT and (b) averaged over 10–16 MLT and 70–78 ILAT.

3.5 erg/cm^{2}s; and Figures 2g and 2h are for energy flux >4.5 erg/cm^{2}s. As seen in Figures 2a, 2b, 2c, and 2d, downgoing electrons with low energy fluxes (<∼1.5 erg/cm^{2}s) are observed in two wider local time regions [∼20–01 MLT and ∼06–10 MLT] and a smaller region at ∼16 MLT. For larger values of the energy flux, very few events are observed in the pre-noon and post-noon regions. When downgoing electron beams with low energy flux are examined, the difference between an illuminated ionosphere and a dark one is very slight. Solar illumination has almost no effect on the occurrence probability of electron beams with energy flux <∼2 erg/cm^{2}s. As the energy flux carried by the beam increases, however, there is further suppression of beams in sunlight compared to darkness.

[7] The observed differences in energy flux could be due either to increased density, increased characteristic energy or a combination of the two. In Figure 3, the characteristic energy is plotted versus energy flux for sunlit (blue) and dark (red) beams, which occurred between 20–24 MLT and 66–72 ILAT (Figure 3a) and between 6–10 MLT and 70–78 ILAT (Figure 3b). An increase in the characteristic beam energy is consistent with an increase in the potential drop above the satellite altitude. On average, beams carrying a higher energy flux are associated with a higher characteristic energy, from ∼1 keV for ∼1 erg/cm^{2}s to ∼4–5 keV for 9–10 erg/cm^{2}s for nightside beams (Figure 3a). The average characteristic energy for the dayside (Figure 3b) events is smaller, but also increases with the energy flux (from ∼400 eV at ∼1 erg/cm^{2}s to ∼1 keV for energy fluxes >∼6 erg/cm^{2}s). Except at the highest energy fluxes, the characteristic energy is consistently higher for dark events than for sunlit events, by a factor of ∼50% for the 20–24 MLT beams and a factor of ∼20% for the 6–10 MLT beams.

[8] The differences between the distribution of energies of dayside (6–10 MLT and 70–78 ILAT) and nightside (20–24 MLT and 66–72 ILAT) beams is shown in Figure 4, which presents a histogram of the number of beams versus characteristic energy for nightside (Figure 4a) and dayside (Figure 4b) regions. Note that these are not normalized plots. The number of nightside beams has a very broad peak at ∼1 keV with many beams at higher energies. In contrast, the number of dayside events, which peaks at ∼400 eV, has a much flatter distribution and drops off rapidly above ∼1 keV. The shape of these histograms does not depend on the illumination conditions.

3. Summary of Observations and Discussion

[9] This statistical study of downgoing auroral electron beams observed by FAST has shown explicitly for the first time that the amount by which their occurrence is decreased when the ionosphere is illuminated depends on the energy flux carried by the beam. The ratio of the occurrence probability in darkness to that in sunlight increases with energy flux. For the spatial region where beams are most common, the ratio increases from ∼1 at 1 erg/cm^{2}s to ∼2.5

Figure 2. The occurrence probability of downgoing electrons beams for less restrictive solar zenith angles: (a) dark and (b) sunlit electron beams with energy flux >0.25 erg/cm^{2}s; (c and d) events with energy flux of 0.5–1.5 erg/cm^{2}s; (e and f) events with energy flux of 2.5–3.5 erg/cm^{2}s; (g and h) energy flux >4.5 erg/cm^{2}s. Note that the scale is different for each energy flux value pair. The average location of the auroral oval is shown in red.

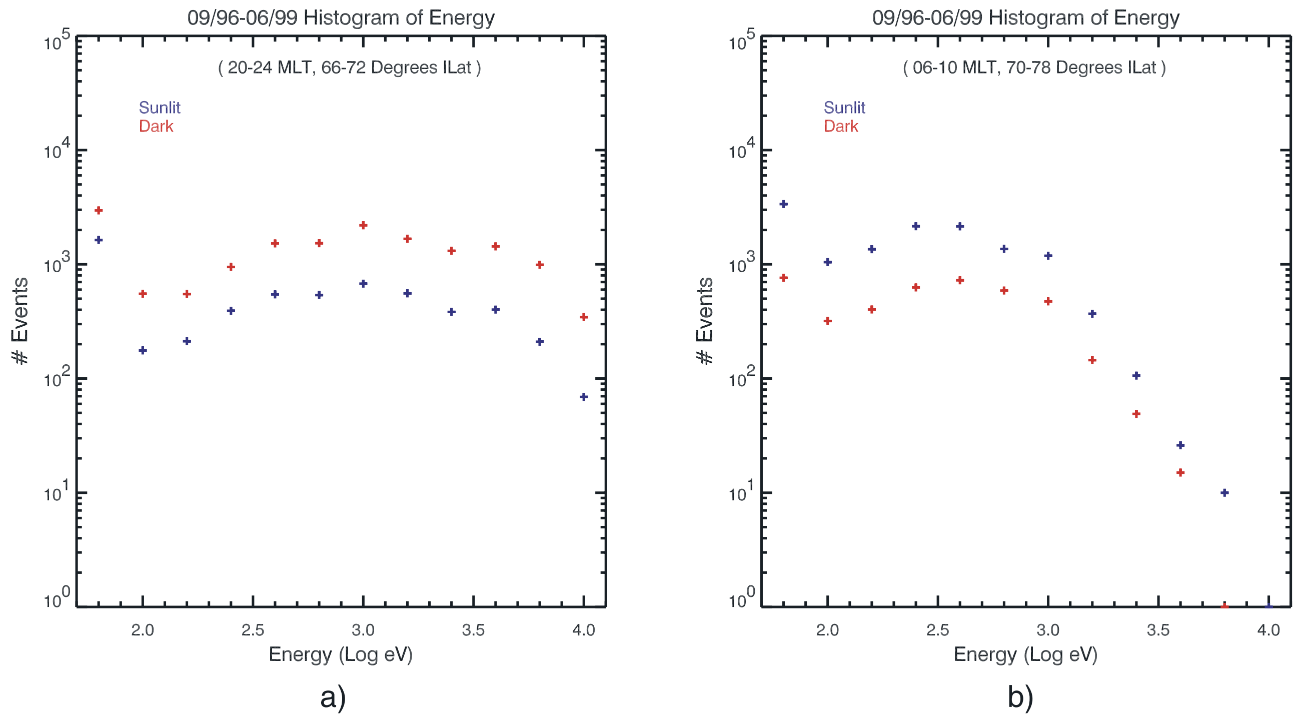

Figure 4. Histogram of the number of beams versus characteristic energy for (a) 20–24 MLT and 66–72 ILAT and (b) 10–16 MLT and 70–78 ILAT. Note that FAST obtained more samples on the nightside (dayside) that are dark (sunlit), which accounts for some of the differences in the number of beams.

at 5 erg/cm^{2}s. The results suggest that, while solar illumination of the ionosphere decreases the probability that a large potential drop will develop in the auroral zone, it does not strongly affect the occurrence of small potential drops. Large potential drops develop primarily in the pre-midnight region.

[10] The difference between an electron beam carrying a large energy flux and one with a small energy flux is principally that the characteristic energy of the beams is larger. This increase in energy occurs for both sunlit and dark events. In addition, for the rare cases where intense aurora occur when the ionosphere is sunlit, their characteristic energy is comparable to that in darkness. The average characteristic energy at a given energy flux is somewhat dependent on solar illumination; the energies are higher by approximately 40% (20%) in darkness compared to sunlight for nightside (dayside) events. This is not inconsistent with the Knight relation [*Knight*, 1973], which states that when the field-aligned current exceeds a critical value dependent on the plasma sheet density and temperature there is a linear relation between the current carried by downgoing plasma sheet electrons and the parallel potential drop over a broad range of potentials. Studies of the illumination dependence of field-aligned currents in the pre-midnight sector have shown that the current density is not strongly dependent on illumination [*Fujii et al.*, 1981]. If the current is similar in darkness and in sunlight, assuming the plasma sheet density is independent of illumination, one would expect similar potential drops in the pre-midnight region. The Knight relation does not provide information on the location and distribution of the parallel potential drop or the mechanism that produces the electric field. However, the relation depends on the altitude at the top of the potential: larger potentials are required to drive the same current when the altitude is lower. *Temerin* [1999] pointed out that the inclusion of the constraints imposed by quasi-neutrality provides a possible explanation for the decrease in energetic beams observed in sunlight. When the ionosphere is illuminated, the ion scale heights are higher and the parallel potential does not need to penetrate as deeply to provide the ions needed to neutralize the plasma sheet electrons. As stated above, the Knight relation shows that a larger potential is required to drive a field-aligned current when the potential is at lower altitude. Since the potential must exist at lower altitudes in darkness (compared to sunlight) to provide the necessary ionospheric ions, one would expect that the potential in darkness would be larger than in sunlight, resulting in more energetic electron beams. Similar conclusions can be reached by examining Vlasov-Poisson models of the altitude distribution of the parallel electric field obtained [*Stern*, 1981; *Ergun et al.*, 2000, 2002]. They have shown that, for a range of ionospheric and plasma sheet particle distributions, the potential drop occurs primarily in two regions: a low altitude double layer that reflects ionospheric electrons and accelerates ionospheric ions to provide the density to neutralize the plasma sheet electrons, and a high altitude potential drop that accelerates the plasma sheet electrons. *Ergun et al.* [2000] stated that when the ion scale height was higher (as occurs when the ionosphere is illuminated), the low altitude double layer moves to a higher altitude and has a smaller potential drop than in the case when the scale height is lower. This would

result in fewer energetic electron beams, assuming that a large fraction of the total potential drop is in the low altitude double layer.

[11] The observations of the solar illumination dependence of downgoing electron beams, described herein, in combination with the upflowing ion results of *Temerin* [1999], are most consistent with a scale height and density dependent mechanism for formation of the parallel potential in the upward current region. Evidence favoring a density-dependent mechanism was recently presented by *Johnson et al.* [2003]. They showed that, at auroral latitudes and 18–24 MLT, the occurrence frequency of large perpendicular electric fields (>100 mV/m) maximizes at altitudes of ~6000–8000 km (consistent with *Lysak and Hudson* [1979]) and is four times larger when the foot of the field line is in darkness than in sunlight. *Lysak and Hudson* [1979] suggested that the parallel potential drop occurs at the altitude where the electron drift velocity maximizes. The large spiky electric fields are most common in the altitude range where the plasma density decreases to median values of <10/cm^3, consistent with production of the fields by a density dependent mechanism. The large electric fields (sometimes called 'electrostatic shocks') have been associated with particle acceleration via a parallel electric field by *Mozer et al.* [1980], *Ergun et al.* [1998], *McFadden et al.* [1999a], and others. Other studies concluding that the parallel electric field in the upward current region was controlled by density and/or scale height include *Temerin* [1999], *Hull et al.* [2003], and *Morooka and Mukai* [2003].

[12] In addition to controlling the altitude and size of the potential drop through the change in the ionospheric density and scale heights, solar illumination may effect auroral acceleration by modifying the solar-wind magnetosphere coupling that powers it, as suggested by two theoretical studies, *Fedder and Lyon* [1987] and *Ridley et al.* [2004] and a recent observational study [*Cattell et al.*, 2003]. Ridley et al. found that the magnitude of the cross-polar cap potential decreased as the ionospheric conductivity increased. Such an effect could result in a decrease in energetic auroral electron beams when the ionosphere is illuminated.

[13] The dependence of both the characteristic energy and the number flux on season was studied by *Liou et al.* [2001] using Polar UVI images. They concluded that aurora near midnight were suppressed in the summer, whereas aurora on the dayside (near 15 MLT) were enhanced, because the energy of the electrons decreased in summer, nightside number fluxes were constant, and dayside number fluxes increased. Note that electron energy and number fluxes were inferred from the ratio of two wavelength bands and were not directly measured. If one interprets the UV observations near 15 MLT as being caused by electrons accelerated by a parallel electric field, these inferences are not consistent with our direct measurements of the electron beams. Our study showed that the characteristic energy was only weakly dependent on solar illumination and did not show illumination dependent changes in the number flux. However, it is likely that the 15 MLT peak is not associated with parallel field acceleration because our study of FAST electron beams also does not show an increase in the probability of events near 15 MLT in sunlight compared to darkness. This suggests that the sunlit 15 MLT peak in UV emission is caused by a mechanism such as either Alfvenic acceleration or scattering into the loss cone in the equatorial plane. This would explain the differences between the FAST observations of beams and the Polar UVI results.

[14] The results presented herein can be compared to previous studies of downgoing auroral electrons. For the same range of solar zenith angle and energy flux values as utilized by *Newell et al.* [1996b], we find similar suppression of energetic (>5 erg/cm^{2}s) auroral electron beams by sunlight. The occurrence of beams with energy flux >0.25 erg/cm^{2}s (Figures 2a and 2b) is similar to that of *Newell et al.* [1996a] for all illumination conditions, although the afternoon peak is less prominent in the FAST data set. There are several differences in the statistical data bases used in the Newell et al. DMSP studies and our FAST study that may contribute to differences in the results: the satellite altitude, the beam selection algorithm and solar cycle coverage. DMSP is at an altitude of 800 km, below the altitude of parallel electric field acceleration. On average however, FAST is within (below) the altitude range of parallel acceleration during darkness (sunlight). It is likely, therefore, that the FAST data set will miss some electron beams in darkness since the acceleration occurred below the satellite. This would explain why the suppression observed by DMSP for energetic beams is somewhat larger than that observed by FAST. The FAST data were obtained at solar minimum, whereas the DMSP data covered almost a complete solar cycle. Because the enhanced EUV near solar maximum affects atmospheric scale heights, additional suppression of beams during illuminated conditions may occur, which could also contribute to the larger effects seen by DMSP. It is possible that the differences seen in the afternoon peak are due to the fact that the FAST beam selection requires a downgoing magnetic field-aligned peak, whereas the DMSP instrument does not obtain full pitch angle distributions and, therefore, only looks at the energy distribution. A detailed examination of the distributions in this local time sector is needed to resolve this question. This is outside of the scope of this analysis and is the subject of ongoing work.

[15] It is also informative to compare the FAST results to *Morooka and Mukai* [2003], although they are not directly comparable since the Akebono data were sectored by season rather than solar zenith angle and by the total potential drop (above and below the satellite) rather than energy flux. In addition, the altitude coverage is different; their lowest altitude bin covers 3000 km to 6000 km compared to the ~1000 km to 4000 km coverage of FAST. *Morooka and Mukai* [2003] found that the average potential drop was independent of season and was higher on the nightside than the dayside, which is similar to our results. For events with large (>2 keV potential drops), they found that the occurrence of electron beams peaked near midnight both in summer and winter with the winter occurrence higher than summer by ~2, similar to our results for high energy flux events. However, their results for total potential drops <2 keV are not consistent with our results for low energy flux since they do not see events in the pre-midnight region and the dayside occurrence is higher in summer than in winter.

4. Conclusions

[16] A study of three years of electron data from the FAST satellite has been made to explore the dependence of

auroral acceleration in the upward current region on solar illumination. The decrease in occurrence probability of auroral electron beams during illuminated conditions increases with energy flux carried by the beam. Only very small changes are seen for electron beams with energy flux less than or equal to a few erg/cm^{2}s; whereas for an energy flux >5 ergs/cm^{2}s, the ratio is ~2 to 2.5, consistent with the results of *Newell et al.* [1996b]. The slightly larger effect observed by Newell et al. is most likely due to the altitude difference since FAST is often within the acceleration region during darkness. The characteristic energy of the beams is higher is darkness than in sunlight with this effect being more pronounces for night side beams.

[17] To contrast the occurrence of parallel potential drops in the upward and downward current regions, we compare the statistical dependence of upflowing electron beams (UFE) observed at FAST altitudes [*Cattell et al.*, 2004] to the results described herein for downflowing beams. The occurrence probability of UFE is ~10 times larger in darkness than in sunlight and increases with altitude over the observed altitude range of ~750 km to ~4000 km. The occurrence probability increases less rapidly with solar zenith angle (or hours since sunset) for lower altitudes than for higher altitudes. Thus, the altitude and occurrence of parallel electric fields in both the downward and upward current regions are strongly dependent on solar illumination. The effect is most dramatic at low altitudes. In the downward current region, the parallel electric field extends below 1000 km in darkness and below 1500 km in sunlight and the parallel potential drop below 4000 km is usually the order of 100 to 300 eV. In the upward current region, a large parallel potential is rare below ~2500 km even in darkness [*Temerin*, 1999] and typical potential drops below 4000 km are the order of 1 keV on the nightside and ~100 eV on the dayside. In both the upward and downward current regions, the altitude distribution and size of the potential is controlled by the field-aligned current and quasi-neutrality. Illumination effects on the ionospheric density and its altitude dependence are similar in upward and downward current regions [*Johnson et al.*, 2001]. It is the difference in the boundary conditions that results in the differences seen at low altitudes, as discussed by *Temerin and Carlson* [1998], *Temerin* [1999], *Paschmann et al.* [2003], and *Cattell et al.* [2004].

[18] **Acknowledgments.** The authors thank the NASA FAST spacecraft and operations teams, the instrument engineering and software teams at UCB and UCLA, and the SOC team at UCB. This work was supported by NASA grants NAG5-3596, NAG5-12590, and NAG5-12761.

[19] Arthur Richmond thanks Kristina A. Lynch and Patrick T. Newell for their assistance in evaluating this paper.

References

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

Carlson, C. W., et al. (2002), The Electron and Ion Plasma Experiment for FAST, *Space Sci. Rev.*

Cattell, C., J. Dombeck, W. Peria, R. Strangeway, R. Elphic, and C. Carlson (2003), FAST observations of the dependence of dayside field-aligned currents on solar wind parameters, *J. Geophys. Res.*, *108*(A3), 1112, doi:10.1029/2001JA000321.

Cattell, C., J. Dombeck, W. Yusoff, C. Carlson, and J. McFadden (2004), FAST observations of the solar illumination dependence of upflowing electron beams in the auroral zone, *J. Geophys. Res.*, *109*, A02209, doi:10.1029/2003JA010075.

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

Ergun, R. E., et al. (1998), FAST satellite observations of electric field structures in the auroral zone, *Geophys. Res. Lett.*, *25*, 2025.

Ergun, R. E., C. Carlson, J. McFadden, F. Mozer, and R. Strangeway (2000), Parallel electric fields in discrete arcs, *Geophys. Res. Lett.*, *27*, 4053.

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.

Fedder, J., and J. Lyon (1987), The solar-wind-magnetosphere-ionosphere current voltage relationship, *Geophys. Res. Lett.*, *14*, 880.

Fujii, R., T. Iijima, T. Potemra, and M. Sugiura (1981), Seasonal dependence of large-scale field-aligned currents, *Geophys. Res. Lett.*, *8*, 1103.

Hull, A. J., J. W. Bonnell, F. S. Mozer, and J. D. Scudder (2003), A statistical study of large amplitude parallel electric fields in the upward current region of the auroral acceleration region, *J. Geophys. Res.*, *108*(A1), 1007, doi:10.1029/2001JA007540.

Johnson, M. T., J. R. Wygant, C. Cattell, F. S. Mozer, M. Temerin, and J. Scudder (2001), Observations of the seasonal dependence of the thermal plasma density in the southern hemisphere auroral zone and polar cap at 1 Re, *J. Geophys. Res.*, *106*, 19,023.

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.

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

Kumamoto, A., and H. Oya (1998), Asymmetry of occurrence-frequency and intensity of AKR between summer polar region and winter polar region sources, *Geophys. Res. Lett.*, *25*, 2369.

Liou, K., P. T. Newell, C.-I. Meng, M. Brittnacher, and G. Parks (1997), Synoptic auroraldistribution: 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.

Lyatsky, W., P. T. Newell, and A. Hamza (2001), Solar illumination as cause of the equinoctal preference for geomagnetic activity, *Geophys. Res. Lett.*, *28*, 2535.

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

McFadden, J., C. Carlson, and R. Ergun (1999a), Microstructure of the auroral acceleration region as observed by FAST, *J. Geophys. Res.*, *104*, 14,453.

McFadden, J., C. Carlson, R. Ergun, D. Klumpar, and E. Moebius (1999b), Ion and electron characteristics in auroral density cavities associated with ion beams: No evidence for cold plasma, *J. Geophys. Res.*, *104*, 14,655.

Morooka, M., and T. Mukai (2003), Density as a controlling factor for seasonal and altitudinal variations of the auroral particle acceleration region, *J. Geophys. Res.*, *108*(A7), 1306, doi:10.1029/2002JA009786.

Mozer, F. S., C. A. Cattell, M. K. Hudson, R. L. Lysak, M. Temerin, and R. B. Torbert (1980), Satellite measurements and theories of low altitude auroral particle acceleration, *Space Sci. Rev.*, *27*, 155.

Newell, P., K. Lyons, and C. Meng (1996a), A large survey of electron acceleration events, *J. Geophys. Res.*, *101*, 2599.

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

Paschamann, G., S. Haaland, and R. Treumann (Eds.) (2003), *Auroral Plasma Physics*, *ISSI Space Sci. Ser.*, Springer, New York.

Petrinic, S., et al. (2000), Dayside/nightside auroral x-ray emission differences: Implications for ionsopheric conductance, *Geophys. Res. Lett.*, *27*, 3277.

Pokhotelov, D., W. Lotko, and A. Streltsov (2002), Effects of seasonal asymmetry in ionospheric Pedersen conductance on the appearance of discrete aurora, *Geophys. Res. Lett.*, *29*(10), 1437, doi:10.1029/2001GL014010.

Ridley, A. J., T. I. Gombosi, and D. L. DeZeeuw (2004), Ionospheric control of the magnetosphere: Conductance, *Ann. Geophys.*, *22*, 567–584.

Russell, C. T., and R. L. McPherron (1973), Semi-annual variation of magnetic activity, *J. Geophys. Res.*, *78*, 92.

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.

Strangeway, R., et al. (1998), FAST observations of VLF waves in the auroral zone: Evidence of very low plasma density, *Geophys. Res. Lett.*, *25*, 2065.

Temerin, M. A. (1999), A FAST satellite statistical study of upgoing ion beams in the auroral zone at altitudes below 4200 km, *Eos Trans. AGU*, *80*, Fall Meet. Suppl., Abstract SM11C-06.

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

C. Carlson and J. McFadden, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA. (ccc@ssl.berkeley.edu)

C. Cattell and J. Dombeck, School of Physics and Astronomy, 116 Church St. SE, University of Minnesota, Minneapolis, MN 55416, USA. (cattell@fields.space.umn.edu)