Modulation of auroral field-aligned electron fluxes under two inverted-V structures at different altitudes

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[1] This paper presents observations of field-aligned electron flux bursts from the auroral sounding rocket flight, Alaska 2000, launched February 25, 2000 from Poker Flat, Alaska. In one particular energetic electron burst, the field-aligned electron flux is observed to be modulated at 22–30 Hz at energies up to 30 keV. By assuming that the observed energy dispersion in the bursts is caused by time-of-flight effects, we obtain characteristic source altitudes of 87 dispersive electron bursts, and find that the average characteristic source altitude of the bursts is 4015 ± 684 km in the first inverted-V and 5411 ± 972 km in the second inverted-V. This result implies that the electron-wave or other interaction depends more strongly on which arc it occurs in, rather than another factor such as energy of the electrons, since dispersive bursts at a wide range of energies and durations were used to arrive at the result. *INDEX TERMS:* 2455 Ionosphere: Particle precipitation; 2407 Ionosphere: Auroral ionosphere (2704); 2483 Ionosphere: Wave/particle interactions; 2451 Ionosphere: Particle acceleration

1. Introduction

[2] The fact that rocket measurements of electrons in the aurora allow remote sensing of wave activity at higher altitudes was used by *Temerin et al.* [1986] to explain the observations of *McFadden et al.* [1984], who measured fluctuations in the field-aligned electron fluxes on earlier auroral sounding rocket flights. The frequencies of the modulation, approximately 2–20 Hz, are similar to that of flickering aurora [*Kunitake and Oguti*, 1984]. *McFadden et al.* [1984] also observed energy dispersion in the electrons, where the higher energy electrons arrived before the lower energy electrons. By assuming that the dispersion is due to a time-of-flight effect, they determined the source distance to be 6000–7000 km altitude, where the local oxygen gyrofrequency is 6–7 Hz. *Temerin et al.* [1986] described a model in which ion cyclotron waves' phase velocity increased with decreasing altitude, so that the electrons would lose resonance at a particular altitude (or a narrow range of altitudes). Since the electrons would then propagate downwards and disperse according to their energy (velocity), it would appear, based on measurements from below, that the electrons were "released" at a particular altitude. Throughout this paper, we call this release altitude the characteristic source altitude. *Temerin et al.* [1986] predicted that modulations should also be observed in the 80–100 Hz range, due to hydrogen cyclotron waves. These were subsequently observed by *McFadden et al.* [1987].

[3] Recently, *Arnoldy et al.* [1999] have presented electron flux measurements from the PHAZE II rocket and have proposed another mechanism for explaining similar modulations at 10 and 100 Hz which involves turning on and off the electrostatic inverted-V potential at the observed electron flux modulation frequencies. Their model was proposed to explain the simultaneous observation of both high- and low-energy electrons that were dispersed in energy and pitch angle.

[4] The present study presents auroral sounding rocket observations of field-aligned electron fluxes that are modulated at frequencies of 22–30 Hz, in between the frequencies of earlier reported observations. The study also examines the characteristic source altitude of the electron bursts by tracing the dispersive bursts using time-of-flight. We find that the average characteristic source altitude of the bursts occurring under the first inverted-V is different from the average characteristic source altitude of the bursts occurring under the second inverted-V.

2. Experiment

[5] Measurements in this study were obtained from Alaska 2000, an auroral sounding rocket experiment launched February 25, 2000 at 7:45 UT (~21 MLT) into the expansion phase of a substorm. The rocket reached an apogee of 1190 km and flew northward into the polar cap before loss of signal 1193 seconds after launch.

[6] We present measurements from the Fast Electron Spectrograph (FES), a magnetic sector electron detector, which measured electrons from 300 eV to 44 keV. The FES was mounted such that its aperture looked up the magnetic field line; the angular acceptance is 12° by 28°. With a 1-ms integration period and average geometric factor of 7.06×10^{-3} cm^2-sr, the FES was designed for high time resolution measurements of the parallel electron distribution.

3. Data

[7] The top panel of Figure 1 shows a summary plot of the FES electron data. As can be seen, the rocket passed through two accelerated electron precipitation regions with energies up to 40 keV. Panel 2 shows a blow-up of the region from 485 to 512 seconds under the first inverted-V where 22–30 Hz dispersed, modulated electrons are observed. Panel 3 is a 1.5-second timespan close-up that shows the modulations in detail. The electron energy flux of the individual channels are shown as line plots in the bottom of panel 3. The 30-Hz modulations can be seen extending from the 3.66 keV to the 28.6 keV channels. It is also apparent that these bursts are dispersive (e.g., the feature between 504.0 and 504.4 seconds), with the higher energy electrons arriving before the lower energy electrons. We perform a time-of-flight analysis, where we determine the characteristic source distance from the slope of the fitted line when the points are plotted on time offset versus inverse velocity axes, and find the characteristic source altitude to be in the 3000 to 7500 km range. Though not shown, the electric field wave experiment did not show appreciable power at 30 Hz, suggesting that the modulations were not due to a local wave-particle interaction.

[8] In Figure 2, we show another portion of the flight that contains lower energy (<11.9 keV) dispersive electron bursts. Throughout the flight, dispersive electron bursts were seen in all energy channels from 307 eV to 38.2 keV, with a typical burst spanning 4 or 5 energy channels from ~1 keV to ~7 keV. The

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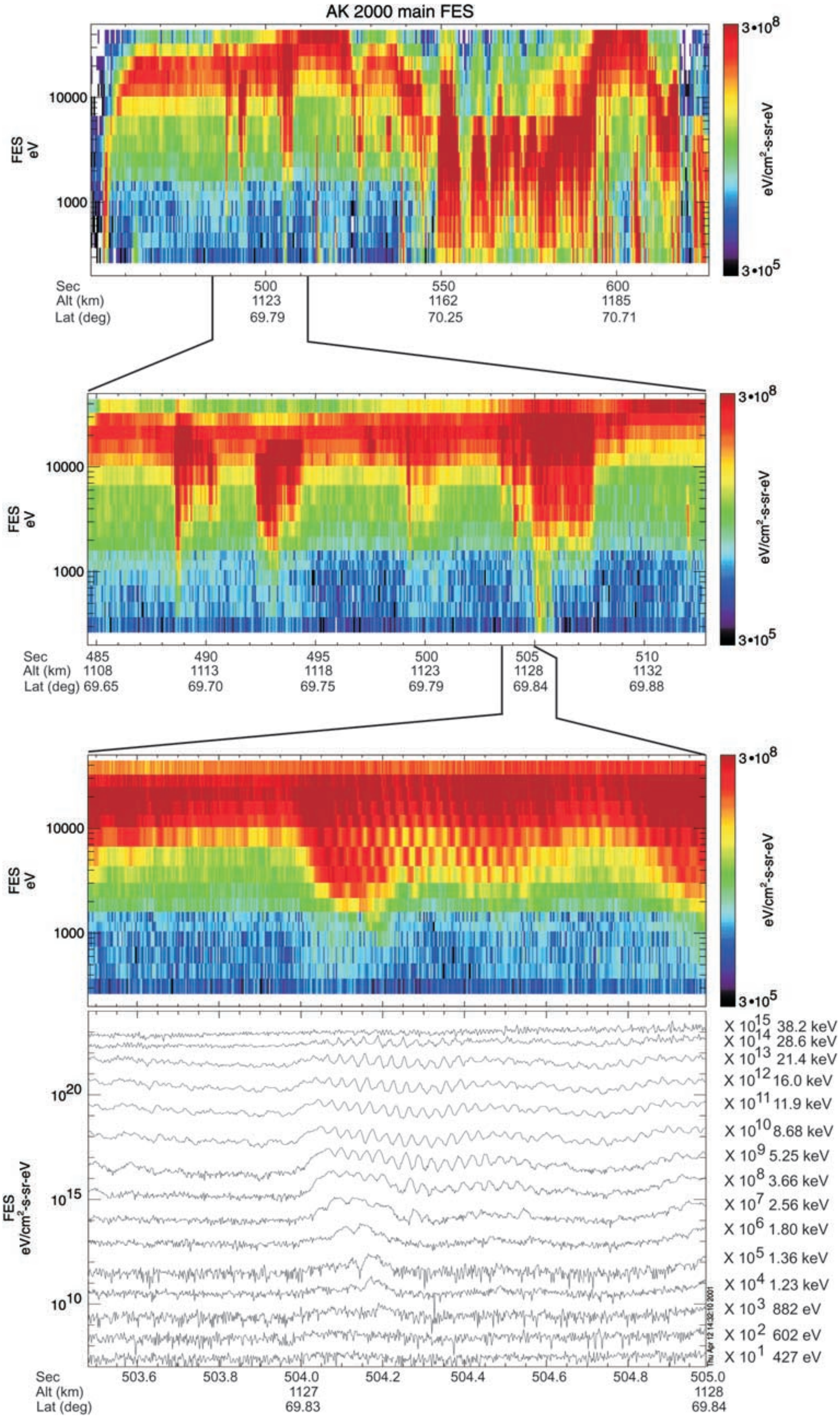

Figure 1. Field-aligned electron summary plot of AK 2000 flight. The top panel shows field-aligned (downgoing) electron data from the Fast Electron Spectrograph (FES) detector. It can be seen that the rocket passed under two inverted-V structures centered at 510 seconds and 600 seconds flight time. The second panel shows a blow-up of a section of the first inverted-V where 22–30 Hz modulations were observed. The bottom 2 panels show a 1.5-second span of FES data, where the modulations are clearly seen. The last panel displays line plots of the energy flux measured by individual FES channels. The modulations are seen most clearly from 504.0 to 504.5 seconds in the 3.66 keV to 28.6 keV channels.

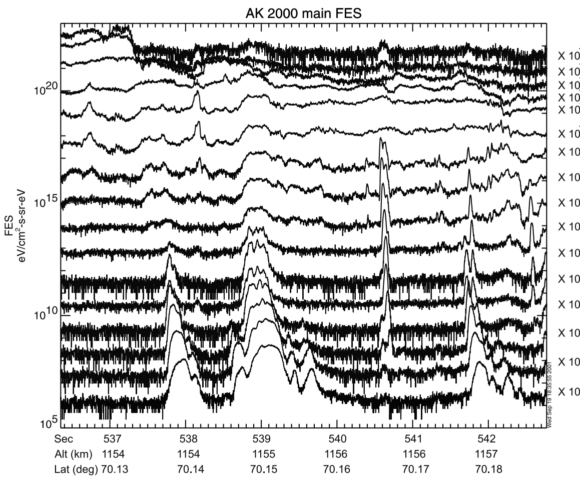

Figure 2. Similar to the last panel of Figure 1, line plots of energy flux measured by individual FES channels during flight time 536.4 to 542.7 seconds are shown. Dispersive electron bursts can be seen at 537.7–538.1 seconds (307 eV to 1.36 keV), 538.2 seconds (5.25 keV to 11.9 keV), 538.8–539.2 seconds (307 eV to 1.80 keV), 540.6–540.7 seconds (602 eV to 5.25 keV), 541.7–541.9 seconds (307 eV to 1.36 keV), 541.7–541.9 seconds (602 eV to 5.25 keV), 542.1 seconds (2.56 keV to 5.25 keV), 542.1 seconds (3.66 keV to 8.68 keV), 542.6 seconds (1.23 keV to 3.66 keV). As can be seen here, the dispersive electron bursts occur over a wide range of energies and are of varying durations.

duration of the bursts varied from ~0.03 seconds to ~0.8 seconds; electron bursts presented in Figure 2 are fairly representative of bursts seen throughout the flight. There was no apparent correlation between energy of the burst and the characteristic source altitude.

[9] In Figure 3, we show the results of systematically tracing each of 87 dispersive electron bursts throughout the flight to obtain a plot of the characteristic source altitude as a function of flight time. The bursts before 540 seconds flight time have a characteristic source altitude in the range of 4015 ± 684 km, while the bursts after 540 seconds have a characteristic source altitude in the range of 5411 ± 972 km. If we re-examine Figure 1 we see that 540 seconds is where the first inverted-V ended.

[10] It is necessary to quantify the certainty of this result, as the time-of-flight source altitude determination has its uncertainties. In this analysis, we used 87 bursts of electrons where a dispersive feature could be seen in the energy flux of at least 3 consecutive channels of the FES. For each burst, a characteristic source distance was determined by plotting the peaks of the burst as observed in each energy channel of the FES on time delay versus inverse velocity axes. The slope determined by fitting a line to these points was used to infer a characteristic source distance. As there were 27 points before flight time 540 seconds and 60 points after 540 seconds, we arrive at the result that the characteristic source altitude in the first inverted-V was 4015 ± 684 km and the characteristic source altitude in the second inverted-V was 5411 ± 972 km. The values and the error bars were obtained from the mean and the standard deviation of the characteristic source altitudes determined by fitting the electron bursts.

4. Discussion

[11] Modulations of field-aligned electrons have been reported in the literature, but these results show several new aspects: (1) they show modulation in electrons up to energies as large as 30 keV (2) the modulation is in the 22–30 Hz range, which lies between the O^+ and He^+ gyrofrequencies at altitudes between 2300 and 6000 km, and (3) the characteristic source altitude of the bursts depends on which inverted-V structure the rocket passed under, rather than the energy of the burst.

[12] Alaska 2000 passed through one of the most energetic electron inverted-V arcs observed by sounding rockets. The peak energy of the arcs exceeded 40 keV (the upper energy bound of the FES detector) at its most energetic point, though the peak energies of the spectra were closer to 30 keV most of the time. The ratio of the electron energy flux at the crest and valley of the modulations ("peak-to-valley ratio") was approximately 3, which represents a significant shift of the energy flux peak relative to the temperature of the distribution. The implication of the large energy flux modulations of high energy (30 keV) electrons is that if wave-particle interaction is responsible for the electron flux modulation, the amplitude of the wave must be large. A quantitative estimate of the amplitude of the waves would require a detailed temperature fit to the measured distributions and assumptions about the altitude range of wave-particle interaction, which is beyond the scope of this letter.

[13] Papers in the literature have reported sources of electron flux modulation as due to ion cyclotron waves [*Temerin et al.*, 1993], kinetic Alfvén waves [*Kletzing and Hu*, 2001], or varying electrostatic potentials [*Arnoldy et al.*, 1999]. If a combination of these mechanisms is responsible for electron flux modulations, our result implies that the altitude of electron interaction depends less on which mechanisms within an inverted-V arc are modulating the electrons, and more on which inverted-V arc the electrons are modulated in.

5. Summary

[14] We have observed auroral field-aligned electron populations on a recent sounding rocket flight that passed through a 30–40 keV inverted-V arc. The inverted-V electron population was time-of-flight dispersed and modulated at 22–30 Hz in portions of the flight. The frequency of the modulations falls between the He^+ and O^+ gyrofrequencies over the altitude range 2300–6000 km of interest. Because the modulation in energy flux had a peak-to-valley ratio of about 3, and electrons up to 30 keV were modulated, a strong amplitude wave would need to be present at altitudes of 3000 to 5000 km if wave-particle interaction is the mechanism responsible for the electron flux modulation.

[15] By using 87 dispersive electron bursts observed on this flight, we have traced, using time-of-flight, the characteristic

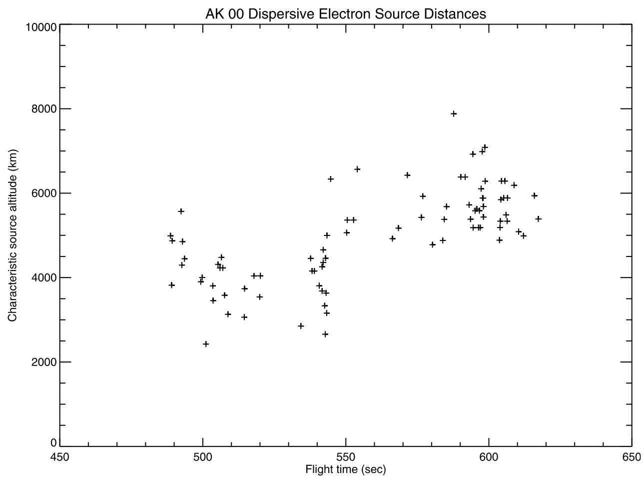

Figure 3. Characteristic source altitudes of FES dispersive electron bursts as a function of flight time. Characteristic source altitudes were determined by assuming that energy dispersion was due to a simple time-of-flight effect.

source altitude of the electron-wave interaction. We have found that the average characteristic source altitude of the bursts is 4015 ± 684 km under the first inverted-V, while the average characteristic source altitude of the electron bursts under the second inverted-V is higher, 5411 ± 972 km. Because the altitudes were computed using bursts of a wide range of electron energies and possibly due to different mechanisms, the result implies that the interaction altitude range is more strongly dependent on the specific arc structure, rather than on another factor such as electron energy or acceleration mechanism.

[16] **Acknowledgments.** The authors acknowledge useful discussion with John Bonnell. This work was supported by NASA grants NAG6-10 and NGT5-50061.

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