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Electron Phase-Space Holes and the VLF Saucer Source Region

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Abstract: The Fast Auroral SnapshoT (FAST) satellite has identified new properties of VLF saucers that are important to understanding their generation and the physical processes in the source region. The most significant finding is a frequent occurrence (~79%) of electron phase-space holes on flux tubes of the VLF saucer source in the downward current region. This finding implies either a common energy source or a direct association between the two phenomenon. FAST observations also demonstrate that VLF saucer vertices are strongly correlated with up-going electron fluxes associated with diverging DC electric field structures. These observations imply parallel electric fields along the source flux tube of VLF saucers.

Introduction

Spatially-coherent solitary structures have been observed in several distinct regions of the Earth's magnetosphere [*Matsumoto et al.*, 1994; *Mozer et al.*, 1997; *Ergun et al.*, 1998a,b; *Franz et al.*, 1998; *Bale et al.*, 1998]. The observed structures have been modeled in 1-D as Bernstein-Green-Kruskal (BGK) solutions to the Vlasov-Poisson equations known as "electron phase-space holes" [*Omura et al.*, 1994; *Krasovsky et al.*, 1997; *Muschietti et al.*, 1999]. Observations in space, in particular of 3-D structures [*Ergun et al.*, 1998a,b; *Franz et al.*, 2000], have sparked several theoretical investigations on multi-dimensional electron phase-space holes [*Goldman et al.*,1999; *Muschietti et al.*, 1999; 2000; *Oppenheim et al.*, 1999; *Miyake et al.*, 2000]. 2-D and 3-D structures have been reproduced in numerical simulations that prescribe bidirectional electron beams as an initial condition [*Goldman et al.*, 1999; *Oppenheim et al.*, 1999; 2001]. The auroral growth mechanism, however, has yet to be established.

Numerical simulations of the two-stream instability indicate mostly 1-D structures ($E_\perp << E_\|$) in the early stages of evolution. The multi-dimensional electron holes form later as a result of their break-up into 2-D and 3-D structures. During this break up, whistler wave emissions are seen in numerical simulations [*Goldman et al.*, 1999; *Oppenheim et al.*, 1999] and predicted by analytic solutions [*Vetoulis and Oppenheim*, 2001; *Newman and Goldman*, 2001; *Newman et al.*, 2001].

We present observations of quasi-electrostatic whistler emissions known as VLF (very low frequency, or kilohertz radio range) "saucers" that are associated with electron phase-space holes. VLF saucers were among the first radio-wave features observed in the auroral zone [*Smith et al.*, 1966; *Gurnett*, 1966] and have been established as a common characteristic [e. g., *James*, 1976, and references therein]. The phenomena has a V-shaped or saucer-shaped appearance in time-frequency-power spectrograms of the wave electric field in the kilohertz frequency range. The V-shape is due to the propagation characteristics of quasi-electrostatic whistlers. Under the cold fluid approximation, near-lower hybrid emissions have a group velocity nearly along the ambient magnetic field (***B***) whereas higher frequency emissions have a more oblique group velocity. Thus, a satellite that passes over a continuous, finite-size, source region detects the higher frequencies farther away from the flux tube of the source and the lowest frequencies as it passes over the flux tube of the source.

Many properties of VLF saucers have been established. *James*, [1976] deduced source regions as small as 0.5 km in latitude and less than 10 km in altitude. An extended source region in longitude is possible [*Temerin*, 1979]. *James* [1976] also postulated that the instability comes from cold (< 5 eV), dense, up-going ionospheric electrons carrying the downward or "return" current in the auroral zone. An instability is predicted as the ionospheric electrons impinge upon a warm magnetospheric population. The up-going electron fluxes, albeit at higher energies, were verified by Viking satellite observations which detected several examples of up-going electrons associated with VLF saucers [*Lonnqvist et al.*, 1993].

The purpose of this letter is to communicate new properties of VLF saucers. FAST observations of the VLF saucer flux tube now reveal that ~85% of VLF saucers events are associated with up-going electron fluxes that have been energized by parallel electric fields [*Carlson et al.*, 1998a]. Of those events, ~79% are associated with electrostatic solitary structures traveling anti-earthward on the same flux tubes as the VLF saucer source region. This association greatly exceeds the ~5% occurrence of electrostatic solitary structures with up-going electron fluxes [*Ergun et al.*, 1998a] and thus suggests a strong connection between the two phenomena.

Observations

The observations are from the FAST satellite [*Carlson et al.*, 1998b]. Figure 1 displays a large-scale view (145 s or ~850 km) of electric field, magnetic field, and electron observations in the morning-side of the Northern auroral zone. The spacecraft was traveling approximately from North to South at ~6 km/s so the horizontal axis is interpreted as distance as well as time.

Panel (a) of Figure 1 displays the DC electric field signal ($E_\perp$) along the velocity of the spacecraft ($\boldsymbol{v}_{sc}$) and perpendicular to ***B*** (the ($\boldsymbol{B}$ x $\boldsymbol{v}_{sc}$) x ***B*** direction). There are several moderate-amplitude (~100 mV/m) DC electric field structures, each of which starts with a negative excursion and ends with a positive excursion. These diverging electric field structures indicate a downward parallel electric field at lower altitude [*Ergun et al.*, 1998c].

Panel (b) displays the perturbation magnetic field ($\Delta\boldsymbol{B}$) perpendicular to a model magnetic field and nearly normal to the space-

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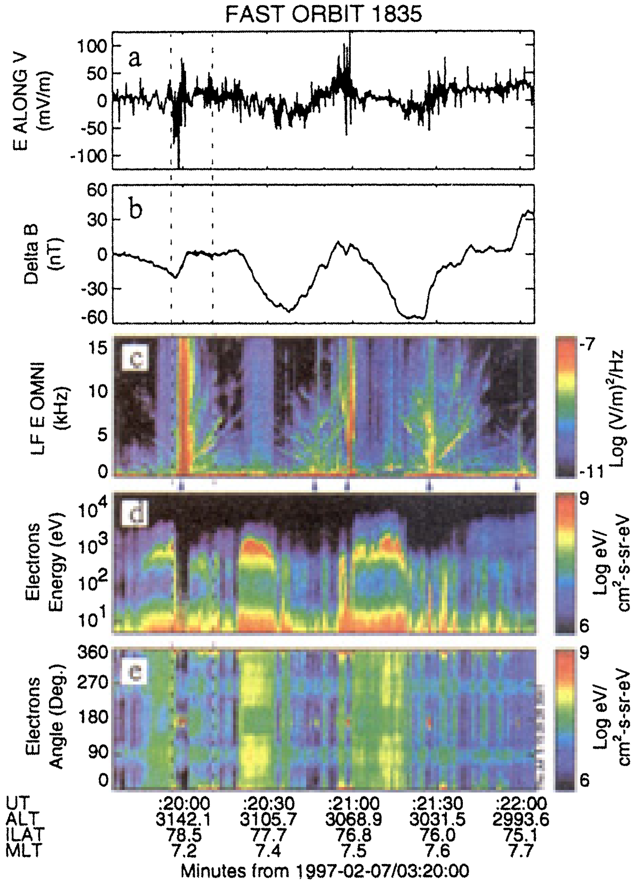

Figure 1. A large-scale view of the VLF source region. (a) The DC electric field perpendicular to $\boldsymbol{B}$ and projected in the direction of the spacecraft velocity. (b) $\Delta\boldsymbol{B}$ perpendicular to a model $\boldsymbol{B}$ and perpendicular to the spacecraft velocity. A positive slope indicates a downward current. (c) The omni-directional electric field spectral power density from ~40 Hz to 16 kHz at 32 Hz resolution and ~1/2 s per spectra. (d) The omni-directional electron energy flux as a function of energy at ~1/3 s per spectra. (e) The integrated electron energy flux in the 10 eV to 30 keV range as a function of pitch angle. 0° is earthward and 180° is anti-earthward.

craft velocity ($\boldsymbol{B} \times \boldsymbol{v}_{sc}$ direction, nearly westward). The slope of the signal indicates current. Assuming a sheet-like structure, a negative slope is an upward current and a positive slope is a downward current. Panel (c) is the omni-directional, electric field spectral power density in the 0 - 16 kHz range. The V-shaped emissions are from a series VLF saucers, five of which are marked at their vertex with a blue arrow. The vertical features are bursts of broadband electrostatic noise that often accompany VLF saucers [*Lonnqvist et al.*, 1993]. We show that these broadband bursts are a series of electrostatic solitary structures which we interpret and electron phase-space holes propagating past the spacecraft.

Panel (d) displays the electron differential energy flux (color) as a function of energy (vertical axis) and time. Panel (e) displays the electron differential energy flux as a function of pitch angel (0° is earthward and 180° is anti-earthward). VLF saucer events all have vertices in regions of intense up-going electron fluxes indicating that the up-going electrons are the energy source [*James*, 1976; *Lonnqvist et al.*, 1993], and all vertices are surrounded by a diverging DC electric field structure indicating that a parallel electric field is on the flux tube at lower altitudes [*Carlson et al.*, 1998a; *Ergun et al.*, 1998c]. The vertices lie in the downward current region as evidenced by the positive slope in $\Delta\boldsymbol{B}$ seen in Panel (b).

More details of the waves and the up-going electron fluxes at the saucer vertex emerge in high-resolution data. Figure 2 displays a 15 s "snapshot" of the wave electric field and electron data during the first VLF saucer event in Figure 1 (marked with vertical lines). Panel (a) is the omni-directional electric field spectral power density in the 0 - 16 kHz range at 32 ms per spectra. Panels (b) and (c) display the electron energy flux at ~80 ms per spectra. Panel (d) is a 25 ms plot of the parallel (to $\boldsymbol{B}$) wave electric field signal. The large-amplitude (~100 mV/m) spikes seen in the trace are solitary structures that are a signature of electron phase-space holes [*Muschietti et al.*, 1999]. High resolution data are not available for the other VLF saucer events in Figure 1, but broadband electrostatic bursts, a spectral signature of electron phase-space holes, are evident.

The above example demonstrates the strong correlation between VLF saucers, up-going electron fluxes, diverging DC electric field structures, electron phase-space holes. In a 100 event study, 85 of the VLF saucer vertices had detectable up-going electron fluxes and diverging DC electric field structures. Of these 85 events, 67 had bursts of broadband electrostatic noise with spectral density > 10^{-8}

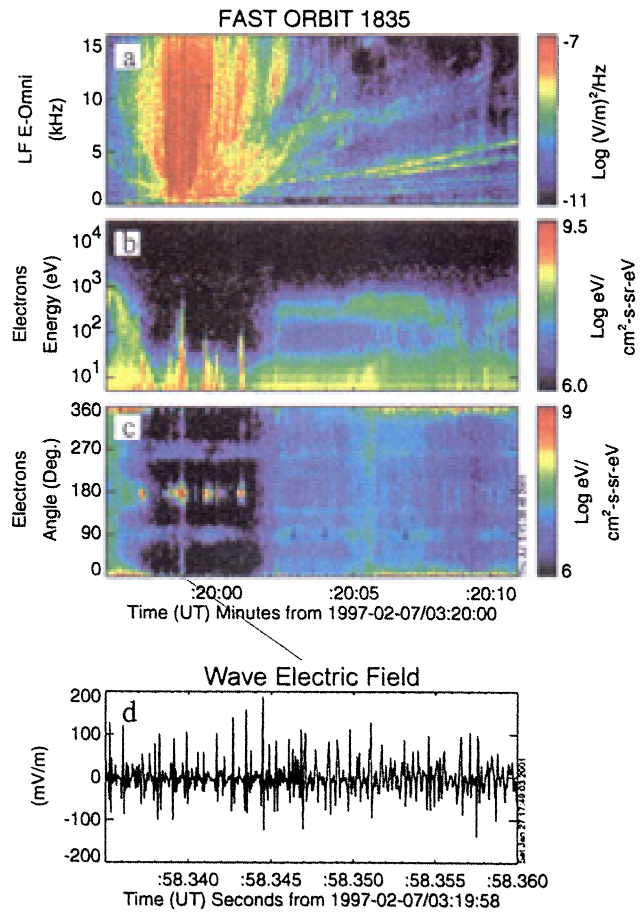

Figure 2. A close-up view of the VLF saucer marked on Figure 1. (a) The omni-directional electric field spectral power density from ~40 Hz to 16 kHz with 32 Hz resolution and 31.25 ms per spectra. (b) The electron energy flux as a function of energy at ~80 ms per spectra. (c) The electron energy flux in the 10 eV to 30 keV range as a function of angle. 0° is earthward and 180° is anti-earthward. (d) A 25 ms sample of the parallel (to $\boldsymbol{B}$) wave electric field signal at 30.5 μs resolution.

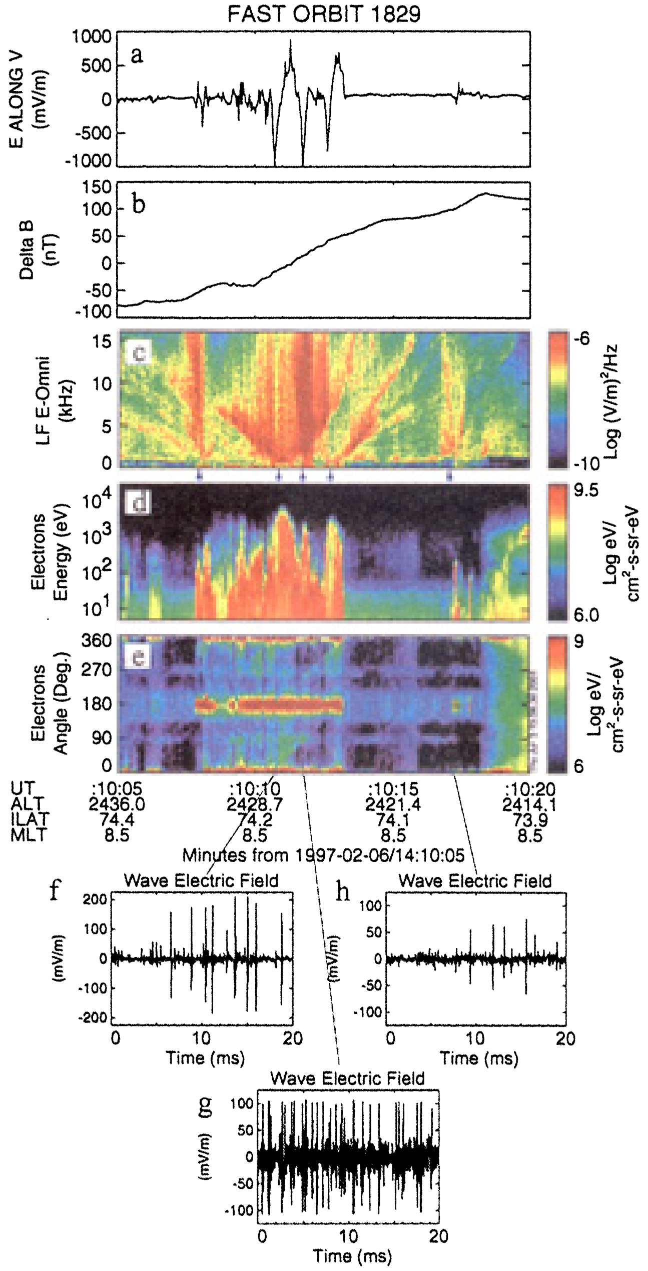

Figure 3. A close-up view of the VLF saucer flux tube. (a) The DC electric field perpendicular to $\boldsymbol{B}$ and projected in the direction of v_{sc}. (b) One component of $\Delta\boldsymbol{B}$. A positive slope indicates a downward current. (c) The omni-directional electric field spectral power density from ~40 Hz to 16 kHz with 32 Hz resolution and 31.25 ms per spectra. (d) The electron energy flux as a function of energy at ~80 ms per spectra. (e) The electron energy flux in the 10 eV to 30 keV range as a function of angle. 0^o is earthward and 180^o is anti-earthward. (f-h) 20 ms snapshots of the parallel (to $\boldsymbol{B}$) wave electric field signal at 30.5 μs resolution.

$(V/m)^2$/Hz. Of those 67 events, 37 were at times of snapshots of high-resolution waveform data. All 37 of the waveform captures verified that the broadband bursts were evidence of electrostatic solitary structures, the signature of electron phase-space holes. Of the 18 downward current region events that had no broadband electrostatic bursts, 5 had waveform captures. Of those 5 waveform captures, 3 had no detectable electron phase space holes and 2 had weak, sparse events. We conclude that electron phase space holes are propagating on the flux tubes of more than 79% (more than 67 out of 85) of the VLF saucers in the downward current region. It may be possible that the uncorrelated events did not cross the source flux tube, so the association may be stronger. It should be noted that there are observations of electron phase-space holes that are not at a vertex of a VLF saucer event.

The survey was made on continuous (lowest resolution) data. Some of the events had complex source regions with multiple saucers that were either not included or counted as one event. Figure 3 shows an event of the latter type with high-resolution snapshot data. It displays 15 s of wave and particle observations during a VLF saucer event in the morning-side of the Northern auroral zone. Again, the spacecraft was traveling approximately from North to South.

Panel (a) of Figure 3 displays $E_\perp$. The negative excursion (starting at ~14:10:10 UT) followed by a positive excursion (ending ~14:10:13 UT) is evidence a diverging electric field structure which implies a downward parallel electric field at lower altitude. The multiple excursions indicate a complex structure. Panel (b) displays the nearly westward (nearly normal to v_{sc}) component of $\Delta\boldsymbol{B}$. $\Delta\boldsymbol{B}$ has a positive slope indicating a downward current.

Panel (c) displays the electric field spectral power density in the 0 - 16 kHz range. The V-shaped emissions are from a series VLF saucers, four of which have vertices (blue arrows) between ~14:10:08 UT and ~14:13:UT. An isolated V-shaped emission can be seen at ~14:10:17 UT. In the "survey" or continuous data (or in data from previous auroral satellites) the four events would appear as a single source and the isolated V-shaped emission at ~14:10:17 UT would appear as a broadband electrostatic burst. Panel (d) and (e) display the electron differential energy flux. Between ~14:10:08 UT and ~14:13:UT there are intense fluxes of < 3 keV field-aligned electrons. Although fluxes are seen at both 0^o and 180^o, the 180^o fluxes dominate in this case [for details of downward current electron fluxes, see *Carlson et al.*, 1998a]. There also is an isolated burst of electron flux at ~14:10:17 UT.

As in Figure 1, the VLF saucer events in Figure 3 all have vertices in regions of intense up-going electron fluxes indicating that the source region is on these flux tubes at lower altitudes [*James*, 1976; *Lonnqvist et al.*, 1993]. All but one, the forth from the left, of the vertices also has broadband electrostatic noise which indicate electron phase-space holes displayed in Panels (g-h). Examination of the high-resolution data appears to support the conclusions based on the lower-resolution, continuous data.

Discussion and Conclusions

The persistent observation of electron phase-space holes at the vertices of VLF saucers has several possible interpretations. One possibility is that the VLF saucers and electron phase-space holes simply share a common energy source, the up-going electrons, and thus are correlated far from the source but have little direct interaction during the growth process. Another possibility is that the whistler waves and electron phase-space holes interact during growth. A nonlinear scenario has some support due to the extraordinarily large-amplitude electric fields and the small size of the source region. The VLF saucer source region size is limited to less than 10 km in altitude [*James*, 1976], requiring $\boldsymbol{O}(1)$ ms growth rate for whistler waves. If the electron phase-space holes emerge from the same source region, they also must undergo rapid growth.

The observations also can be interpreted in the light of the predicted whistler emission during the growth and evolution of electron phase-space holes [*Vetoulis and Oppenheim*, 2001; *Newman and Goldman*, 2001; *Newman et al.*, 2001]. The 1-D electron phase-space holes that emerge in the early stages in numerical simulations break-up into 2-D and 3-D structures emitting whistler waves during the process. The numerical simulations see the whistler wave emission after ~100 ($1/\omega_{pe}$) to ~1000 ($1/\omega_{pe}$), consistent with the $O(1)$ ms growth ($\omega_{pe} \sim 10^5$ s^{-1}). This break-up process has been investigated analytically. *Newman et al.* [2001] predict a transverse instability in 1-D electron phase-space holes which emit waves below the bounce frequency of the trapped electrons (typically ~1/3 ω_{pe}). These emissions propagate as whistler waves as they emerge from the source region. *Vetoulis and Oppenheim*, [2001] model a kinetic instability which result in transverse wave emission at or above the bounce frequency. These processes may explain the observations of the electron phase-space holes at the vertex of the VLF saucers.

Interestingly, the electron phase-space holes appear on the flux tubes of VLF saucers with source regions as far away as ~2000 km, the limit of our distance estimates. Since electron phase-space holes have velocities of $O(1000)$ km/s [*Ergun et al.*, 1998a], the life time of the structures may be as long as $O(1)$ s or 10^5 ω_{pe} implying that the observed structures, that is, those that propagate to the spacecraft, are highly stable and dissipate slowly. This finding is in consort with the Polar observations of weak solitary structures with no apparent electron fluxes [*Bounds et al.*, 2000].

Finally, we interpret the VLF saucer observations in the light of the recent uncovering of energetic (>> 10 eV), up-going electron fluxes that are accelerated by parallel electric fields [*Carlson et al.*, 1998a; *Ergun et al.*, 1998c]. The strong correlation between the VLF saucer source flux tube and diverging electric field structures should come as no surprise. The uncovering of the parallel electric fields as the primary energy source of up-going electrons and the previous association with VLF saucers with up-going electrons suggest such a correlation. The intense, highly-confined source of the VLF saucer emissions, however, suggests that the distribution of the parallel electric field along the source flux tube is also highly confined. Thus, the source region may be very near, if not within, the region where parallel electric fields accelerate the up-going electron fluxes. The emerging fluxes not only acquire a strong anti-earthward drift velocity, but also show evidence of strong wave-particle interactions which results in substantial parallel heating [*Carlson et al*, 1998a; *Ergun et al.*, 1999a,b]. It is thus possible that the process of electron acceleration, VLF saucer wave emission, and electron-phase space hole generation are interrelated and occur in a highly localized region (< 10 km).

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