Vlasov simulations of auroral processes

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Geometry

We model an auroral flux tube from a source at the magnetospheric equator to the ionosphere, as is illustrated in Fig. 1a. Our model applies to the centre of the arc, where the electric and magnetic fields are parallel. Off centre, the perpendicular electric field component causes the plasma to drift along the arc with a drift velocity $\mathbf{v}_d = \mathbf{E}\times\mathbf{B}/B^2$ (Fig. 1b), and there our model is valid in the drift frame. In that frame $E_\perp = 0$. Satellite crossings of the auroral cavity show that $E_\perp$ field falls in thin layers at the edges of the cavity with small or zero field inside [Hull et al., 2003]

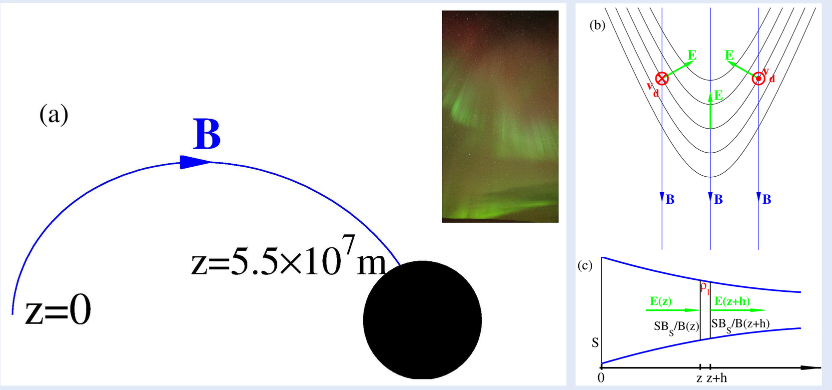

Figure 1: (a) A field line for the $L = 7$ shell. (b) Cross section of an auroral arc. (c) Flux tube cross section z dependence.

Theory

We write the distribution function as $f(z, v_z, \mu, t)$, where z is the spatial coordinate parallel to the magnetic field, v_z is the parallel velocity, and $\mu = \frac{mv_\perp^2}{2B(z)}$ is the magnetic moment. Assuming $\dot{\mu} = 0$, the Vlasov equation for our system is

$$\frac{\partial f}{\partial t} + v_z\frac{\partial f}{\partial z} + \frac{1}{m}\left(qE - \mu\frac{dB}{dz} + ma_g\right)\frac{\partial f}{\partial v_z} = 0. \quad (1)$$

Applying Gauss' law to a fluxtube segment with no perpendicular electric fields, as illustrated in Figure 1c, we obtain

$$\frac{d}{dz}\left(\frac{B_S}{B}E\right) = \frac{\rho_l}{S\epsilon}, \quad (2)$$

where the charge per unit length of the flux tube is given by the line charge $\rho_l = \sum_s q_s \int f_s(v_z, \mu)d\mu dv_z$, which represents the net charge per unit length of the flux tube. By introducing an artificial relative dielectric constant ϵ_r such that $\epsilon = \epsilon_0\epsilon_r$ in Eq. (2) we can run a simulation on a coarser spatial grid and with a longer time step, because $\lambda_D \sim \sqrt{\epsilon_r}$ and $\omega_p \sim 1/\sqrt{\epsilon_r}$ [Rönnmark and Hamrin, 2000]. With $\epsilon_r = \max\left(1, (a\omega_p\Delta t)^2\right)$, the plasma frequency will be reduced so that there are $2\pi a$ time steps per plasma period. Here, ω_p is taken to be the maximum plasma frequency in the system, and the resulting ϵ_r is applied uniformly everywhere. A consequence of introducing an $\epsilon_r > 1$ is that sharp gradients become less sharp.

A description of the simulation model was published by Gunell et al. [2013a]. Fortran source code of the simulation program is available at <http://www.herbertgunell.se/software.php>.

Upward current region

An example of distributions and fields is shown in Fig. 2 for the case when 3 kV was applied over the system. An electric double layer forms near $z = 5\times10^7$ m, and electrons are trapped between it and the magnetic mirror.

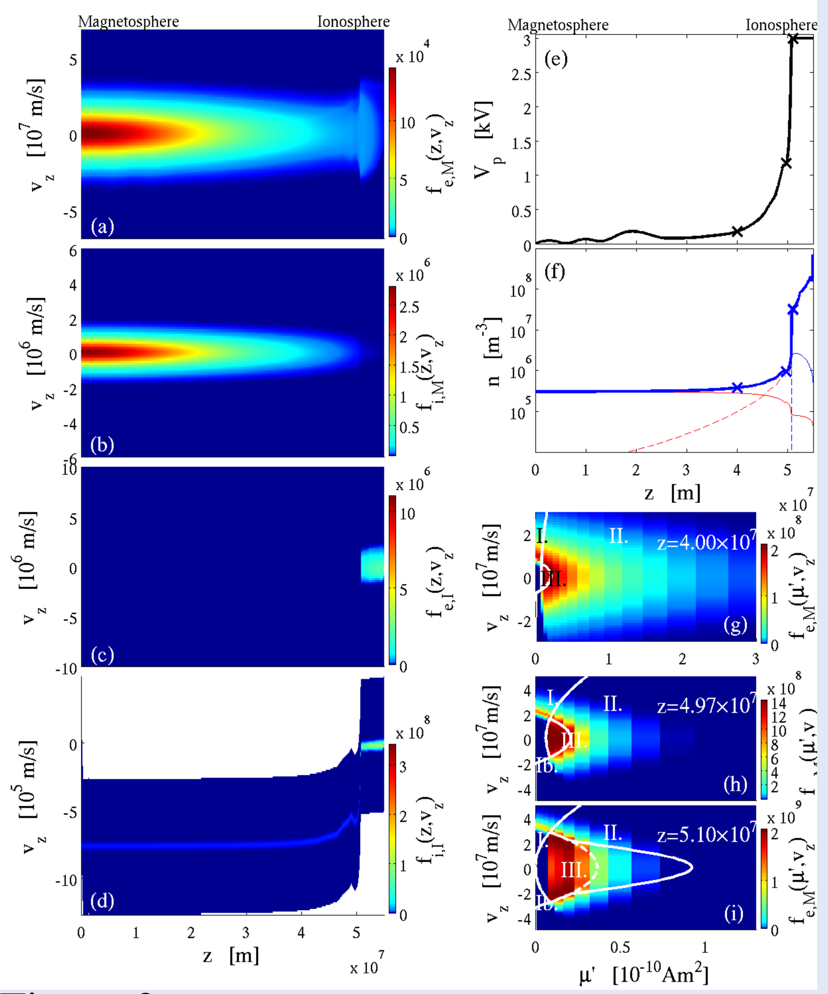

Figure 2: (a-d) Phase space densities $f(z, v_z)$ at $t = 5$ s for (a) magnetospheric electrons; (b) magnetospheric protons; (c) ionospheric electrons; and (d) ionospheric protons.
(e) Plasma potential. (f) Densities.
(g-h) Phase space densities $f(\mu', v_z)$ for magnetospheric electrons at (g) $z = 4\times10^7$ m; (h) $z = 4.97\times10^7$ m; and (i) $z = 5.1\times10^7$ m. These positions are marked in panels (e) and (f).

Similar simulations have been performed for several cases with different voltages. Thus we arrive at a current-voltage relation as shown in Fig. 3, which also shows the double layer position as a function of voltage.

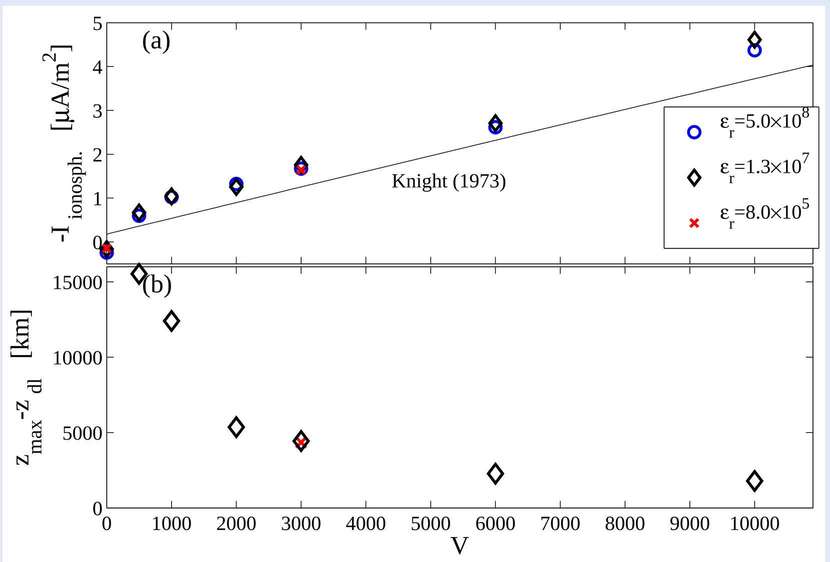

Figure 3: (a) Current density scaled to the ionosphere as a function of the total voltage over the system. The solid line shows Knight's current-voltage relation [Knight, 1973].
(b) Double layer position as a function of the total acceleration voltage.

Downward current region

We applied 100V over a flux tube, with a polarity that would lead to upward acceleration of electrons. The density at the ionospheric end of the system was reduced to $1.45\times10^8\,\mathrm{m}^{-3}$.

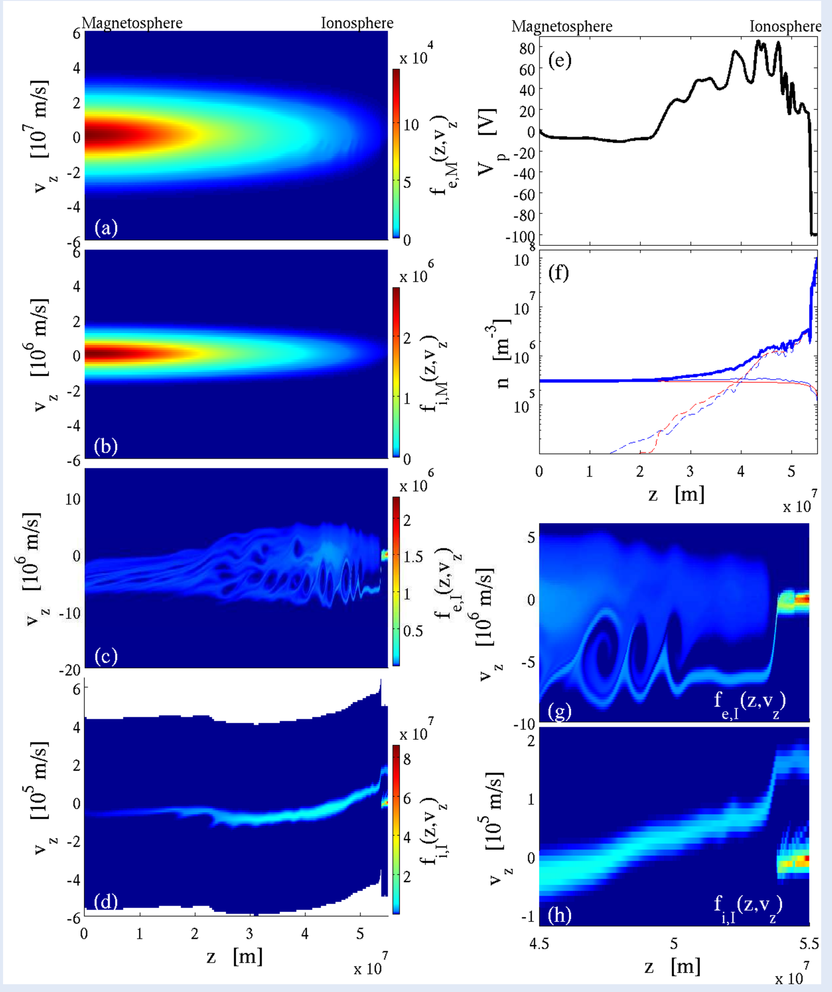

Figure 4: Distributions, potential, and density at $t = 120$ s.

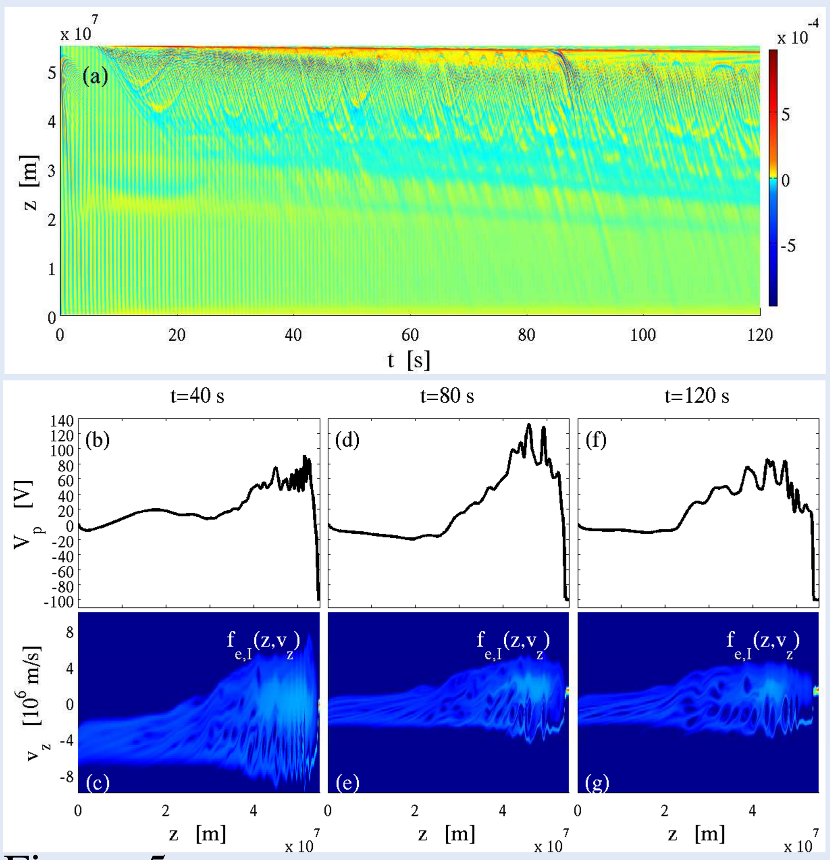

Figure 5: (a) $t - z$ diagram of the electric field. (b-g) Potential profile and distribution of the ionospheric electrons.

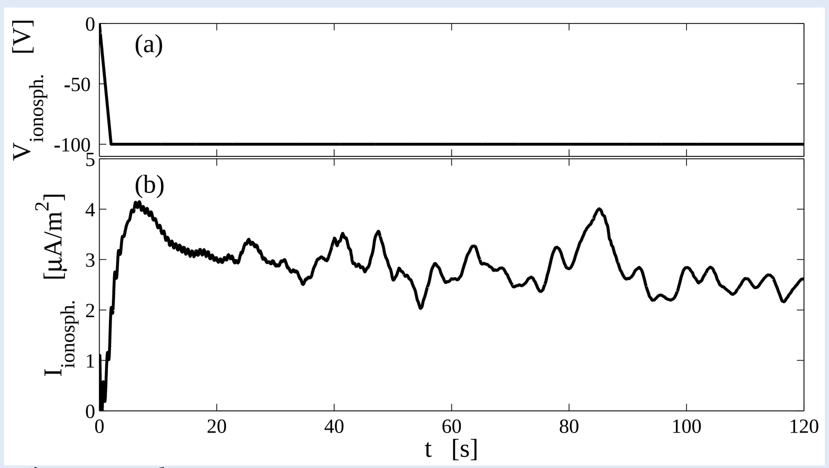

Figure 6: (a) The potential of the ionosphere is lowered from 0 to -100 V in 1 s and then held constant. (b) Current density through the system, scaled to the ionosphere.

Simulated experiments

We have run computer simulations of a proposed laboratory experiment that could be used to model auroral acceleration. A discharge source on the left hand side represents the magnetosphere, and a Q-machine source on the right hand side corresponds to the ionosphere [Gunell et al., 2013b]. The mirror ratio is 25.

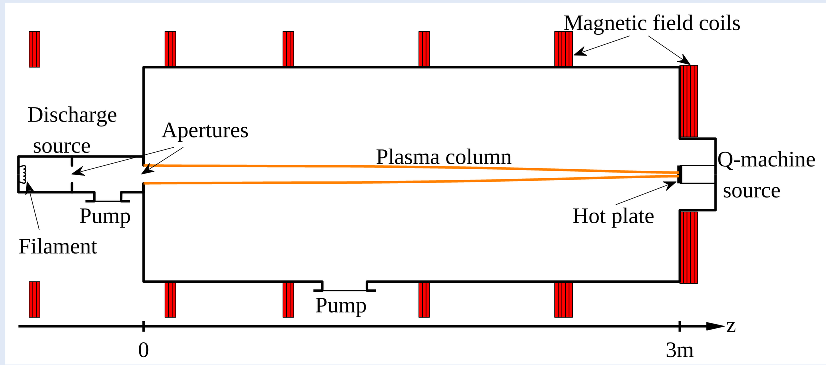

Figure 7: Schematic of a possible plasma device.

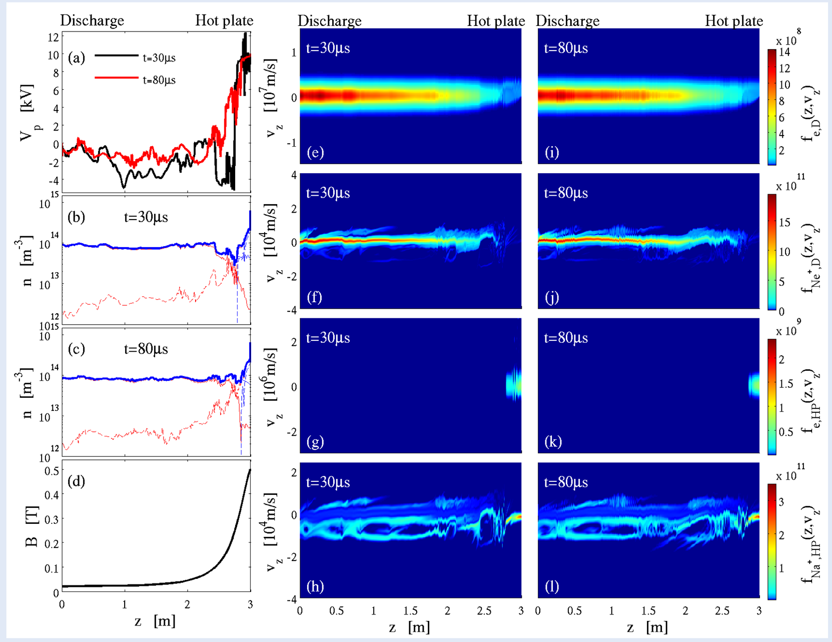

Figure 8: Various quantities for the simulated laboratory experiment. The total voltage is 10 V.

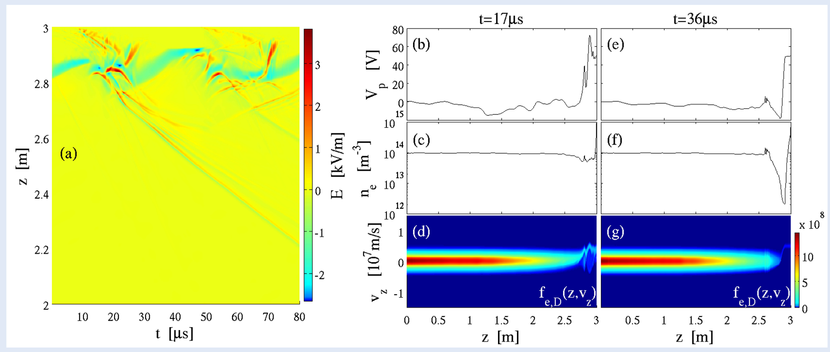

Figure 9: (a) E-field, (b) plasma potential, and (c) distribution function for the discharge electrons, for $t = 17\,\mu$s. (d-f) same as (b-d) but for $t = 36\,\mu$s. The total voltage is 50 V.

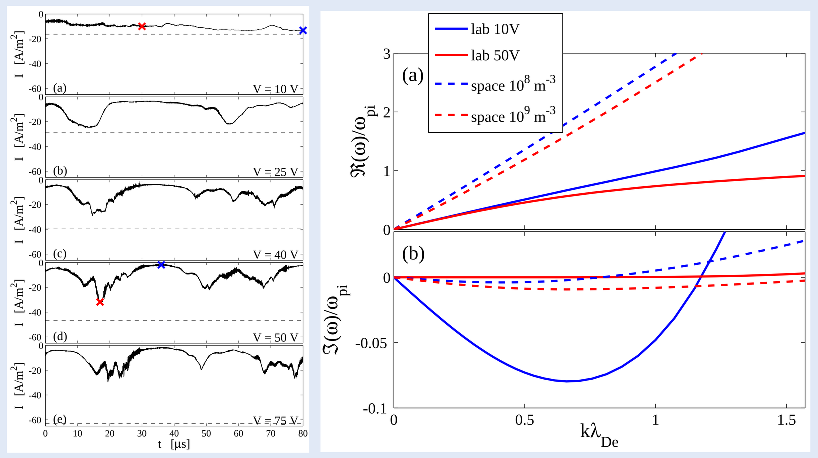

Figure 10: Simulated currents (left). Dispersion relations computed using simple pole expansions [Gunell and Skiff, 2001] (right).

Conclusions

- We use a 1d2v electrostatic Vlasov simulation code to study the physics of auroral flux tubes Gunell et al. [2013a]. Fortran source code of the simulation program is available at <http://www.herbertgunell.se/software.php>.
- In the upward current region, a stable and stationary double layer holds the majority of the voltage, and the current-voltage relation approximately follows the Knight relation.
- Electrons are trapped during the formation of the potential profiles.
- Also in the downward current region double layers form. These are non-stationary, moving toward higher altitudes [c.f. Song et al., 1992].
- Similar to observations in the downward current region [Andersson et al., 2002] waves are seen near the double layer, and there are electron holes on the high potential side of the double layers.
- The voltage in the downward current region is much smaller than that in the upward current region when these carry the same current, even when the density of the ionosphere is reduced.
- It is possible to simulate auroral flux tubes in the laboratory, using a discharge source and a Q-machine source to model the magnetosphere and the ionosphere. Ion acoustic waves are more prominent in the experiment due to the low temperature of the ions from the discharge.

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