Vlasov simulations incorporating the results of a Monte Carlo ionospheric model

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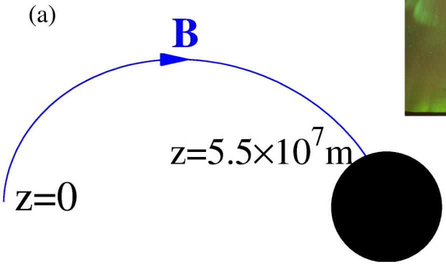
Simulation model

The distribution function is $f_s(z, v_z, \mu)$ and the Vlasov equation

$$\frac{\partial f_s}{\partial t} + v_z \frac{\partial f_s}{\partial z} + \frac{1}{m_s}\left(q_s E - \mu \frac{\partial B}{\partial z} + m_s a_g \right) \frac{\partial f_s}{\partial v_z} = 0$$



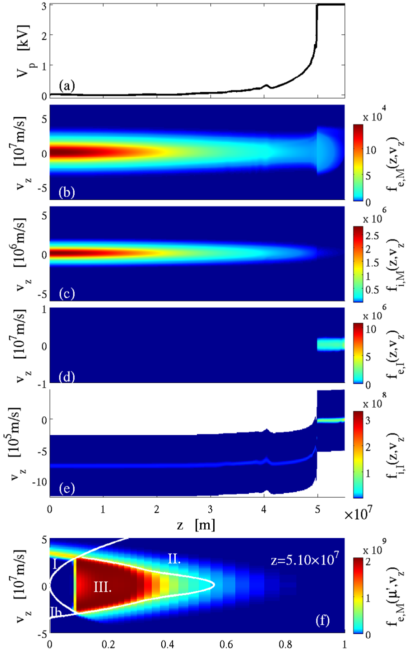
$$\mu = \frac{m_s v_\perp^2}{2B}$$

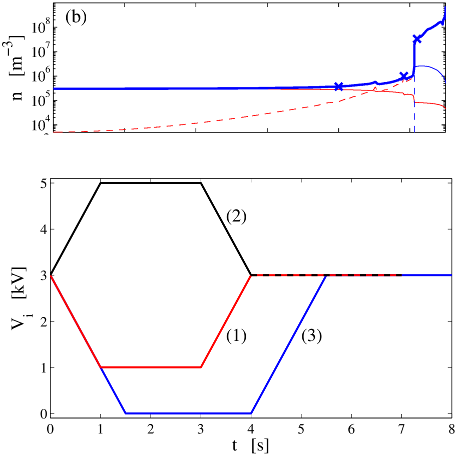
is a constant of motion. The electric field is given by

$$\frac{d}{dz}\left(\frac{B_\mathrm{S}}{B} E\right) = \frac{\rho_I}{S\epsilon}$$

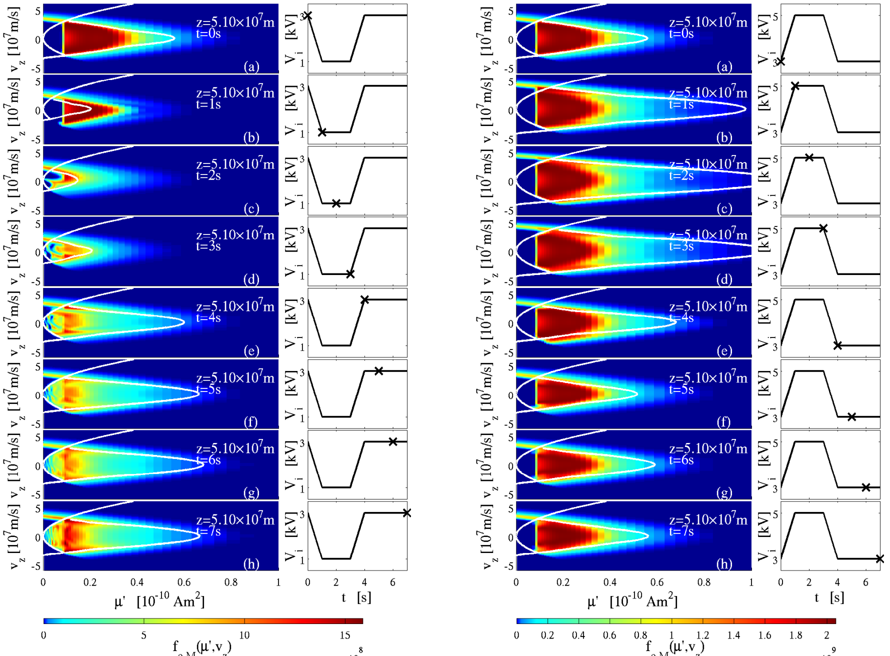
Computer code published by Gunell et al. (2013a)

Upward current region — numerical experiments

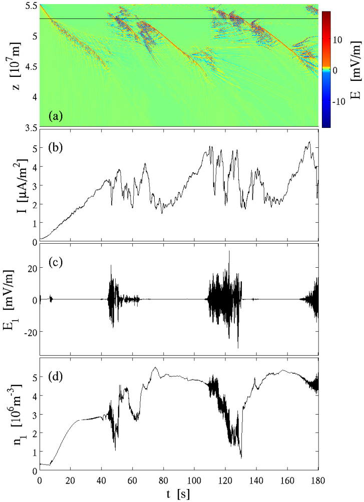


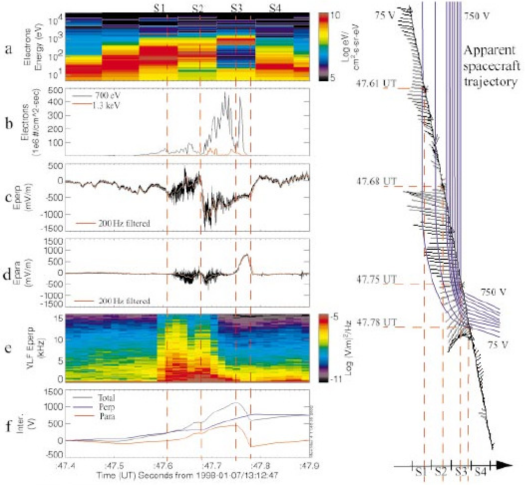


$f(\mu, v_z)$ at $z = 5.1 \times 10^7$ m (Gunell et al., 2015b)



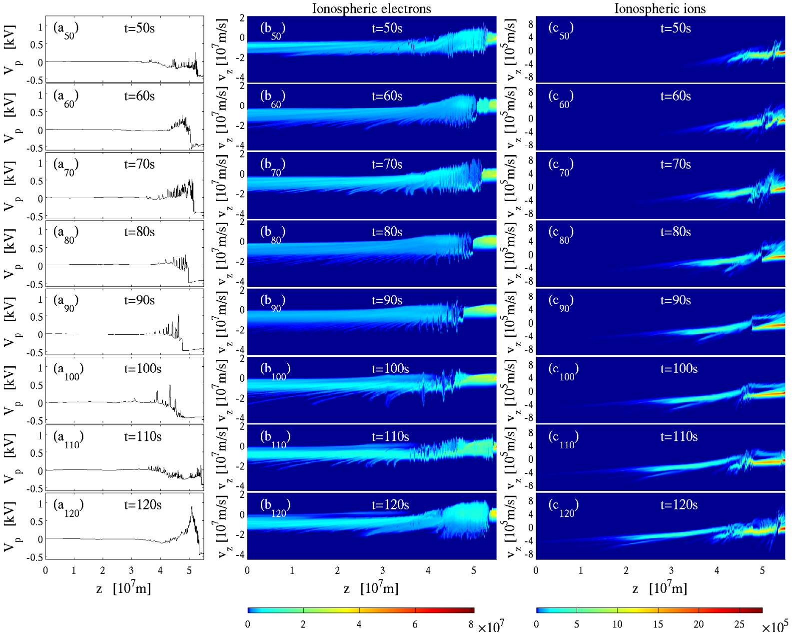
Downward current region (Gunell et al., 2015a)





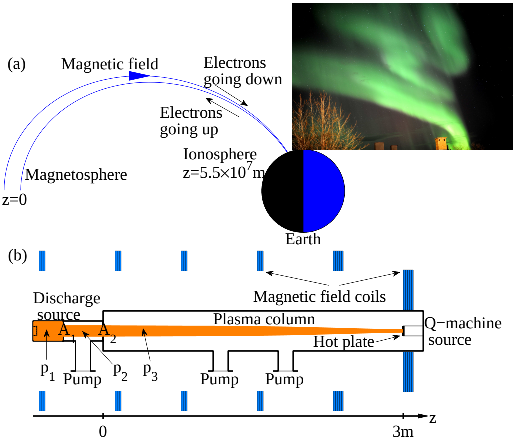
Left: simulations. Right: FAST observations (Andersson et al., 2002).

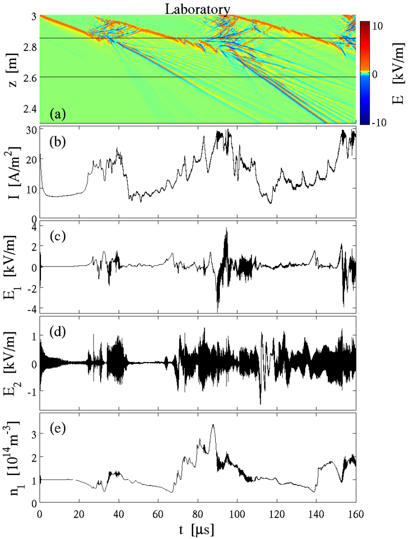
Double layer motion



click!

Other applications — lab (Gunell et al., 2013b, 2016)





Other appl. — Jupiter (David Constable & Licia Ray)

What are we doing?

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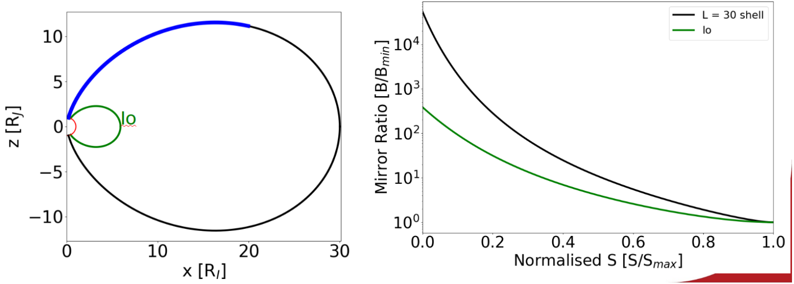
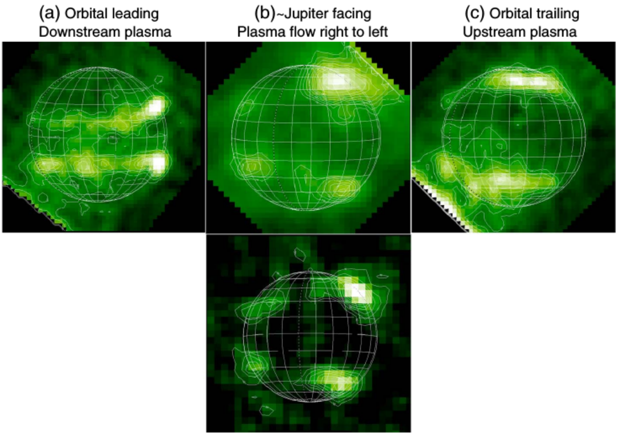
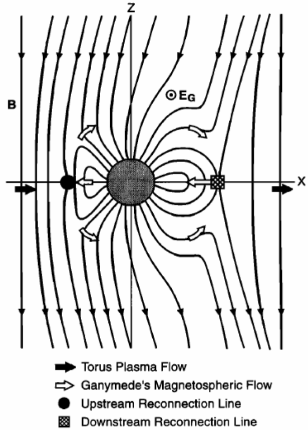
- Develop a time-dependent, 1-D spatial, 2-D velocity space Vlasov model for Jupiter's high-latitude flux tubes:
  - Couples ionosphere and middle magnetosphere (L=30 shell).
  - Allows time dependent phenomena to be observed.
  - Large scale sizes and mirror ratios present issues.
  - Examine reduced region of flux tube.
  - Dipole field configuration (for now).
  - Treat species as Boltzmann (on hold for now).



Other appl. — Ganymede (proposal under evaluation)





Including Monte Carlo results for the ionosphere I

Benoît Hubert has run a Monte Carlo simulation for incoming (down to the ionosphere) electrons at 43 different energy levels, $E_{\mathrm{k,in,t}}$, and with 9 different pitch angles, α_{t}. This results in output (upgoing) electrons resolved on 249 999 energy levels $E_{\mathrm{k,out,t}}$.

The Vlasov code first reads the whole file and stores the information in a three-dimensional ($43 \times 9 \times 249\,999$) array,

$$\mathcal{T}(E_{\mathrm{k,in,t}}, \alpha_{\mathrm{t}}, E_{\mathrm{k,out,t}}),$$

before the real simulation starts.

Including Monte Carlo results for the ionosphere II

Then a *reflection function*, $\mathscr{R}$, is created for each species that represents electrons. The reflection function is a 4-D array, and the Monte Carlo contribution to the distribution function at the ionospheric boundary can be computed as a product of the reflection function and the incoming flux:

$$f_{\mathrm{out}}(v_{z,\mathrm{out}}, \mu_{\mathrm{out}}) = \sum_{v_{z,\mathrm{in}},\mu_{\mathrm{in}}} \mathscr{R}(v_{z,\mathrm{out}}, \mu_{\mathrm{out}}, v_{z,\mathrm{in}}, \mu_{\mathrm{in}})\Gamma_{\mathrm{in}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}}). \tag{1}$$

The flux $\Gamma_{\mathrm{in}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}})$ is computed and normalised to $1\,\mathrm{mW\,m^{-2}}$,

$$\Gamma_{\mathrm{in}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}}) = \frac{v_{z,\mathrm{in}} E_{\mathrm{k,in}} \Delta\mu_{\mathrm{in}} \Delta v_{z,\mathrm{in}} f_{\mathrm{in}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}})}{1\,\mathrm{mW\,m^{-2}}}, \tag{2}$$

Including Monte Carlo results for the ionosphere III

The reflection function is given by

$$\mathscr{R}(v_{z,\mathrm{out}}, \mu_{\mathrm{out}}, v_{z,\mathrm{in}}, \mu_{\mathrm{in}}) = \sum_{E_{\mathrm{k,out,t}}} \frac{\Delta E_{\mathrm{k,out,t}}}{v_{z,\mathrm{out}} \Delta \mu_{\mathrm{out}} \Delta v_{z,\mathrm{out}}} \mathcal{T}(E_{\mathrm{k,in,t}}, \alpha_{\mathrm{t}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}}), E_{\mathrm{k,out,t}}(v_{z,\mathrm{in}}, \mu_{\mathrm{in}})), \quad (3)$$

In the preliminary version, the output bin ($v_{z,\mathrm{out}}$, μ_{out}) is found from $E_{\mathrm{k,out,t}}$ and α_{t} under the assumption that

$$\alpha_{\mathrm{t,out}} = \pi - \alpha_{\mathrm{t,in}}. \quad (4)$$

This will be corrected in the next version.

First test

- I conducted a little test,
- starting from the initial state used by Gunell et al. (2015b), which in turn is based on (Gunell et al., 2013a), but with a higher μ resolution.
- I ran the simulation for 1000 time steps ($1000\,\Delta t = 1\,\mathrm{ms}$) both with and without the MC ionosphere.
- The difference between the two runs was negligible.

Does the ionosphere matter at all?

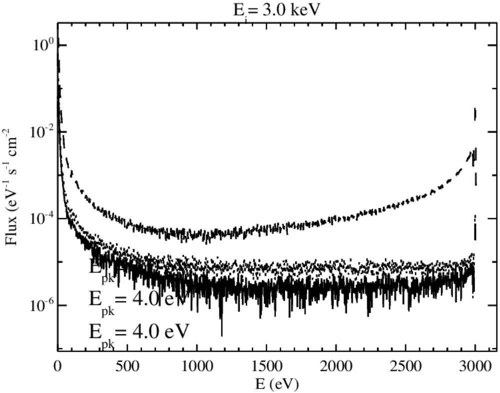


Figure from Benoît Hubert, showing the upward flux resulting from incoming $3\,\mathrm{keV}$ electrons.

Simulation result: $E_{\mathrm{k,in}} \approx 3\,\mathrm{keV}$, $J \approx 2\,\mu\mathrm{Am}^{-2}$, and $\Gamma = E_{\mathrm{k,in}} J/e = 6\,\mathrm{mW\,m}^{-2}$.

Integrating the figure we get $2.5 \times 10^5\,\mathrm{s}^{-1}\mathrm{m}^{-2}$ upgoing flux.

This should then be compared to the downgoing flux of $J/e \approx 1.2 \times 10^{13}\,\mathrm{s}^{-1}\mathrm{m}^{-2}$, which is higher by a factor of about 5×10^7.

Ongoing and future work

- Benoît is running new simulations.
- I will change the assumption in Eq. (4) and update the computation of $\mathscr{R}$.
- A treatment of the ions must also be implemented.
- Test, make new runs, and publish.

Bibliography I

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