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Discussions

Interactive comment on "Hybrid-Vlasov modelling of nightside auroral proton precipitation during southward interplanetary magnetic field conditions" *by* Maxime Grandin et al.

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We thank the Reviewer for their careful analysis of our manuscript as well as their valuable comments and suggestions. Our preliminary responses to the comments are shown in blue, while the original text written by the Reviewer is shown in black.

This is interesting and important study of ion precipitations in the magnetotail. Authors use quite developed simulation tool to check the effect of fast plasma flows on formation of precipitating ion fluxes. The brief comparison of simulation results and published observational data shows a reasonable agreement. I believe this paper should be published in Angeo after Authors address several (quite minor) questions.

Introduction: there are several important references related to proton aurora investigations that may be included: 10.1029/2008JA013099, 10.1134/S001679321805016X, 10.1134/S0016793218040114.

Thank you for suggesting those references, which can indeed be added in the introduction.

Page 7, eq. (8): this equation assumes that ion energy is conserved along the bounce trajectory, i.e. there is no field-aligned electric fields in the system. It would be useful to show 2D plot with the parallel electric field distribution and quickly discuss the weakness of this electric field effect on ion dynamics.

We can add to Supplementary Material Figure 1 below showing the parallel component of the electric field at the same time step and with a similar format as Fig. 3. This parallel component was averaged over 120 s, which corresponds roughly to a quarter of the bounce period for 10 keV protons at $L = 9$ (virtual spacecraft S1).

As can be seen in the figure, the parallel electric field between S1 or S2 and the inner boundary is of the order of 1e-5 to 1e-4 V/m. When integrated along the field line between S1 and the inner boundary, this corresponds to a potential difference of the order of 1 kV. In their discussion of the effect of potential drops in the auroral acceleration region on precipitating protons, Liang et al. (2013, 10.1002/jgra.50454) estimate that for ions with energies $\gg 1$ keV the acceleration resulting from typical potential drops in the AAR (∼1 kV up to ∼4 kV occasionally) can be neglected, which enables a reasonable mapping of auroral latitudes to the central plasma sheet.

The above discussion can be added in a revised version of the manuscript.

Page 8, Line 17: <1° of the loss-cone is an estimate based on nondisturbed magnetic field models. It would be useful to provide also a loss-cone estimate for magnetic field enhancements at the dipolarization front accompanied fast flows (where Bz is significantly larger than the magnetotail Bz).

This is a good point. Using eq. (5), we can estimate the value of the loss-cone angle at a dipolarisation front in the equatorial plane whose Bz component is, e.g., 30 nT (see, e.g., Juusola et al., 2018a, 10.5194/angeo-36-1183-2018, or Runov et al., 2017, 10.1002/2017JA024010). Assuming a mapping to auroral latitudes (B_0 of the order of 6e4 nT), we obtain a loss cone angle of about 1.3°. We can mention this point in a revised version of the paper.

Page 17, Lines 1-5: Previous models of pitch-angle scattering (e.g., Sergeev and Tsyganenko, 1982) were developed for the quiet time magnetotail current sheet, whereas in this paper Authors consider ion precipitation from the acceleration (fast plasma flow) region, what is closer to simulation results shown in 10.1029/2012JA018171, 10.1029/2012JA017677. Any relations to pitch-angle scattering on the magnetic field line curvature should be confirmed by corresponding estimates of the kappa parameter, e.g. kappa dependence on x and time would support Authors' conclusions.

Thank you for this suggestion. Figure 2 below shows the value of the kappa parameter along the x-axis between $-25R_E$ and $-6R_E$ (which corresponds to the regions of interest in our study) as a function of time from $t = 1000$ s until the end of the simulation, as in Fig. 5.

As can be seen in this figure, at the time of highest precipitating proton fluxes (i.e., after $t = 1800$ s) beyond $X \sim -10R_E$ in the plasma sheet, kappa exhibits mostly values below $\sqrt{8}$, hence fulfilling the Sergeev et al. (1983) criterion according to which protons get scattered into the loss cone on stretched field lines. This indeed confirms that this mechanism is the cause for auroral proton precipitation in this Vlasiator simulation.

The two references suggested by the Reviewer can be discussed in a revised version of the manuscript, and the figure showing kappa could be added as supplementary material.

There are two model features that require some explanations/discussions: Figure 3: what is a local temperature minimum around S1 position? Temperatures earthward

and tailward from S1 are higher than in the S1 location. Is there any analogy of such temperature minimum in the statistical spacecraft observations? As I know, the temperature profile along the magnetotail is generally monotonous (see, e.g., 10.1029/2008JA013849, 10.1002/2016JA023710.)

First of all, something to note is that the shown temperature is the temperature of an isotropic plasma which would have the same total pressure as the simulated distribution, and thus does not represent the temperature of the bulk plasma but rather the measured effect of a combined bulk plasma and fast additional flow.

The local temperature minimum seen in Fig. 3 comes from the fact that hot plasma associated with the precipitating protons originates from the current sheet region, which leads to temperature enhancements propagating earthwards in terms of L shells. At the time step chosen for Fig. 3 (1800 s), a stream of hot ($T = 2\text{e}7$ K) plasma coming from the transition region is reaching S1, leading to a local enhancement of the proton temperature compared to its background value at S1.

It is difficult to compare our results to those shown in the two suggested references, as in 10.1029/2008JA013849 the statistical observations are obtained with slow flows ($V_\perp < 150$ km/s) whereas in the situation shown in our Fig. 3 $V_\perp$ is essentially greater than 200 km/s for $X < -7R_E$. As for the T_i profile along the magnetotail shown in 10.1002/2016JA023710, it consists of only three points with X between $-10R_E$ and $-30R_E$, meaning that (i) the spatial resolution is too coarse to capture such small-scale variations as that pointed in our Fig. 3 and (ii) measurements at $X > -10R_E$ are not available.

Figure 4: some of shown distributions are definitely unstable (they contain ion beams with positive slobs along the parallel velocity direction). Thus, some discussion is needed to explain if these instabilities are too slow to influence ion distributions or they are simply suppressed in the numerical calculations.

Thank you for raising this issue. In Vlasiator, instabilities are resolved in the numerical calculations provided their wavelengths are larger than the grid resolution in ordinary space. According to Gary (1989, 10.1007/BF00196632; see especially Table II p. 385), there are several instabilities which can arise from interactions between a proton beam and a proton core population in a plasma.

The ion/ion right-hand resonant instability ("magnetosonic" or "fast MHD"), of much lower frequency than the ion gyrofrequency, can develop when the field-aligned drift velocity v_0 of the protons is greater than the Alfvén speed v_A, and when the ratio between beam (n_b) and core (n_c) densities is "very small". If we consider the distribution shown in Fig. 4a of our manuscript, we have $v_0 \sim 1000$ km/s, $v_A = 4379$ km/s, $n_b = 1.1$e4 m^{-3} and $n_c = 1.2$e5 m^{-3}, i.e., $v_0/v_A \sim 0.2$ and $n_b/n_c = 8.6$e-2. Since the condition on the velocities is not fulfilled, it is unlikely that this instability grows at the location where the VDF is observed.

The ion/ion left-hand instability also requires $v_A < v_0$, and in addition it requires that the ion beam to be hot, i.e., with a thermal velocity greater than the beam drift velocity. This instability is therefore not expected to grow in the considered situation of Fig. 4a.

The ion/ion nonresonant instability ("firehose") can develop if $v_A \ll v_0$. Hence, it cannot grow in this situation either.

In conclusion, in the $v_A > v_0$ regime which characterises the plasma in the vicinity of virtual spacecraft S1 and S2, we do not expect that the instabilities listed above can grow fast enough to significantly affect the ion distributions on the time scale needed for precipitating protons (i.e., essentially the field-aligned beam) to reach the inner boundary or even the ionosphere.

We can include a shorter version of this discussion in a revised version of the manuscript.

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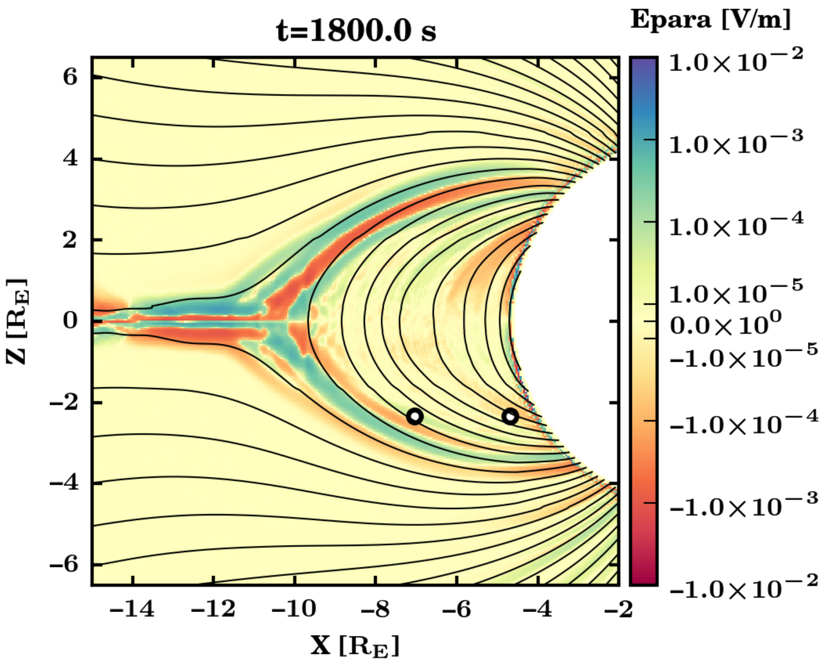

Fig. 1. Parallel electric field at t = 1800 s, averaged over 120 s

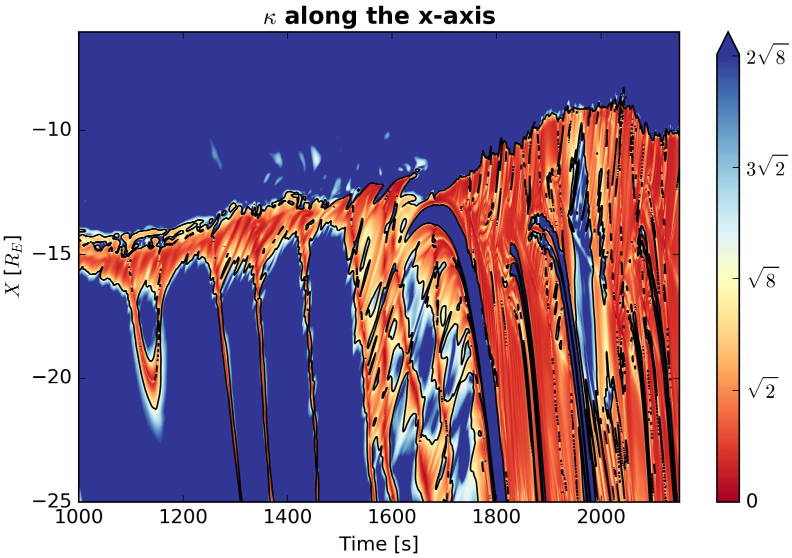

Fig. 2. Keogram of the kappa parameter along the nightside x-axis