Beyond-MHD: flexible fluid-kinetic geospace model

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Outline:

- I. Context and motivation
- II. Spectral approach: SPS
- III. LWS-SC project: GAMERA-SPS
- IV. Conclusions

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I. Several approaches to account for beyond-MHD physics are being pursued

- Beyond-MHD physics important in the Earth's magnetosphere
- Fully kinetic modeling of the whole system is not possible

Several approaches under development

- Augmented fluid models [Wang+, 2018]
  - 5-, 10- or 20-moment method; limited by closure assumed
- Hybrid models [various groups: Omidi; Winske; Karimabadi; Roytershteyn; Palmroth; Omelchenko; Lin, …]
  - Miss electron kinetic physics
- Embedded kinetic models [Sugyama&Kusano, 2007; Michigan group; Ho+, 2018; this talk]
  - Fluid-kinetic coupling
  - State-of-the-art but hard interface and one might not need fully kinetic
- MARBLE (Hall MHD+Fokker Planck)
- Spectral approach [Delzanno+; this talk]

II. SPS solves the kinetic equations with a spectral approach

Transform (i.e. spectral) methods:

- Phase space discretization with moment expansion (spectral)

$$f(t,x,v) = \sum_n C_n(t,x)\Psi_n\left(\frac{v-u}{\alpha}\right) \qquad \psi_\zeta(\xi_\beta^s) = \left(\pi\, 2^\zeta\, \zeta!\right)^{-\frac{1}{2}} \mathcal{H}_\zeta(\xi_\beta^s)\exp\left(-(\xi_\beta^s)^2\right),$$

- Fourier, Hermite basis [Armstrong et al., 70; …]
- Truncated moment system
- Major advantage (for AW Hermite and Legendre basis):
  - **Fluid-kinetic coupling**: naturally bridges between fluid (few moments) and kinetic (large number of moments)
- Spectral Plasma Solver (SPS) framework
  - Delzanno, 2015; Koshkarov+, 2021 (and references therein)
  - 3D3V Vlasov-Maxwell spectral solver

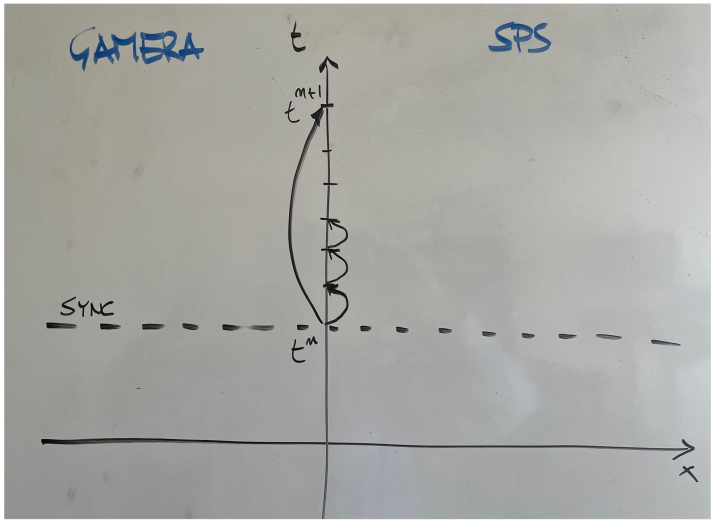
II. A spectral approach naturally encompasses most alternatives introduced earlier. In my opinion, it is the optimal way to include microscopic physics in large-scale modeling

- Can be seen as an advanced fluid model, when you truncate the expansion early
  - We do not have to truncate at 5,10 or 20 moments. We treat the closure in a convergence sense, the only limitation comes from computer power
- It can be seen as an hybrid method, when you truncate electron expansion early
  - With flexible electron model
- Fluid-kinetic coupling is built-in but without the limitations of a kinetic-MHD-type approach
  - Adapt spectral terms in space and time
  - Seamless transition from one regime to the other overcomes the hard interface problem
- Fluid, hybrid and fully-kinetic all in one approach

III. LWS-SC 'Beyond MHD' project

- Develop a GAMERA-SPS capability
  - Embed SPS box in the tail (or elsewhere)
- Overarching goal: understand the role of microscopic processes in the global dynamics of the Earth's magnetotail
  - What physics determines the structure of the magnetotail current sheet?
  - What processes control magnetic reconnection onset in the magnetotail?

III. Automated coupling GAMERA-SPS implemented

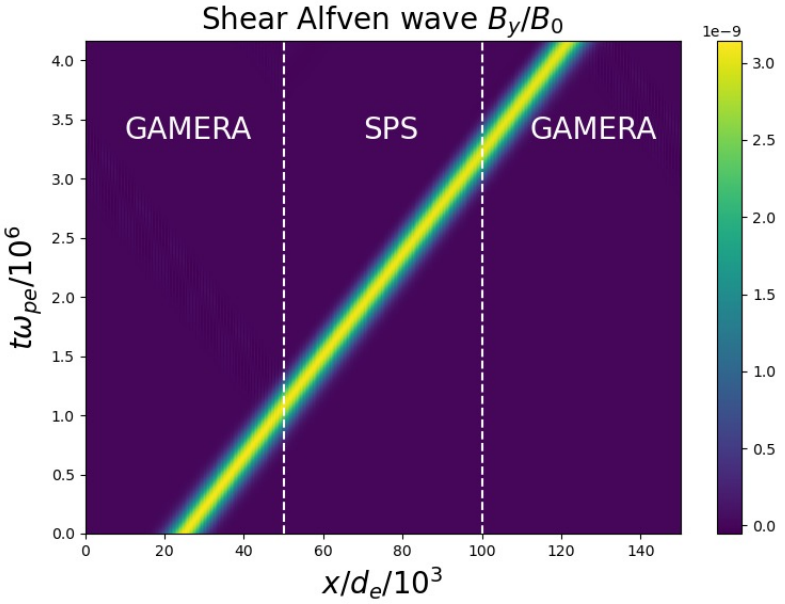


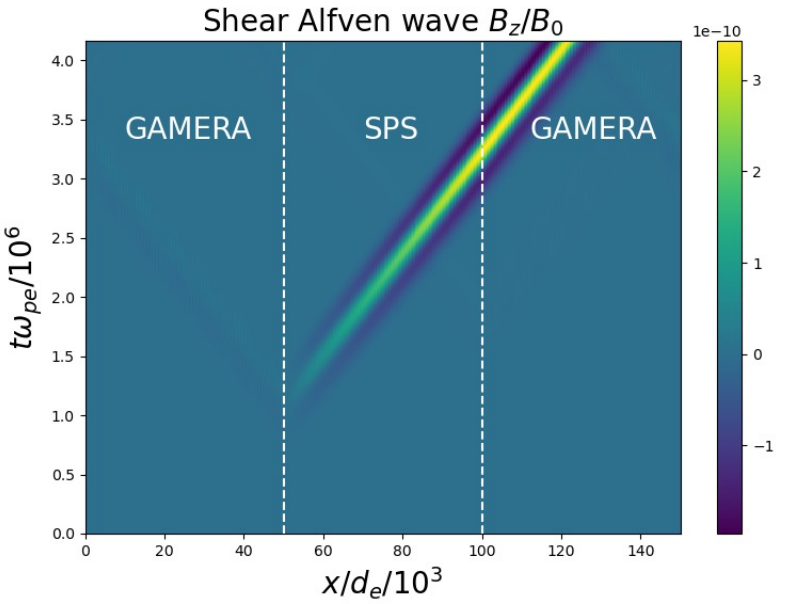
Coupling algorithm (dominated by SPS cost):

- Uses MPI infrastructure to treat GAMERA and SPS independently
- Synchronization files at t=0 to establish rank connectivity; runtime with pure MPI calls
- Spatial coupling, via ghost cells (no buffer zone)
  - Note: SPS does not have spatial stability constraints (can step over Debye length)
  - Challenge: GAMERA → SPS requires assumptions (quasi-neutrality, pressure partition)
  - Mitigation: Hall MHD, e- pressure equation in GAMERA, adjusting SPS moments towards boundary
- Temporal coupling, interpolate GAMERA information at smaller SPS time steps
  - Challenge: explicit SPS must resolve fastest frequency
  - Mitigation: implicit time stepping (requires preconditioning), IMEX approach

III. Propagation of shear-Alfven wave packet

- SPS with 4^3 Hermite modes (advanced two fluid, physical mass ratio)





Wave packet width: $400d_i$

Reflection and field rotation are due to two-fluid effects
Multi-D infrastructure developed and undergoing testing

IV. Conclusions

- GAMERA-SPS could be a promising capability for global magnetospheric modeling
  - LWS-SC project creates necessary infrastructure
  - Flexibility of SPS (fluid, hybrid, fully kinetic) is key
  - As computer power grows, SPS embedded modeling can grow too to account for progressively better kinetic physics

III. Some estimates of computational cost for GAMERA-SPS

- Targeting a [10x1x1]R_E SPS box
- Implicit SPS is a must
  - to step over scales that are not of interest
- Realistic parameters: 3D, ion scale resolution ($0.3d_i$ and $0.3w_{ci}$) → 2.5M core-hrs for one hour of real-time with 6^3 Hermite modes
  - Based on estimates from preliminary results
  - No electron kinetic physics
- Rescaled parameters: 3D, $R_E=10d_i$ (instead of 28) cost drops to ~30,000 core-hrs
  - We will make ample use of rescaling
- Using SPS as hybrid would significantly speed code up
- Resolving electron physics will be done in 2D
  - 4.2M core-hrs for the rescaled simulation