2D simulations of the Biermann battery mechanism in partially ionized plasmas

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In the absence of an initial seed, the Biermann battery term of a non-ideal induction equation acts a source that generates weak magnetic fields. Here, we study this mechanism in the context of partially ionized plasmas, using a model in which the charged and neutral components of the plasma are treated as two different fluids that interact by means of collisions. We investigate the effect that the ionization degree and the charged-neutral interaction have on the generation of magnetic field. We use the numerical code MANCHA-2F to perform 2D simulations of the Kelvin-Helmholtz instability. We study how the magnetic field generated by the Biermann battery process depends on the ionization degree of the plasma and on the different collisional terms included in the equations of the model. We find that when the collisional coupling is taken into account, the generation of magnetic field is increased as the ionization degree is decreased. We also find that this effect depends on the total density of the plasma and that as this parameter is increased, the numerical two-fluid results converge to the analytical results from a single-fluid model.

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Context of the research

- *The induction equation of ideal magnetohydrodynamics (MHD) does not allow the creation of a new magnetic field when starting from a completely field-free initial condition.*
- ***Biermann (1950)*** *showed that weak magnetic field seeds can be created if spatial variations of the density and pressure of electrons are taken into account in a non-ideal induction equation.*
- *The Biermann battery process has been invoked to explain the origin of the magnetic field of stars (**Mestel & Roxburgh, 1962**), the interestellar medium (**Lazarian, 1992**; **Kulsrud et al., 1997**), the early universe (**Widrow et al. 2012**), or the Sun's local dynamo (**Khomenko et al., 2017**), among other astrophysical scenarios.*
- *However, most of the previous studies have focused on fully ionized plasmas or have considered the effect of partial ionization by means of single-fluid models, which have their range of applicability restricted to the limit of strong coupling between the different components of the plasma.*
- *Here, we aim to investigate the Biermann battery mechanism in partially ionized plasmas using a two-fluid model and improve the understanding of the effect of the charged-neutral collisional interaction.*

Description of the work

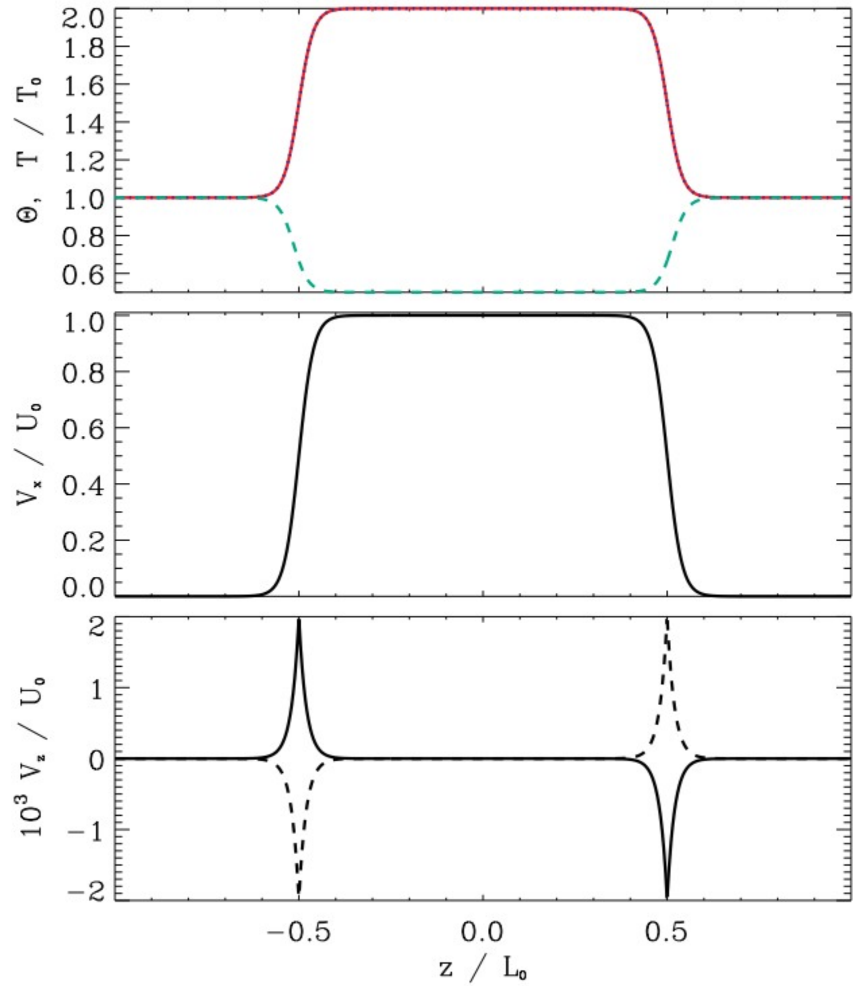
- *We use the numerical code **MANCHA-2F** to solve the non-linear equations of a two-fluid model that includes momentum and heat transfer terms due to collisions between the charged and neutral species of the plasma (**Popescu Braileanu et al., 2019**).*

- *Initial density profile is a function of the vertical direction (z): a denser central region moving between two lighter regions which are at rest. There are smooth transitions of density and velocity between the different regions (as shown in the plot on the right).*

- *There is no initial background magnetic field: **B_0 = 0**.*

- *We apply a vertical velocity perturbation at the transition layers, which triggers the Kelvin-Helmholtz instability (**Chandrasekhar, 1961**).*

- *2.5D setup: only derivatives along x and z, but y-components of vector quantities are also allowed to evolve.*

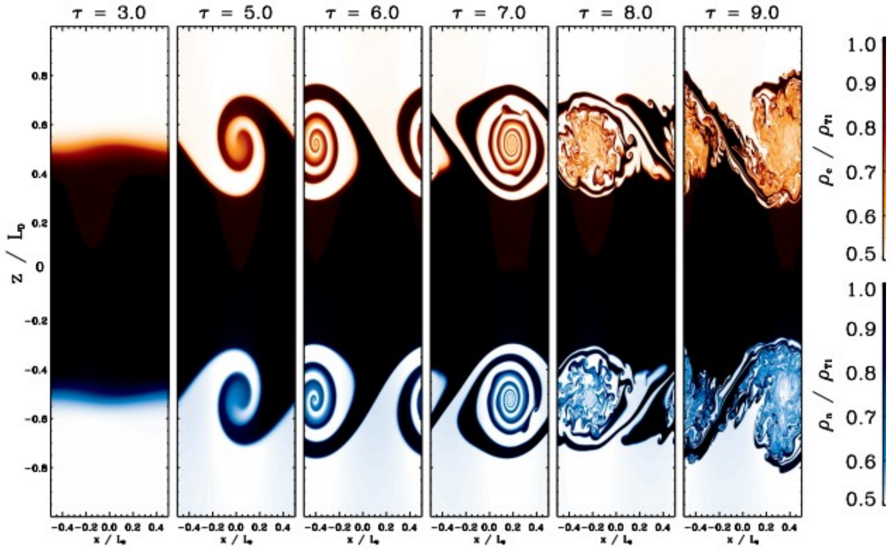


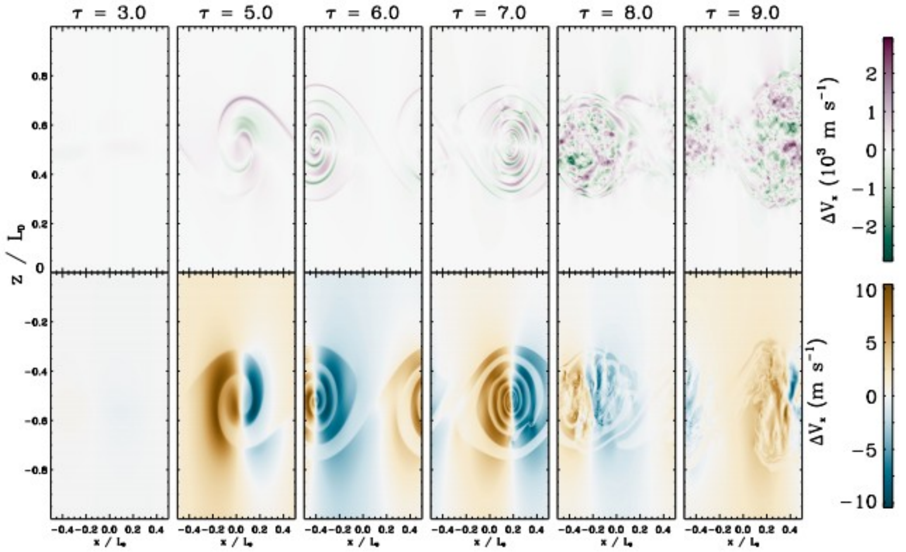
***Vertical cuts of the initial setup. Top:** normalized density (red) and temperature (green); **middle:** x-component of velocity; **bottom:** z-component of velocity at x = -L_0 /4 (solid) and at x = L_0 / 4 (dashed).*

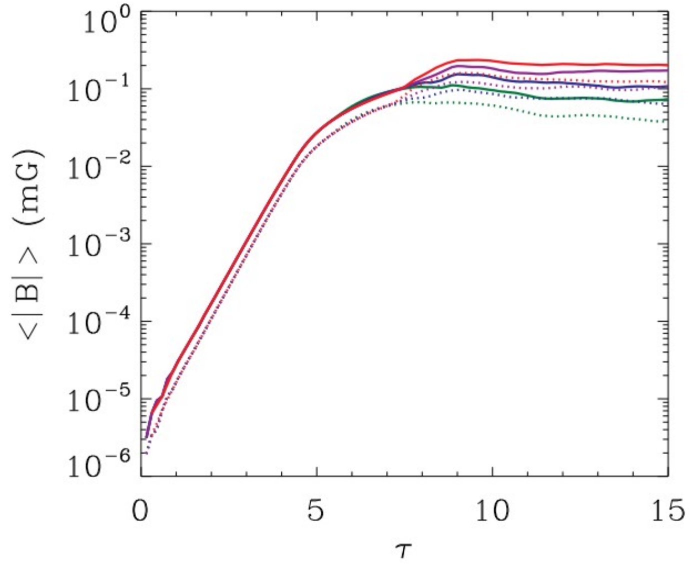
Results (I). Temporal evolution of the KHI

- ***Left plot:*** *snapshots of the density of the charged fluid (top half) and the neutral fluid (bottom half) in a simulation with no collisions between the two species.*

- ***Center plot:*** *velocity drift between the charged and neutral fluids ($\Delta V_x = |V_{x,c} - V_{x,n}|$). Top and bottom halves correspond to the cases without and with collisional coupling, respectively. Velocity drifts are 3 orders of magnitude larger when there is no coupling.*







- ***Right plot:*** *spatially averaged magnetic field as a function of time in simulations with an ionization degree of x_c = 0.1. When the collisional coupling is taken into account (solid lines), larger magnetic fields are obtained in comparison with the cases without coupling (dotted lines). Colors represent simulations with different resolutions: larger magnetic fields in simulations with smaller grid sizes.*

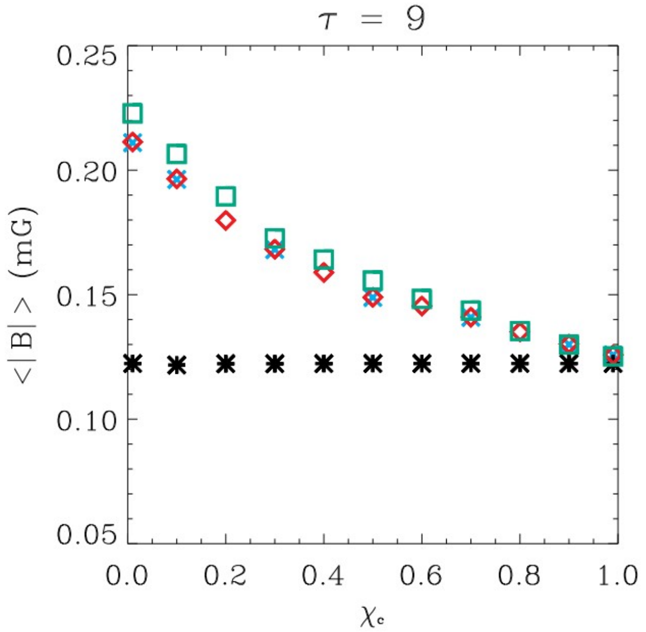
Results (II). Dependence on the ionization degree

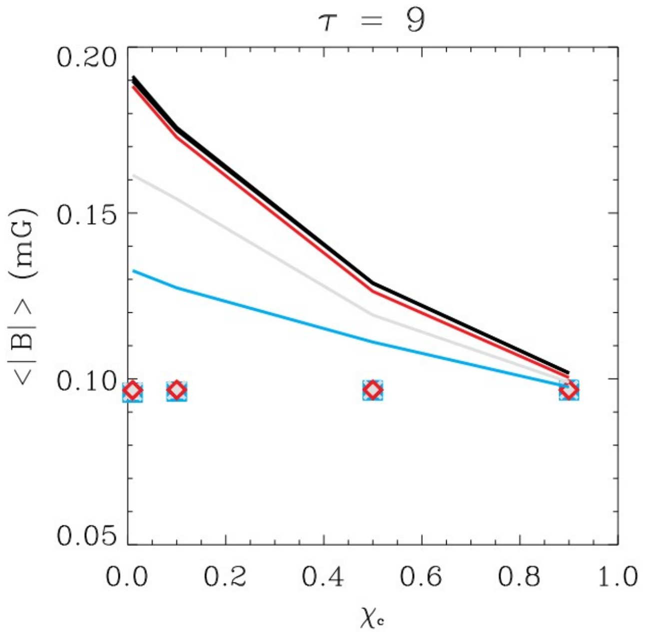
- ***Top panel:*** *spatially averaged magnetic field at a given time as a function of the ionization degree of the plasma.*
  - *1) black: no coupling between the charged and neutral fluids.*
  - *2) red: coupling by means of elastic collisions.*
  - *3) blue: collisional term in induction equation is also taken into account.*
  - *4) green: charge-exchange collisions are also considered.*

- ***Bottom panel:*** *study of effect of the coupling degree (which depends on the total density of the plasma) on the previous results.*

- *Solid lines correspond to the case with elastic collisions while the symbols correspond to the case without coupling. Blue, grey and red colors correspond to total densities of* $\rho_T = 10^{-11}$, 10^{-10} *and* 10^{-9} *kg m*$^{-3}$*, respectively.*

- *Black line represents the analytical results obtained with the single-fluid equations used by* ***Kulsrud et al. (1997)***.





Conclusions and prospects for the future

- ***In partially ionized plasmas, the collisional interaction between the charged and neutral species enhances the generation of magnetic field by means of the Biermann battery mechanism.***
- ***A larger increase of the generated magnetic field is found as the ionization degree is reduced.***
- ***The effect of the charged-neutral interaction depends on the coupling degree between the two fluids, which is a function of the total density of the plasma (and also of the temperature).***
- ***For larger values of the total density, the two-fluid numerical results converge to the analytical predictions from single-fluid models, which assume a strong coupling.***
- ***Many studies on the Biermann battery mechanism applied to a wide range of astrophysical scenarios resort to single-fluid models. The results of the present work show that those single-fluid models may overestimate the effect of the charged-neutral interaction.***
- ***A paper including these results is in preparation and will be submitted to A&A.***