

Computational Simulation of Particle Dynamics in a Magnetic Reconnection Event in the Heliosphere.

L. S. P. Santos & R. A. M. Cerda

¹ Plasma Physics Laboratory, Institute of Physics, University of Brasília. e-mail: llaurapsoares@gmail.com

Abstract. Space weather events, such as coronal mass ejections and fluctuations in the solar wind, can directly affect the geospace environment and technological systems on Earth. Magnetic reconnection is a key mechanism behind these events, efficiently converting magnetic energy into particle heating and acceleration. This work uses numerical simulations to investigate the motion of charged particles in heliospheric current sheets under different guide-field strengths. By analyzing phase-space distributions for strong and weak guide-field regimes, we identify clear differences in confinement and acceleration efficiency. These results contribute to a deeper understanding of how energetic particles propagate through the heliosphere.

Resumo. Eventos de clima espacial, como ejeções de massa coronal e variações no vento solar, podem afetar diretamente o ambiente geoespacial e sistemas tecnológicos na Terra. A reconexão magnética é um mecanismo fundamental por trás desses eventos, convertendo eficientemente energia magnética em aquecimento e aceleração de partículas. Este trabalho utiliza simulações numéricas para investigar o movimento de partículas carregadas em folhas de corrente heliosféricas sob diferentes intensidades de campo guia. Ao analisar distribuições em espaço de fases nos regimes de campo guia forte e fraco, identificamos diferenças claras nos padrões de confinamento e eficiência de aceleração. Os resultados contribuem para uma compreensão mais profunda sobre como partículas energéticas se propagam pela heliosfera.

Keywords. magnetic reconnection, guide field, solar wind, heliospheric current sheet, particle acceleration, phase-space dynamics, space weather, energetic particles.

1. Introduction

Space weather encompasses a wide range of phenomena linked to solar activity and its interaction with the interplanetary medium, with magnetic reconnection playing a central role by rapidly converting magnetic energy into plasma heating and particle acceleration. In the heliosphere, reconnection occurs in large-scale current sheets, such as the heliospheric current sheet, shaping the solar wind and influencing the transport of energetic particles. The solar wind, a highly conductive and turbulent plasma continuously emitted by the Sun, interacts with Earth's magnetic field to produce radiation belts, auroras, magnetic disturbances, and diverse electromagnetic waves, all of which have important implications for satellite operations, communication systems, GPS accuracy, and astronaut safety. Within this dynamic environment, magnetic reconnection is one of the key mechanisms responsible for the rapid release and redistribution of magnetic energy in astrophysical plasmas, occurring in the Sun, the interplanetary medium, Earth's magnetosphere, and laboratory plasmas. This process drives efficient particle acceleration and contributes to the formation of nonthermal energy distributions observed throughout the heliosphere. Understanding how charged particles behave in reconnection regions—especially under different guide-field intensities—is therefore essential for improving predictions of energetic particle propagation, interpreting their origins within the heliosphere, and advancing our broader understanding of Sun–Earth interactions and the impacts of space weather.

2. Methods

To reproduce the scenarios proposed in this study, a computational model was developed based on the framework presented by Zharkova and Khabarova (2015). The simulations consider

two distinct guide-field configurations within a magnetic reconnection region, allowing the analysis of particle dynamics under different magnetic-field conditions.

Main configurations

- **Strong guide field:** $B_y = 0.5B_0$, with $B_0 = 10^{-8}$ T.
- **Weak guide field:** reduced values of B_y , while preserving the same current-sheet geometry.
- **Simulated particles:** electrons and protons initially distributed within the reconnection plane.
- **Analyzed variables:** velocity component u_x as a function of the coordinate y ; separation of particle populations; and spatial distribution of protons.

The model reproduces both individual scenarios—strong and weak guide fields—as well as an averaged distribution combining the two cases. This approach allows the evaluation of differences in particle behavior and facilitates comparison with observational conditions of the solar wind.

3. Results

The simulations reveal distinct acceleration behaviors depending on the guide-field intensity. Under a strong guide field, particles remain more confined, producing a more ordered phase-space structure. Under weak guide-field conditions, particle trajectories become significantly more dispersed, indicating more efficient yet less stable acceleration. The averaged distribution shows intermediate characteristics, suggesting that particle energization depends not only on the guide-field strength but also on the local structure of the current sheet. These results reinforce the regulating role of the guide field in particle confinement and acceleration throughout the heliosphere.

Image 2025-12-09 at 18.11.34.eps

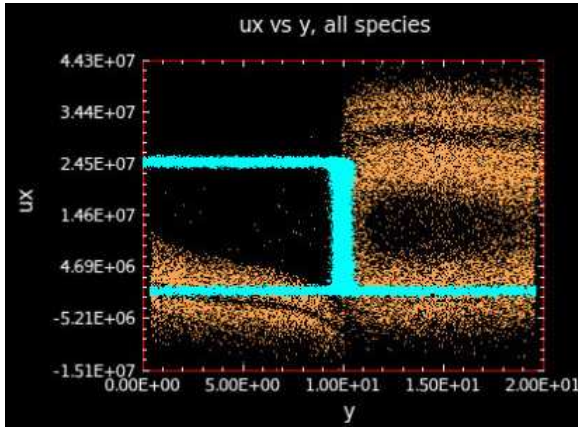


FIGURE 1. Distribution of u_x vs. y for the strong guide field.

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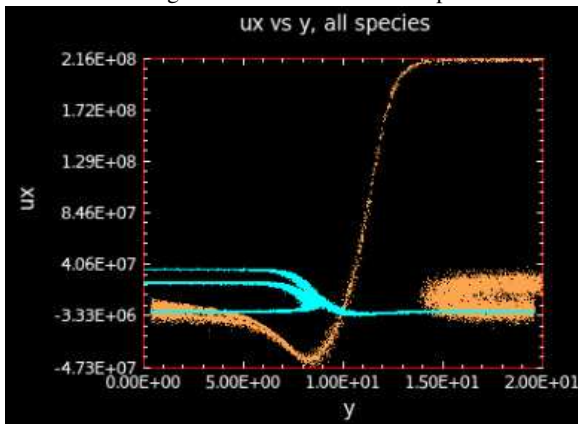


FIGURE 2. Distribution of u_x vs. y for the weak guide field.

I. Strong guide field

The strong guide-field simulation exhibited a clear separation between electron and proton populations, with a significant ejection of protons toward the negative semiplane ($x < 0$). This behavior is consistent with the trends described in the reference study, indicating a more organized phase-space distribution and a more stable acceleration regime.

II. Weak guide field

For the weak guide field, the velocity distribution became less symmetric, with greater dispersion between electrons and protons. Particle acceleration occurred in a more scattered manner, showing the direct influence of the reduced guide-field intensity on particle dynamics and resulting in greater instability and variability in phase space.

III. Average between strong and weak guide fields

The averaged distribution smooths the particle trajectories, highlighting global trends in the dynamical behavior while reducing the visibility of local structures, such as the clear electron separation observed in the strong guide-field case. The mean value obtained in this combined configuration was approximately 2.5×10^{-2} .

Image 2025-12-09 at 17.57.31.eps

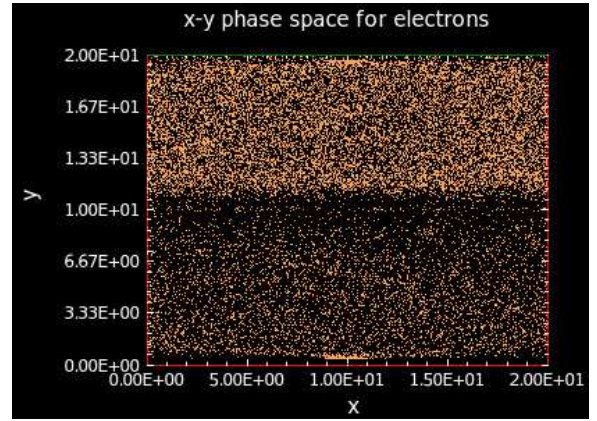


FIGURE 3. Average distribution: xy phase space for protons.

4. Discussion and Conclusion

The results obtained from reproducing the simulations of Zharkova and Khabarova (2015) made it possible to analyze the relationship between the velocity u_x and the coordinate y in different magnetic reconnection scenarios. In the strong guide-field case ($B_y = 0.5B_0$), a clear separation between electrons and protons was observed, with a significant ejection of protons toward the negative semiplane ($x < 0$), consistent with the behavior predicted in the reference study. In the weak guide-field regime, the reduction in magnetic intensity altered the acceleration pattern, producing greater dispersion and asymmetry in particle velocities.

The analysis of the averaged results from both strong and weak guide-field simulations yielded a mean value of approximately 2.5×10^{-2} , smoothing important local structures such as the complete electron separation seen under strong guide fields. While this averaging highlights global dynamical trends, it reduces the visibility of finer features in phase space. Nonetheless, the comparison reinforces the regulatory role of guide-field intensity in particle acceleration and separation mechanisms, in agreement with theoretical results reported by Birn and Priest (2007).

Overall, this study successfully reproduced the scenarios presented in the reference paper and provided insight into how different guide-field intensities influence particle dynamics during magnetic reconnection events in the heliosphere. Despite limitations such as the lack of realistic turbulence and time-varying solar-wind conditions, the results approach observational behavior and emphasize the importance of computational simulations for predicting space-weather phenomena. Future extensions include incorporating turbulence, time-dependent magnetic fields, and comparisons with satellite data.

(OOPIC Simulation Code:

The OOPIC code below was used to reproduce the results presented in Zharkova and Khabarova (2015). It configures the simulation domain, particle species, electric and magnetic fields, and beam emitters for electrons and protons.)

References

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- Zharkova, V. & Khabarova, O. 2015, Ann. Geophys., 33, 457