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Kelvin-Helmholtz instability at the hermean magnetopause: impact of the magnetic field and density gradients

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Abstract. The main goal of this project was to study the dawn-dusk asymmetry of the Kelvin-Helmholtz instability along the magnetopause of Mercury while taking into account the gradients of density and magnetic field present along the magnetopause. However, an unexpected results broadened our study: when the gradients are strong enough, kinetic instabilities are able to grow structures at large scales, which interplay with the Kelvin-Helmholtz vortices. We therefore mainly studied how the kinetic and fluid scale instabilities interplay along a magnetopause-like layer. In particular, we showed with our simulation that for a strong enough gradient of density, the Kelvin-Helmholtz instability can be suppressed by the kinetic instabilities.

1. Introduction

Mercury is one of the less well known planets of our solar system, as only two missions went to visit it. On those missions, only one (the NASA mission MESSENGER) crossed the hermean magnetosphere. By doing so, this mission observed a strong asymmetry in the development of Kelvin-Helmotz instability (KH) at the magnetopause (i.e. the boundary of the magnetosphere) between the dusk and dawn sides of the magnetosphere. However, due to the lack of data, we have to rely on simulations to further understand what's happening. This work is done in the context of the ESA-JAXA mission BepiColombo, which will once again visit Mercury in 2025.

The dawn-dusk asymmetry at the hearmean magnetopause has already been studied with simulations. Nakamura et al. (2010), in particular, proposed an explanation. In their work, they notice that the width of the velocity shear layer differ between dawn and dusk side. The width of this layer has a huge impact on the KH. They explained the difference in the widths by the coupling between ion gyromotion and velocity shear. Depending on the magnetopause side, the ions will be co- or counter-rotating with the KH vortices. By doing so, they can enlarge the layer and affect the KH. This phenomenon is especially noticeable at Mercury as the magnetopause is thin compared to the ion gyroradius. However, other parameters can affect both the width of the shear layer and the ion gyromotion. For instance, Gingell et al. (2015) introduced heavy ions, which are quite common in the hermean magnetosphere. In this work, we are interested in the impact of magnetic field and density gradients in the dawn-dusk asymmetry.

Nowadays, most of KH simulations consider a velocity shear with a uniform density and/or magnetic field. But Mercury is an extreme case: due to its weak magnetic field and its proximity to the Sun, we expect strong gradient of density and magnetic field along the magnetopause. Such gradients cannot be neglected anymore. In particular, the gradient in magnetic field produces a current whose sign differs between dusk and dawn sides, naturally introducing an asymmetry. To address this problem, we performed a parametric study by changing the magnetic field and density asymmetries and looking the effect of these parameters on the KH development. By doing so, we observed that for strong gradient, some other instabilities strongly develop along the magnetopause, interplaying with the KH.

2. Results

2.1. Numerical results

In the initial project, we planned to use a PIC simulation code (SMILEI) to realize a total of eighteen simulations with a common velocity shear layer, but different profiles for the layer (3 magnetic configurations and 3 density configurations at dawn and dusk sides). The first simulation we ran confirmed the estimations we made in the proposal regarding scalability and the CPU.hour consumption. However, we got a result that affected the rest of the project: the growth of an unexpected instability along the layer, strongly modifying the layer. This result will be developed in section 2.2, but facing this problem we decided to conduct several test simulations in order to confirm that the result was not an artifact. Due to this new result, we decided to modify our simulation plan and we finally made the following simulations:

- 6 simulations following the initial plan (a velocity shear, one magnetic configuration and 3 density configurations at dawn and dusk sides).
- one simulations with a magnetic field gradient, a density gradient, but without velocity shear.
- 5 simulations with a smaller box and the same layer's profile (without velocity shear) but with different mass ratio between ions and electrons.

2.2. Scientific results

The initial goal of this work was to study the dawn-dusk asymmetry of the KH instability along the magnetopause of Mercury, but our first results changed our priorities and opened a new field of study. Indeed, the simulations showed that, in presence of gradients of magnetic field and density, kinetic instabilities grow along the magnetopause and, for strong enough gradients, these instabilities become dominant over the KH instability. Consequently, we prioritized the study of this new phenomenon, while keeping the original subject for a second time.

In figure 1, we see the results for late times of the simulations with a velocity shear at the dusk side (simulation 2, 3 and 4 respectively). On top of those, we also used for this study another simulation identical to simulation 2, except for the velocity shear (simulation 1, without velocity shear). We were expecting KH waves to grow unsteady and form vortices (like in simulation 4), eventually with secondary kinetic instabilities. While the very turbulent vortices observed in simulation 3 were within our expectations, the finger-like structures that grow into simulation 2 were totally unexpected. We explained how those simulations evolved so differently by studying the different phases of the simulations. Indeed, the simulations can be divided into three main periods: a first one with the linear growth of a kinetic instability called the Lower-Hybrid drift instability (LHDI), a second one, that we will

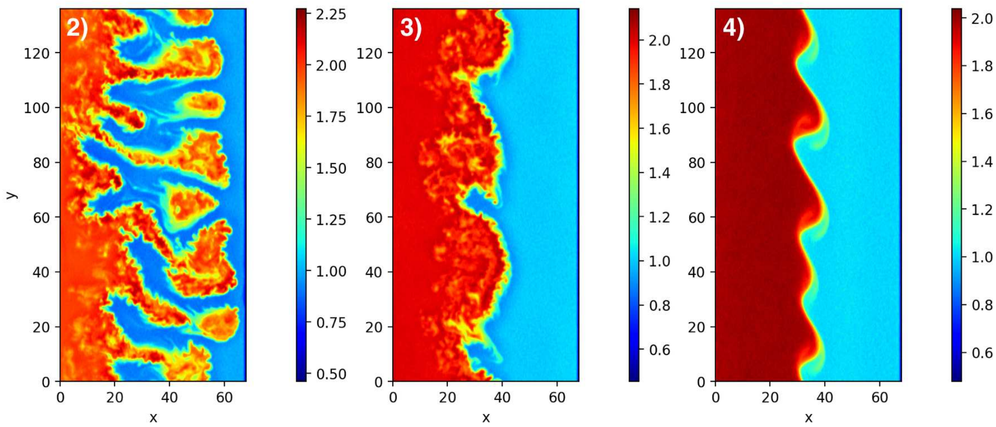

Fig. 1. Magnetic field along z at t=350ω_{ci}^{-1} for the simulations with a velocity shear at the dusk side (simulation 2, 3 and 4 respectively). Those simulations have initially the same profiles, except for the density asymmetry between the two sides of the layer. The asymmetry of density (n_{right}/n_{left}) for simulation 2, 3 and 4 is n_{right}/n_{left}=10, 5 and 1, respectively. Published in Dargent et al. (2019).

call the nonlinear phase of LHDI, where the finger-like structures observed in simulation 2 (figure 1) begin to grow and finally a third one, corresponding to the linear growth of the KH instability, with the formation of KH vortices. In the linear phase of LHDI, we observe the growth of the LHDI into each simulation with a density gradient (simulations 1, 2 and 3). This instability develops quickly all along the layer but remains at small spatial scales. In those simulation, in the second phase, we then observed a an inverse cascade of energy leading to the growth of large scale finger-like structure along the layer. Those structures grow faster in the simulations with a stronger density asymmetry. The instability behind those structure is still under study and remains to be identified with certainty. However, we were able to characterize the growth of those structure in order to compare it with the KH instability. Finally, we observed the growth of the KH vortices in simulations 3 and 4, but not in simulation 2 where they were expected. We showed that the reason is the growth of the finger-like structure, whose growth rate is higher that the KH instability in simulation 2, thus preventing the growth of the latter. On contrary, in simulation 3, the KH instability's growth rate is higher, and the KH vortices developed, albeit perturbed, despite the growth of the finger-like structures. These results have been published in Dargent et al. (2019).

To be sure that the instability growing the finger-like structures has an impact in real data, we have to identify the instability and study its sensitivity to the mass ratio of ion over electron. Indeed, for practical reasons, the simulations we made used a reduced mass ratio of 25. Our first concern was therefore to confirm that the instability is not slow down, if not negligible, for realistic mass ratio. We realized five simulations, corresponding to a smaller version of simulation 1, with different mass ratio. The simulations, hereafter called simulations *a*, *b*, *c*, *d* and *e*, have been implemented with a mass ratio of 25, 36, 64, 100 and 144, respectively. The evolution of those simulation is shown in figure 2 and we observed no strong dependance on the mass ratio. Further investigation showed us that there seems to be a dependance on mass ratio, with a faster instability as the mass ratio increase but this dependance remains weak. Therefore, this instability is expected for realistic mass ratio.

Finally, we looked at the initial subject of the project: the dawn-dusk asymmetry. This subject has not been as developed as expected, but we noted that the KH growth rate is sig-

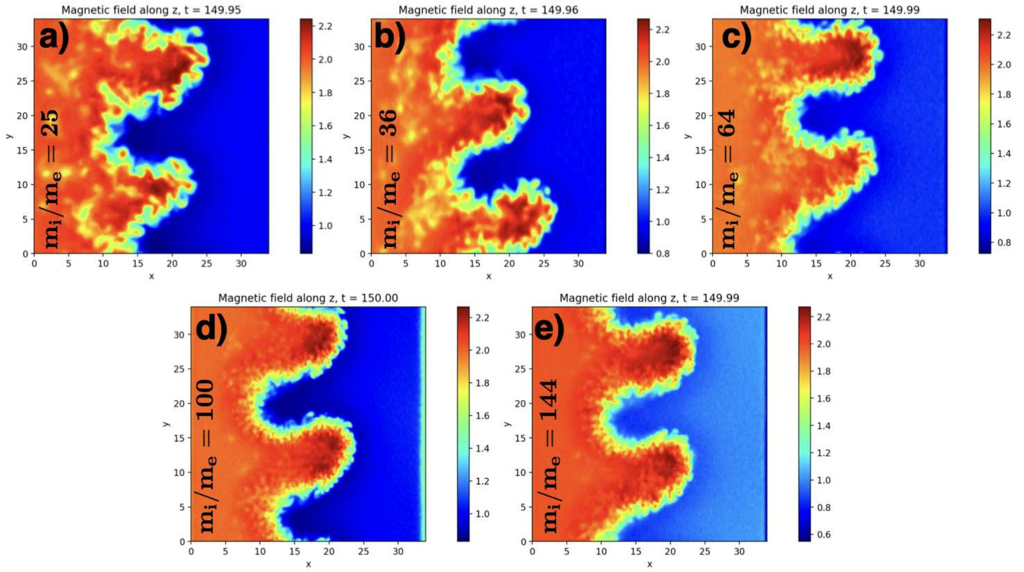

Fig. 2. Magnetic field along z at t=150ω_{ci}^{-1} for the simulations *a*, *b*, *c*, *d* and *e*. Those simulations have initially the same exact same profiles, but are initialized with different mass ratio between ion and electron: 25, 36, 64, 100 and 144, respectively.

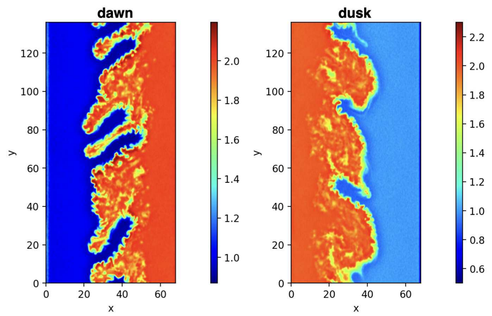

Fig. 3. Magnetic field along z at t=400ω_{ci}^{-1} for the simulations 3 (right panel) and its dawn side equivalent (left panel).

nificantly faster on the dusk side, compared to the dawn side. This leads to an interesting case in simulation 3 (dawn and dusk versions): as we can see in figure 3, while the KH instaiblity dominates along the layer in the dusk simulation, the kinetic instability seems to be dominant in the dawn simulation. This is an interesting feature to be studied in the frame of the dawn-dusk asymmetry at Mercury.

3. Conclusions

The simulations realized in the frame of this project have given excellent results, exceeding our expectations. We have observed that, in the frame of Mercury, kinetic instabilities can produce structures at large scales, interplaying with the (fluid scale) KH instability. Those results opened a new path in the study of the hermean magnetopause: the interplay between kinetic and fluid instabilities. Until now, the kinetic instabilities have only been seen as secondary instabilities growing along the primary fluid instability. With this work, the interactions between kinetic and fluid scale have been proven to be non negligible in the magnetopause dynamics of Mercury. Thanks to this grant, we have been able to initiate this field of study. This work is already developing thanks to an ISCRA B project looking into other features of the hermean magnetosphere, such as the presence of heavy ions.

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