Modelling of Energy-Transfer Processes at Ganymede's Upstream Magnetopause

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Abstract

Ganymede is the only Solar System moon to maintain a permanent magnetosphere. Dynamics inside Ganymede's magnetosphere are likely driven by interactions with external Jovian magnetospheric plasma along the upstream magnetopause boundary, particularly magnetic reconnection and Kelvin-Helmholtz (K-H) instability. Here we assess the viability of both interactions using an analytical model of Ganymede's magnetopause. We find that magnetic reconnection can occur anywhere on the magnetopause at significant rates, allowing for possibilities of multiple X-lines or transient flux-transfer events on the boundary. Linear K-H waves can also occur along magnetopause flank regions, but the instability growth rate is insufficient for nonlinear K-H vortices. These results suggest that magnetic reconnection should be the dominant energy-transfer mechanism at Ganymede's upstream magnetopause.

Introduction

In 1996, the Galileo spacecraft detects evidence of Ganymede's permanent magnetic field, thought to arise from dynamo action inside an Earth-like molten iron core. The magnetic field is close to dipolar but possesses complex dynamics likely consistent with a secondary field induced by convection inside a large subsurface ocean. Ganymede orbits Jupiter at 15 R_J in a plane close to Jupiter's ecliptic plane, experiencing large variations in plasma/magnetic conditions inside the ~3 R_J thick Jovian plasma sheet. Unlike the solar wind, the Jovian plasma is dominated by O, S heavy ions (~90%) with fewer protons (~10%). The plasma can be considered as a single fluid flowing at sub-Alfvénic speed, creating a cylindrical Ganymedean magnetosphere with long Alfvén wings. Our interaction analyses focus on a small upstream equatorial region where Ganymede's magnetic field lines are closed i.e. partly antiparallel to the Jovian field.

Analytical Model Set-Up

We consider a fixed magnetopause surface in a Ganymede-centred Cartesian coordinates (GphiO) where X is along Jovian plasma flow, Y points toward Jupiter, and Z is along Ganymede's spin axis. We project the magnetopause onto a Y-Z plane and estimate plasma/magnetic conditions just outside/inside the boundary (Fig. 1). Ambient Jovian plasma flow velocity, mass density, and pressure are taken from Jia et al. (2008) and then parametrised by simple sinusoidal equations (the simplicity does not affect main conclusions drawn). The Jovian magnetic field is then calculated using pressure conservation before/after compression. Finally, the Ganymedean magnetic field is calculated via pressure balance across the magnetopause.

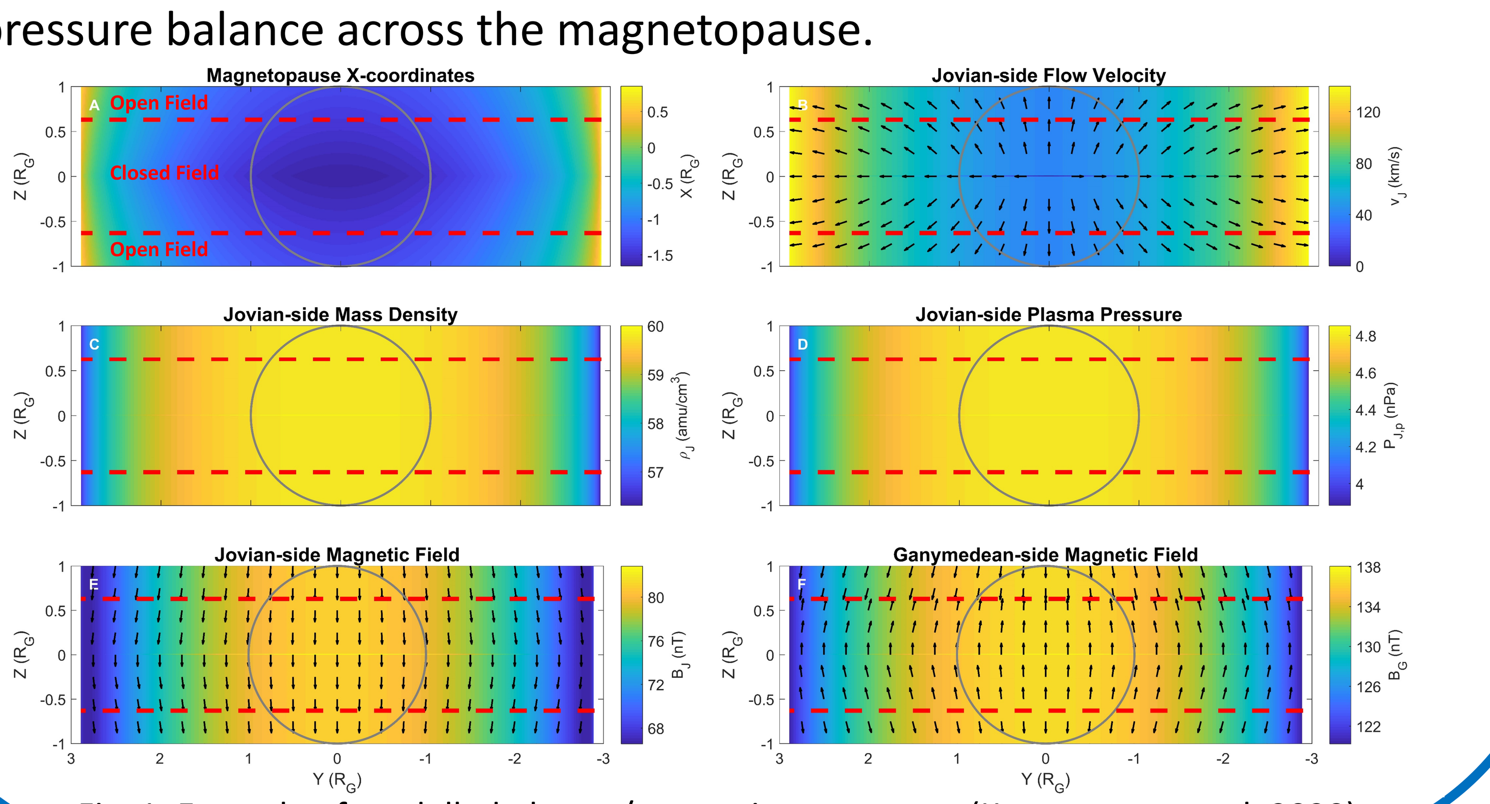

Fig. 1: Example of modelled plasma/magnetic parameters (Kaweeyanun et al. 2020).

Magnetic Reconnection Assessment

We calculate magnetic reconnection electric field where all three reconnection onset conditions are satisfied on Ganymede's closed-field magnetopause. We consider cases when Ganymede lies at centre of (Fig. 2A) and furthest above/below (Fig. 2B/2C) the Jovian plasma sheet. The electric field is non-zero throughout the closed-field magnetopause in all cases, indicating that reconnection can occur anywhere on the surface. The electric field range (2.6-5.6 mV/m) is large compared to planetary magnetopauses (<0.01-0.2 mV/m Earth, <0.1 mV/m Jupiter), so Ganymede's reconnection rates are significant everywhere and less orderly reconnection structures (e.g. multiple X-lines, widespread flux ropes) are possible.

The average electric field increases from Fig. 2A to Figs 2B/2C due to stronger Jovian magnetic field away from the plasma sheet centre. The Jovian field is bijective to time of day on Jupiter. Therefore, magnetic reconnection rate at Ganymede is effectively driven by Jovian rotation. For more info, see Kaweeyanun et al. (2020).

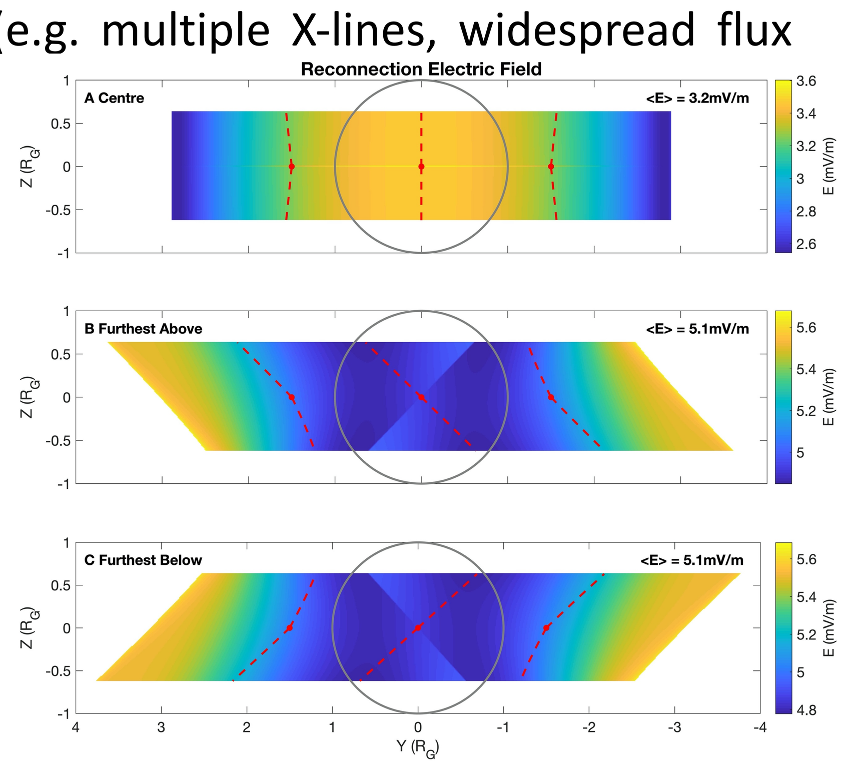

Fig. 2: Magnetic reconnection assessment at Ganymede's magnetopause (Kaweeyanun et al. 2020)

K-H Instability and Finite Larmor Radius Effect

K-H instability can transfer energy in its nonlinear vortices, whose formations depend on the K-H growth rate (γ) along magnetopause flanks. Unlike planetary cases, γ is unequal between Ganymede's sub-Jupiter and anti-Jupiter flanks due to finite Larmor radius (FLR) effect from Jovian plasma ions (O, S). We calculate γ at a point along each flank (Fig. 3) and find ~5% larger γ along the near-Jupiter flank, implying small FLR effect. The γ values for both flanks (0.20-0.61 s^{-1}) are comparable to dawnside of similar-sized Mercury's magnetopause where no K-H vortex is observed, so we expect no energy transport via K-H instability at Ganymede's magnetopause. We also assess MHD K-H instability onset condition across the magnetopause (Fig. 4), finding prevalence of K-H waves along magnetopause flanks propagating in flow direction of nearby Jovian plasma.

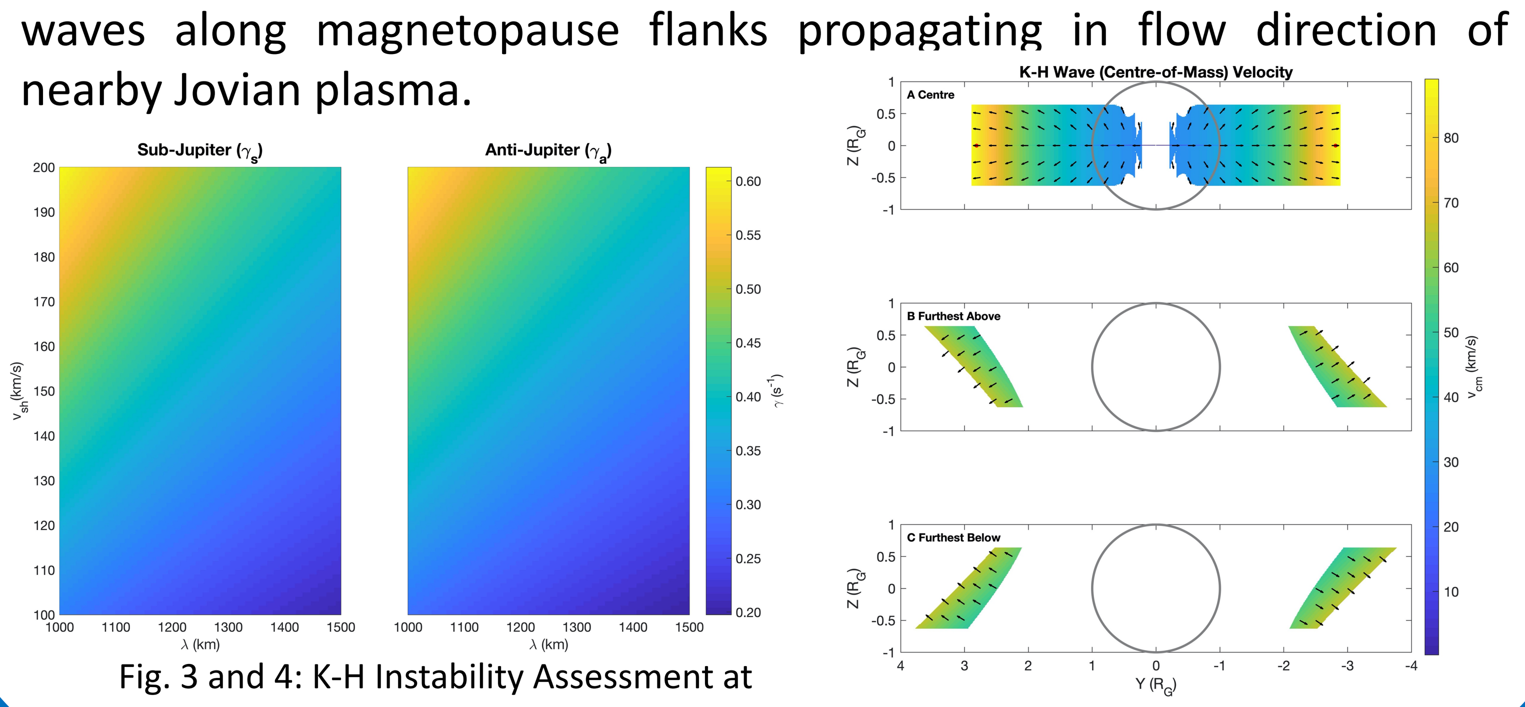

Fig. 3 and 4: K-H Instability Assessment at Ganymede's magnetopause

Conclusion

Ganymede has a highly dynamic magnetopause where both magnetic reconnection and K-H linear waves are common, but the former is likely the primary energy-transfer process across the boundary. These predictions provide greater insights into Ganymede's magnetic environment which may be useful for the upcoming JUpiter ICy moon Explorer (JUICE) mission.

References

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