Space Environment and Ohmic Heating of TRAPPIST-1 Exoplanets Exposed to Interplanetary Coronal Mass Ejections

Filip Elekes *, ***Joachim Saur, Alexander Grayver***

University of Cologne

Institute of Geophysics and Meteorology, University of Cologne
*Contact: f.elekes@uni-koeln.de

Overview

Introduction: Trappist-1 is a remarkable stellar system with 7 terrestrial exoplanets. The central M-dwarf is a flaring star, which likely exerts a large impact on the space weather surrounding the planets. The effect of flare-associated coronal mass ejections (CMEs) on the space environment of exoplanets is an important aspect that can strongly influence atmospheres, the planets interior energy budget, their magnetospheres, if any, and ultimately the habitability of such planets.
Methods: We perform magnetohydrodynamic (MHD) simulations in which we study the interaction of CMEs with the space environment of Trappist-1b and e. We study the interaction of magnetized and non-magnetized planets with density-pulse (DP) and fluxrope (FR) CMEs, the magnetic variability at the surface of the planets, and resulting interior heating.
Results: Magnetic variability in DP CME models is dominated by compression, whereas for FR CMEs the inherent magnetic variability is transported almost directly to the planet. Time-averaged heating rates Q_{avg} for FR CMEs are almost constant for all planetary magnetic field strengths considered, whereas for DP CMEs, Q_{avg} scale with the planetary magnetic field and increase by 3 orders of magnitude. Above 0.1 G, Q_{avg} saturates for all models and reaches 1 and 10 TW for Tr-1e and b, respectively. We complement the planetary equilibrium temperature T_{eq} with the Ohmically dissipated heat within the planet and find that the T_{eq} could increase by 15 to 20 K for one CME. We furthermore find that most heating occurs in the upstream hemisphere where planetary magnetic field lines are radial.

Model

We use the PLUTO ideal MHD code [2].

- Planetary magnetic dipole fields B_p (0 – 0.15 G), aligned with planet's rotation axis
- CME associated with flare energy $E_{bol} = 10^{31}$ erg
- CME velocity $v \approx 2200$ km/s, duration: ≈ 1 hour
- **Density pulse CME (DP)**: Density ρ enhancement
- **Fluxrope CME (FR):** Magnetic fluxrope

Magnetic variability and post–processing

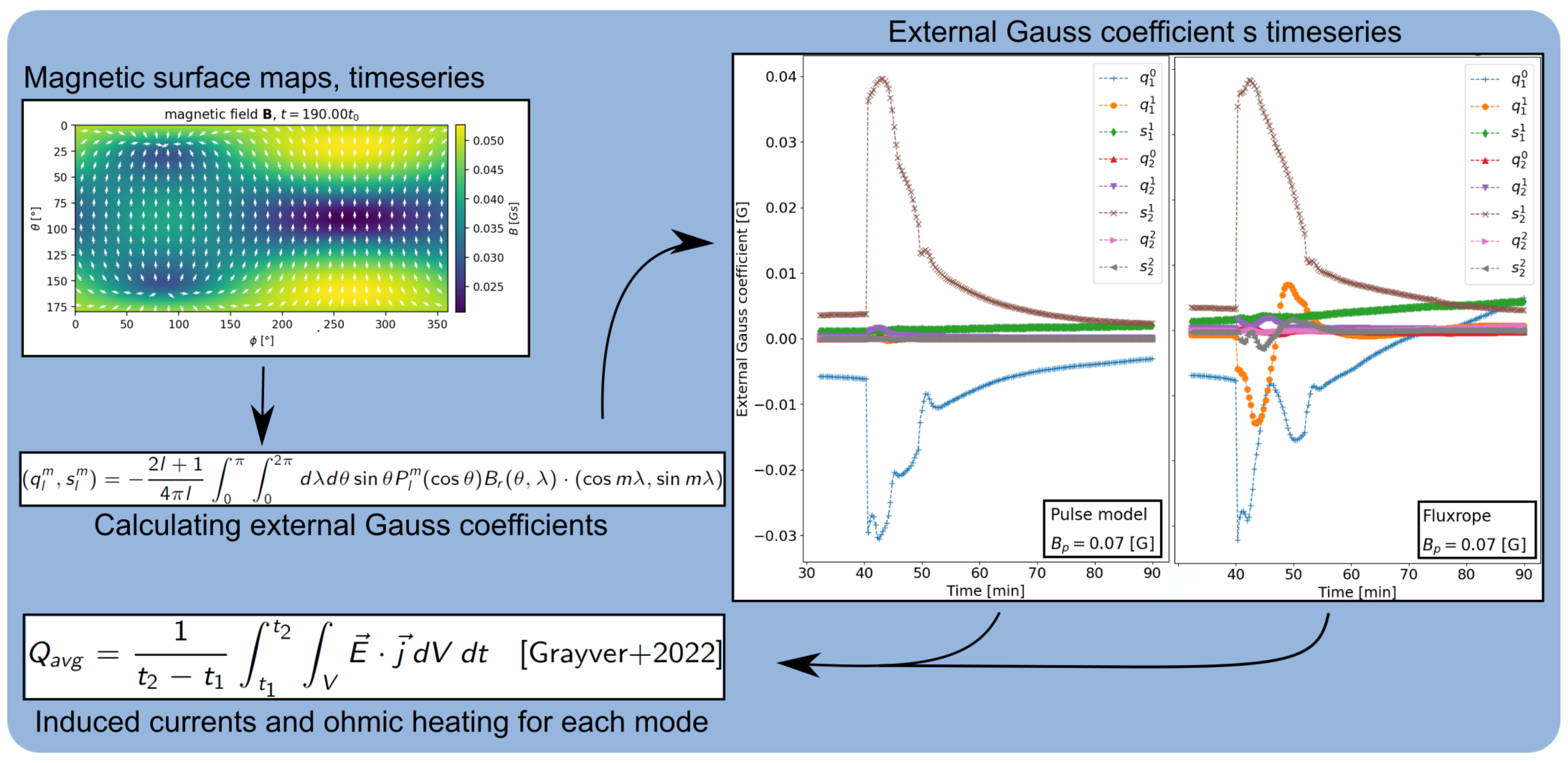

Figure 1: Interior heating post–processing pipeline.

- Decomposition of external field into Gauss coefficients
- External field variations induce currents in planetary subsurface
- Calculation of time–averaged interior Ohmic heating rates [1]

References

[1] Grayver, A., Bower, Dan J., Saur, J. et. al (2022) *Astrophysical Journal letters*, 941, 1 :L7.
[2] Mignone, A., Bodo, G., Massaglia, S. et. al (2022) *The Astrophysical Journal Supplement Series*, 170, 1, pp. 228-242.

Magnetospheric structure during CME

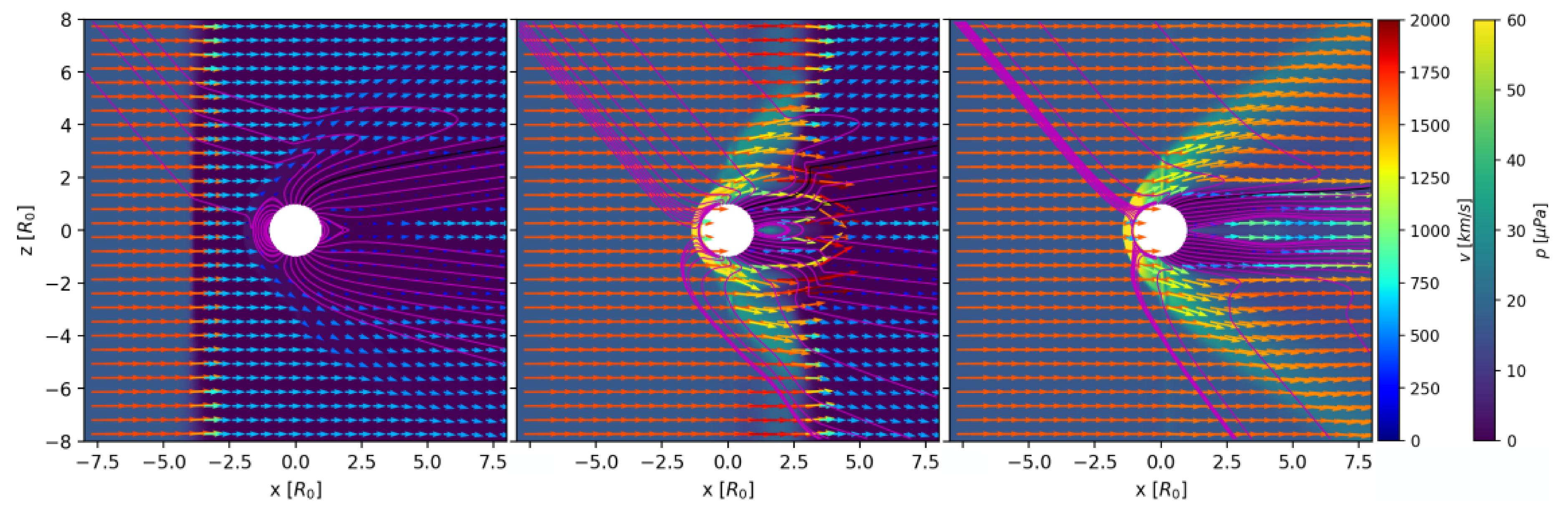

Figure 2: Planetary magnetosphere with $B_p = 0.05$ G during CME shock crossing (Density pulse). **Arrows:** velocity vectors, **contours:** thermal pressure, **magenta lines:** Magnetic field lines.

Results: Interior heating

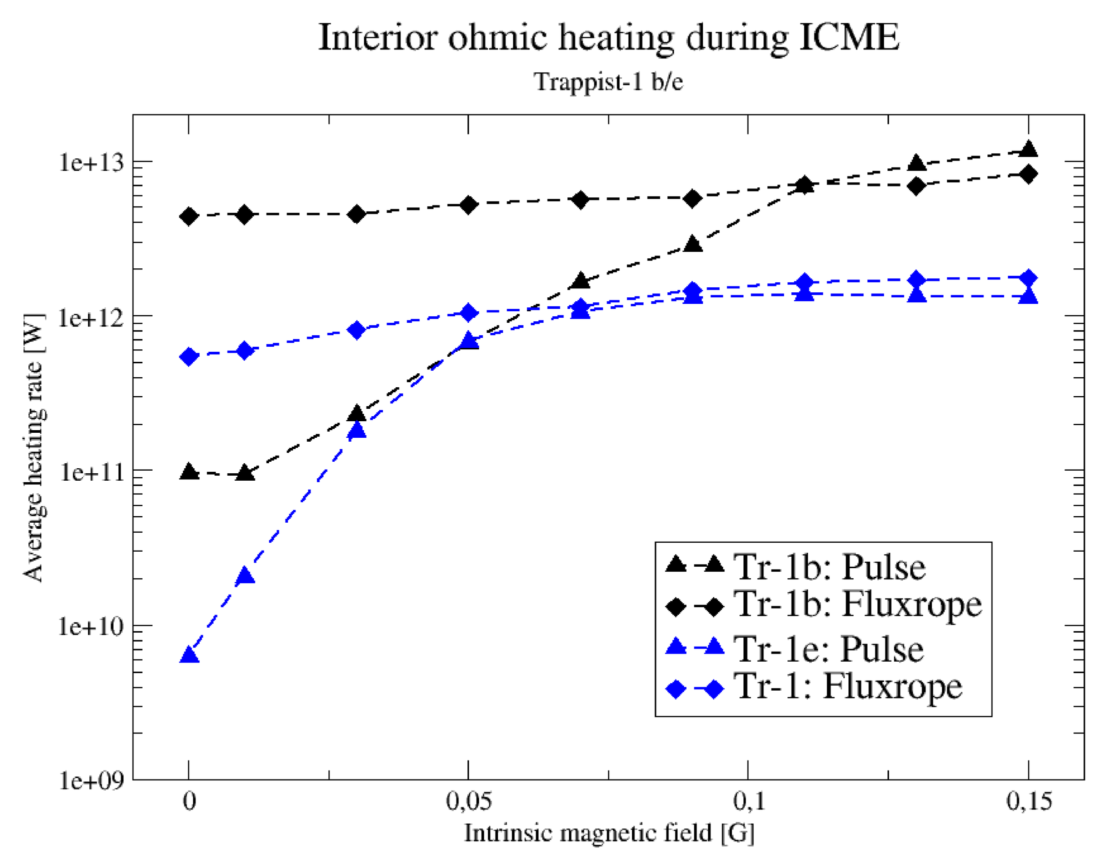

Figure 3: Time–averaged interior Joule heating rates Q_{avg} as function of planetary magnetic field B_p

- Homogeneous sphere
- Conductivity $\sigma = 0.01$ S/m
- Heating only in low depths
- Saturation: $B_p > 0.1$ G
- **DP:** 0.01 – 1 TW
- **FR:** 0.1 – 10 TW

Heating effects and localization

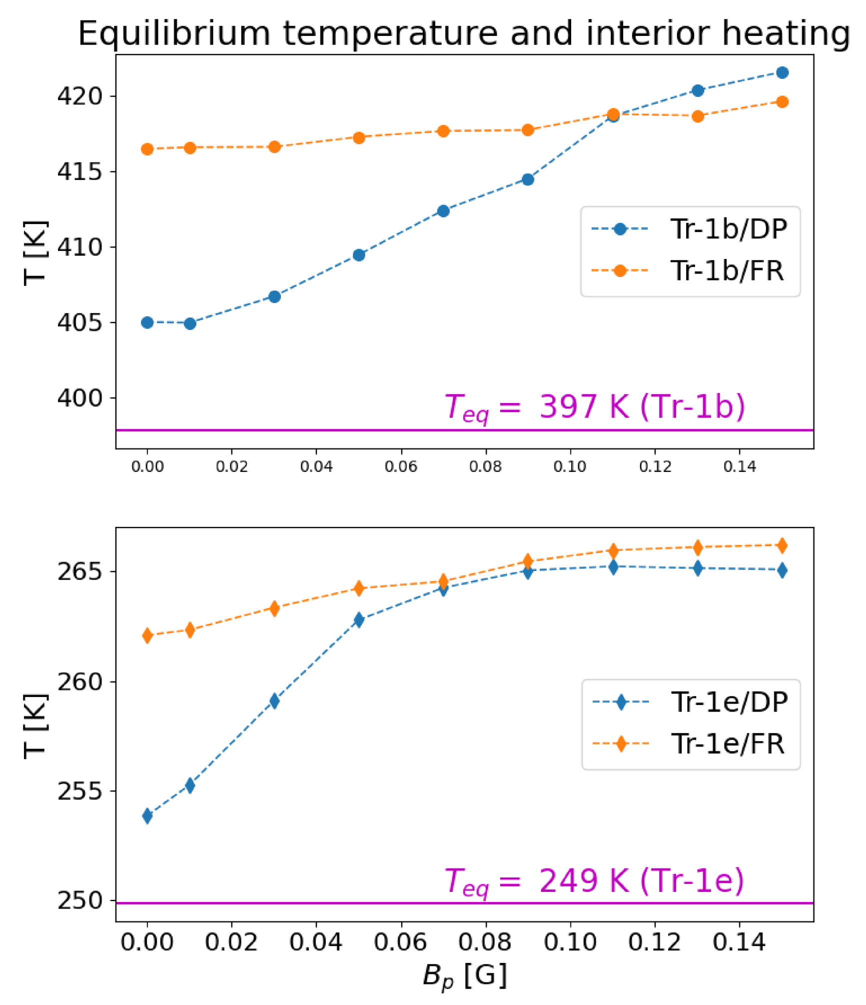

Figure 4: CME heating rate and enhanced equilibrium temperature, $T_{eq}^4 = \frac{L_*}{16\pi\sigma a^2} + Q_{avg}$, plotted as a function of B_p.

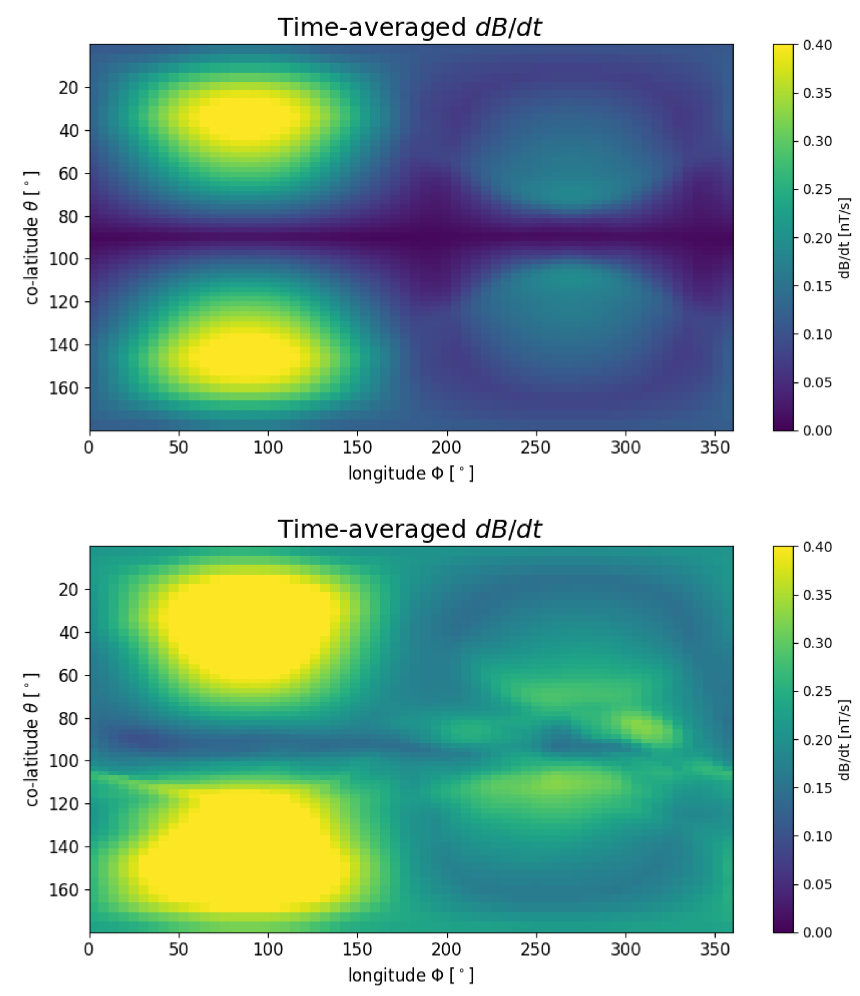

Figure 5: Time–averaged magnetic variability dB/dt at planetary surface with $B_p = 0.15$ G. Upstream hemisphere is at $\Phi < 180°$. High dB/dt corresponds to strong heating.

Conclusions

- Magnetic variability at planet is dominated by upstream magnetopause compression
- Intrinsic magnetic variability in fluxrope CMEs directly contributes to heating → Weak B_p–dependence
- Density pulse CMEs carry mostly kinetic energy that compresses B_p and results in strongly variable magnetic field at the planet's surface → Strong B_p–dependence
- Maximum heating rates for strong B_p, 1 – 10 TW (Tr-1e and b)
- Heating saturates above ≈ B_p 0.1 G
- Most heating at upstream hemisphere, low depths