PS8.1 Poster EGU23-5578
Thu 27 Apr, 16:15–18:00
Hall X4 | X4.357

Interior heating of rocky exoplanets from stellar flares with application to TRAPPIST-1

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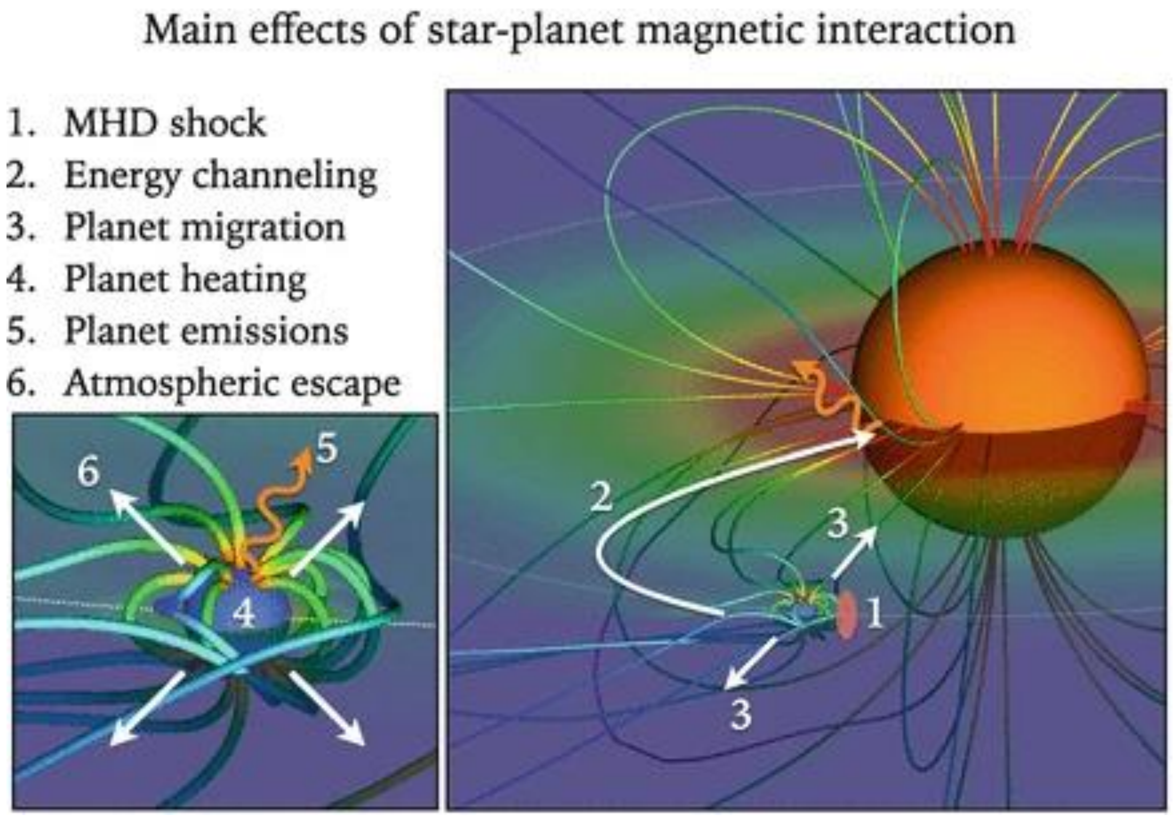
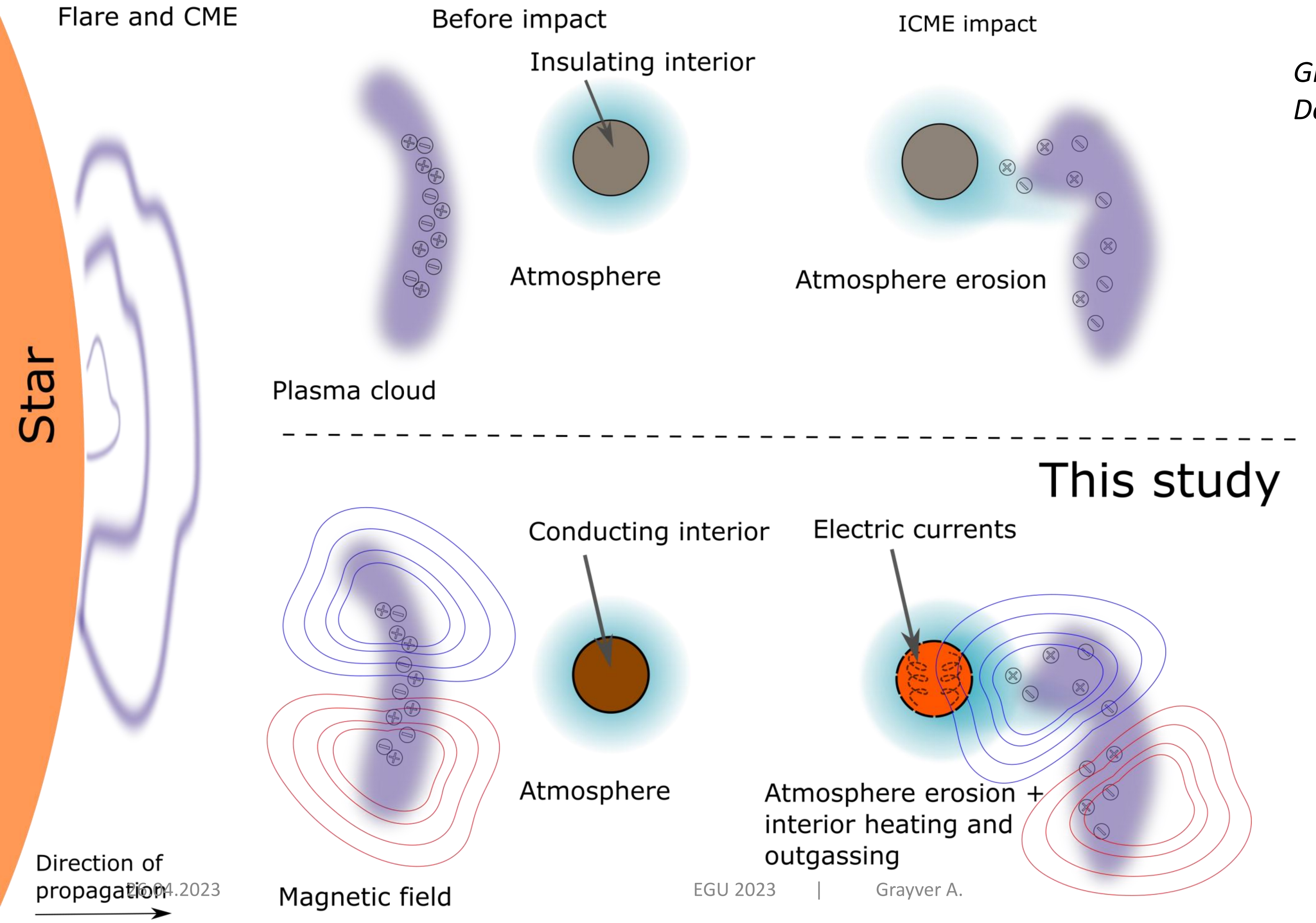
Motivation



Strugarek 2017

Is heating due to different electromagnetic interactions between a star and a (magnetized) planet significant?



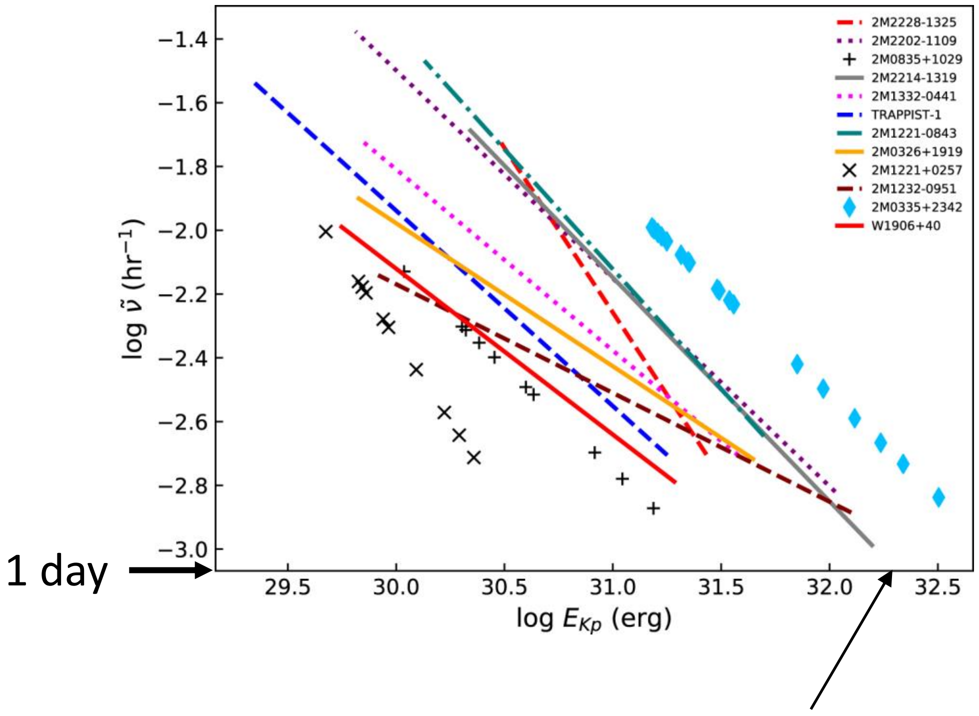
Grayver, Bower, Saur, Dorn, Morris, 2022, ApJL

Inducing mechanism

- Stellar flares and Coronal Mass Ejections (CMEs)
  - Cause magnetic perturbations at planets, thus produce heat in the interior
  - Facilitate atmospheric loss

- Factors affecting amount of heat:
  - Star activity
  - Distance to planet
  - Probability of impact
  - Interior conductivity

Paudel et al. 2019



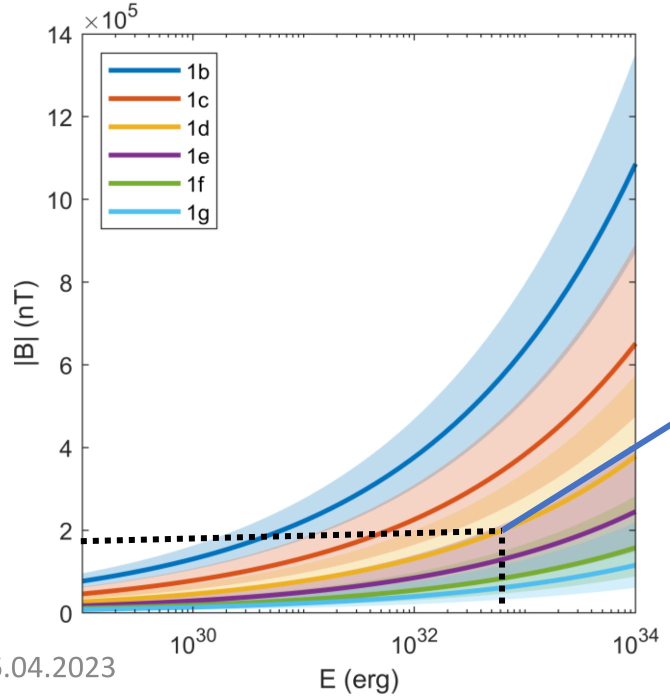
(1859 Carrington event $10^{32} - 10^{33}$ erg)

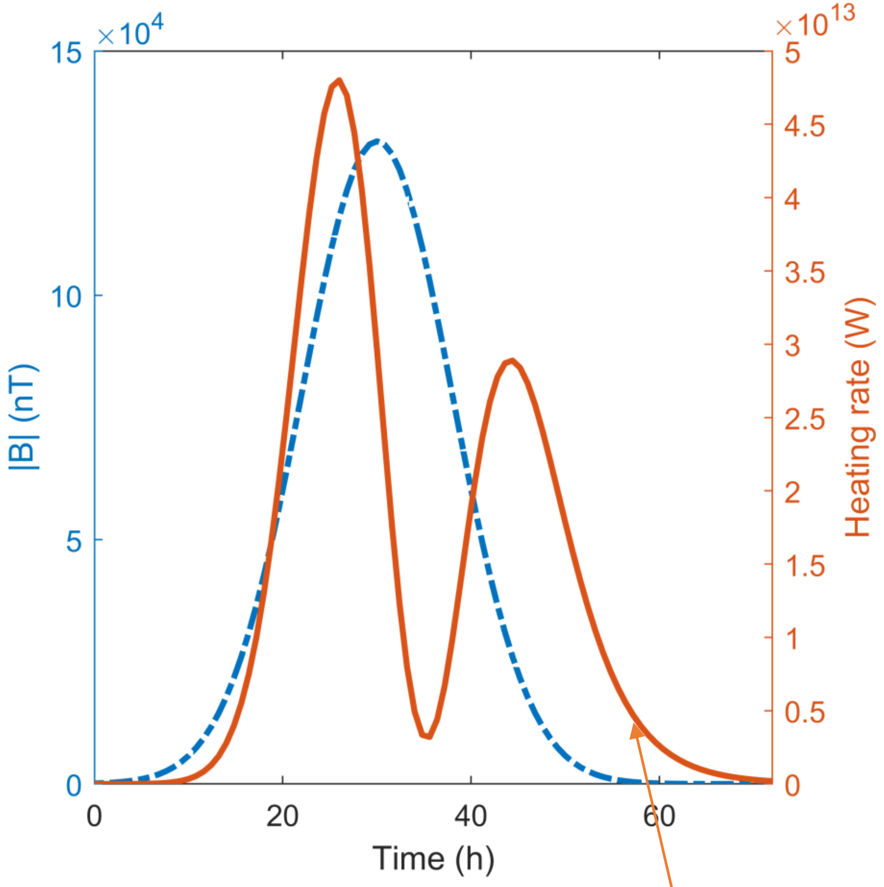
For Sun, Flare-CME association rate is >90% (Youssef 2013)

Flaring activity for the TRAPPIST-1 star

- TRAPPIST-1 was observed by Kepler for 70.6 days, detecting 39 flares (≈ 200 flares/year).

- CME are propagated to planets using flux-rope model of Samara et al. 2021:

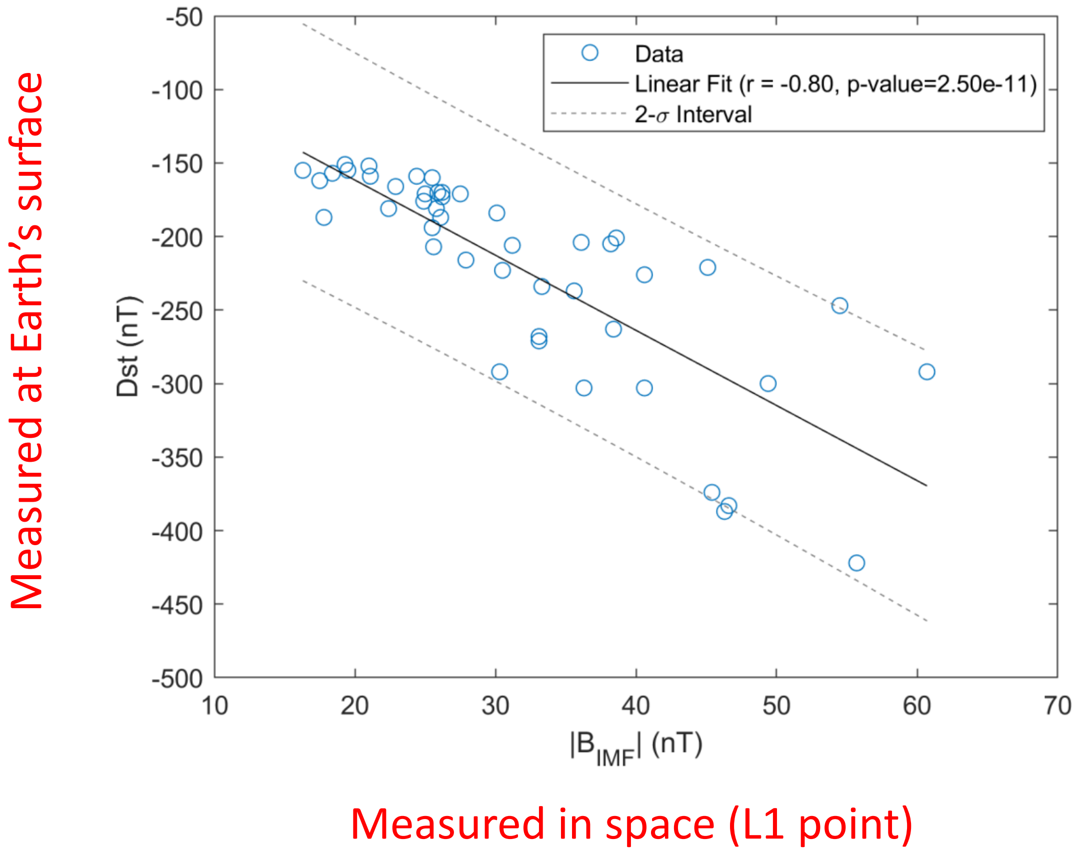




$$Q_{avg} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \int_V [\mathbf{E} \cdot \mathbf{J}] \, \mathrm{d}V \mathrm{d}t$$

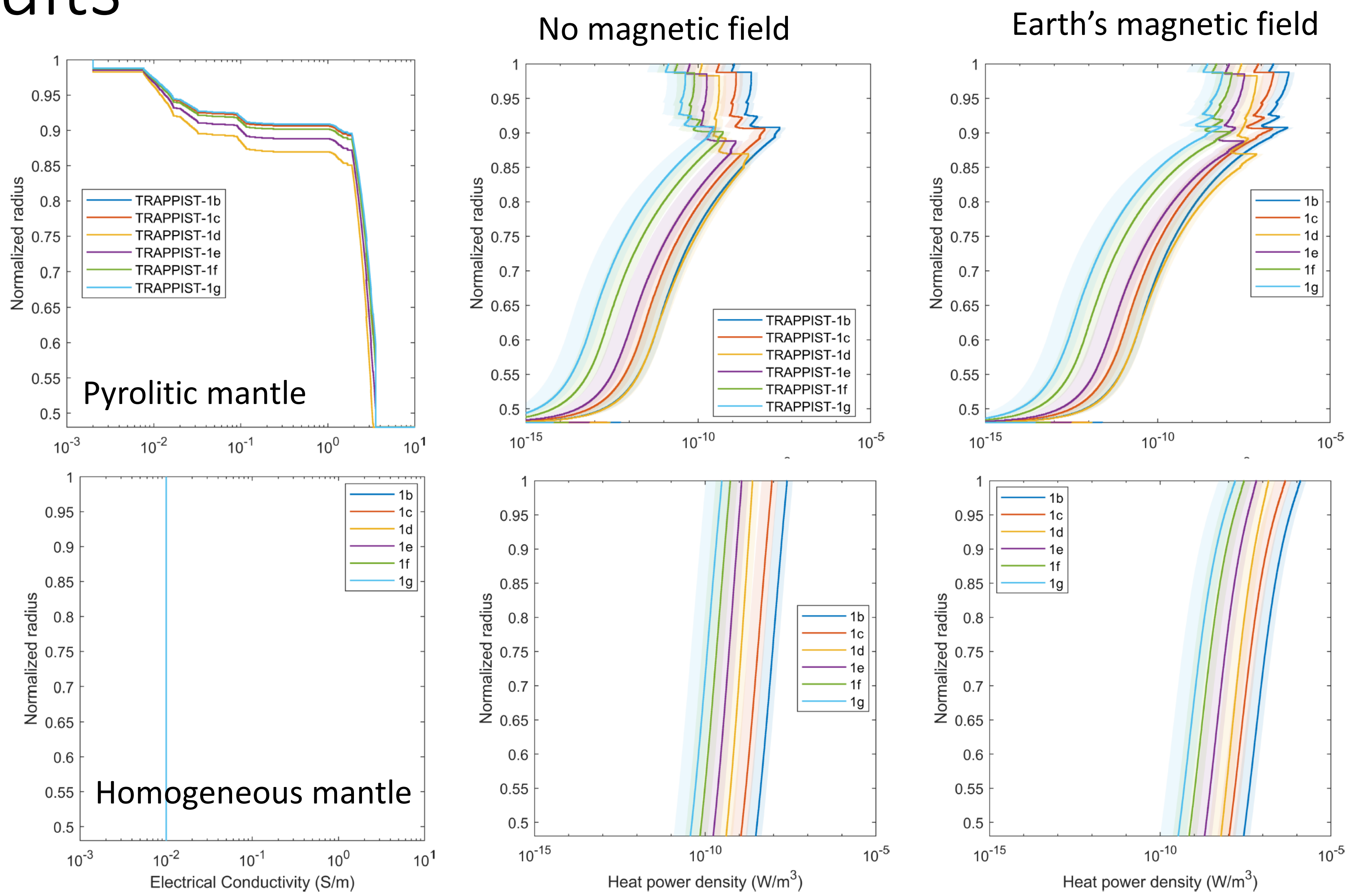
Effect of planet's intrinsic field

Effect of Earth's magnetosphere on IMF:



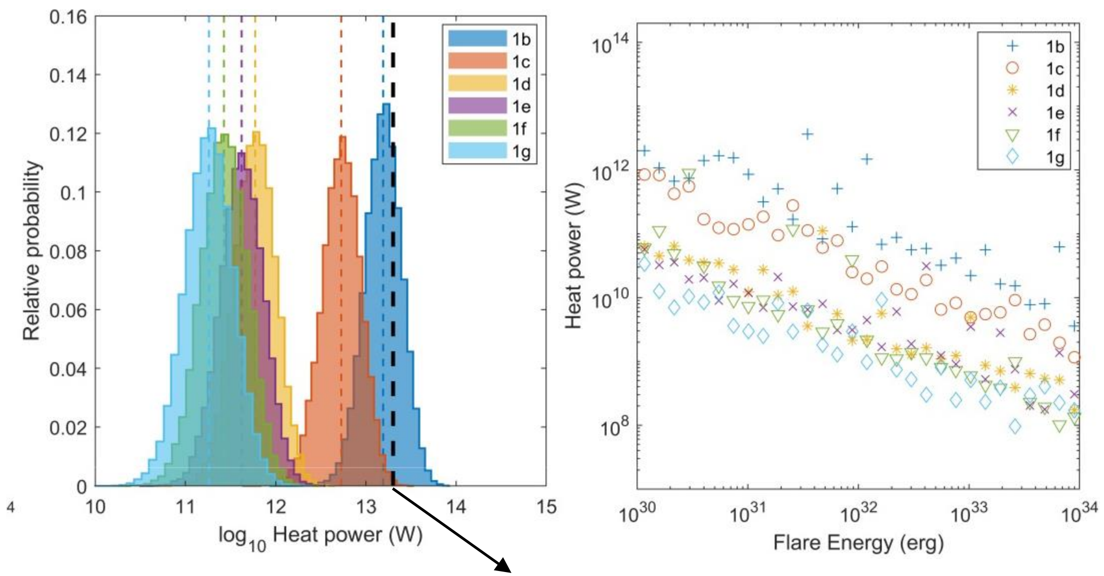
- Dst: magnetic disturbance index measured on Earth (describes zonal component of magnetosphere current)
  - |Dst| > 50 nT indicates a storm
- IMF: interplanetary magnetic field (measured at L1 point)
- Intrinsic magnetosphere amplifies the IMF during a storm -> more energy dissipated as heat

Results


No magnetic field
Earth's magnetic field
Pyrolitic mantle
Homogeneous mantle
Normalized radius
Electrical Conductivity (S/m)
Heat power density (W/m^3)
TRAPPIST-1b
TRAPPIST-1c
TRAPPIST-1d
TRAPPIST-1e
TRAPPIST-1f
TRAPPIST-1g
1b
1c
1d
1e
1f
1g
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
10^{-15} 10^{-10} 10^{-5}
1 0.95 0.9 0.85 0.8 0.75 0.7 0.65 0.6 0.55 0.5

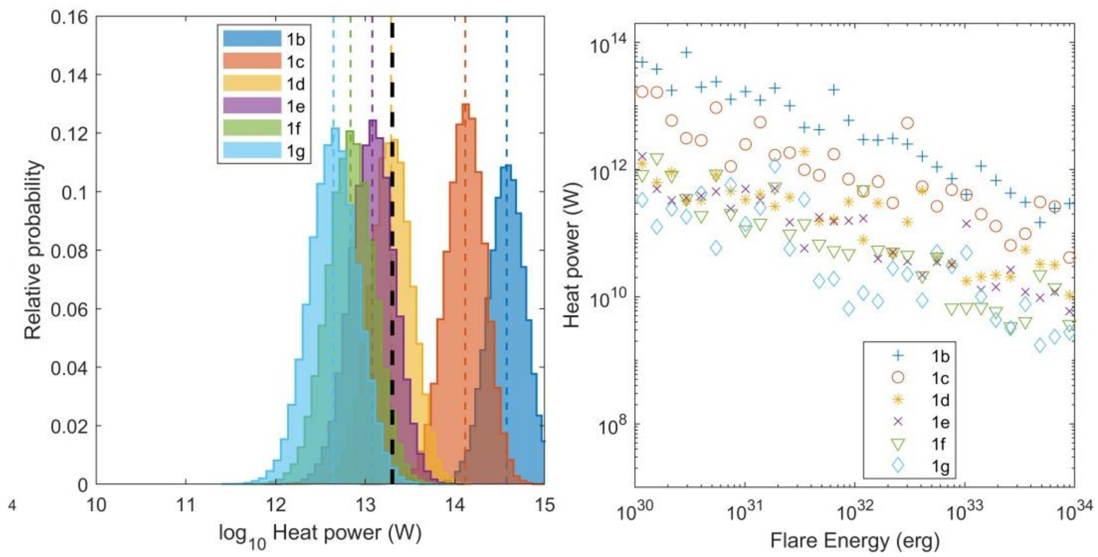
Results

No magnetic field



Earth's radiogenic heat release $\approx 20\ TW$

Earth's magnetic field



- Long-lived source of heating, significant for compact systems
- Intrinsic magnetic field leads to more dissipated heat

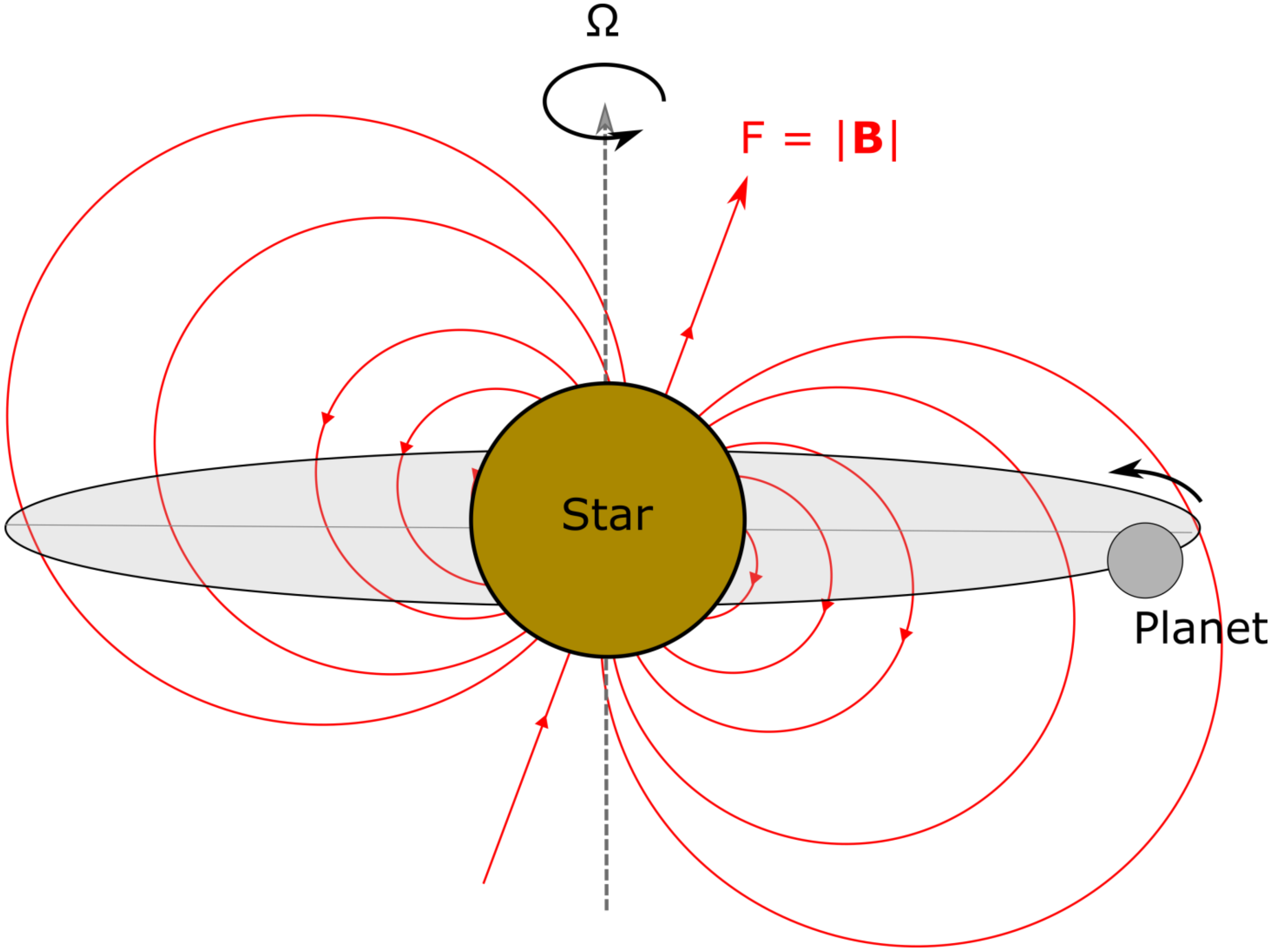
- Integrating with interior-atmosphere models
- Applying model to other planetary systems, more elaborate CME propagation models

  (see Poster **EGU23-15078** by **Filip Elekes**)

More on the poster and in the paper:
Grayver et al., 2022, ApJL

Inducing mechanisms

- Motion through the stellar field
  - Campbell 1983 for binary systems
  - Laine et al. 2008 for hot Jupiters
  - Applied to TRAPPIST-1 in Kislyakova, Noack et al. 2017
- Key variables:
  - Inclination and strength of the field
  - Distance to a planet and orbital plane
  - Period and direction of rotation
  - Conductivity of the mantle



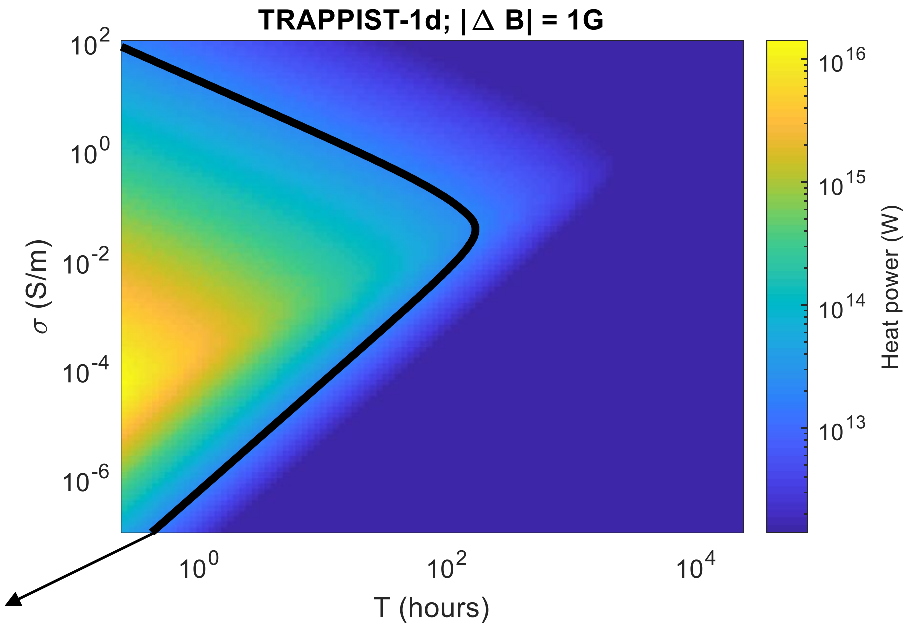
Example

For a homogeneous ($n = 1$) monochromatic (with angular frequency ω) external field and a homogeneous sphere of radius R and conductivity σ, the dissipated power is:

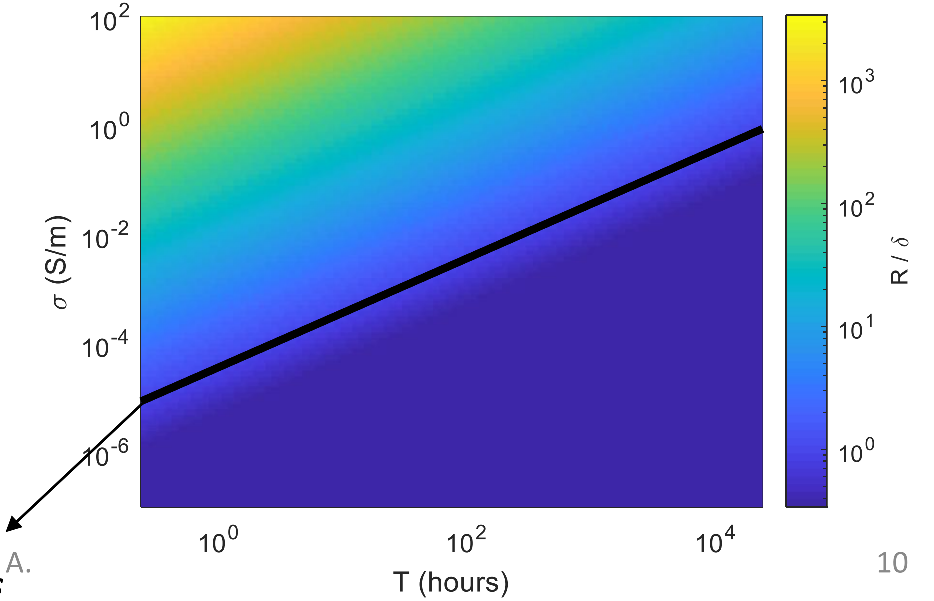
$$
\begin{aligned}
Q &= \frac{1}{2\sigma}\int_V |\mathbf{J}|^2 \, \mathrm{d}V \\
&= \frac{\pi R^3 \omega \Delta B^2}{\mu} \mathrm{Im}\left[\frac{j_2(kR)}{j_0(kR)}\right] \\
&\approx \frac{\pi R^3 \omega \Delta B^2}{\mu} \mathrm{Im}\left[\frac{(kR)^2}{15} + \frac{(kR)^6}{1575}\right] \\
&\approx \frac{\pi \sigma R^5 \omega^2 \Delta B^2}{15}\left[1 - \frac{4R^4}{105\delta_s^4}\right].
\end{aligned}
$$

where wavenumber, k, and skin depth, δ_s, are given by

$$k = \sqrt{2\mathrm{i}}/\delta_s, \quad \delta_s = \sqrt{2/\omega\mu\sigma}$$

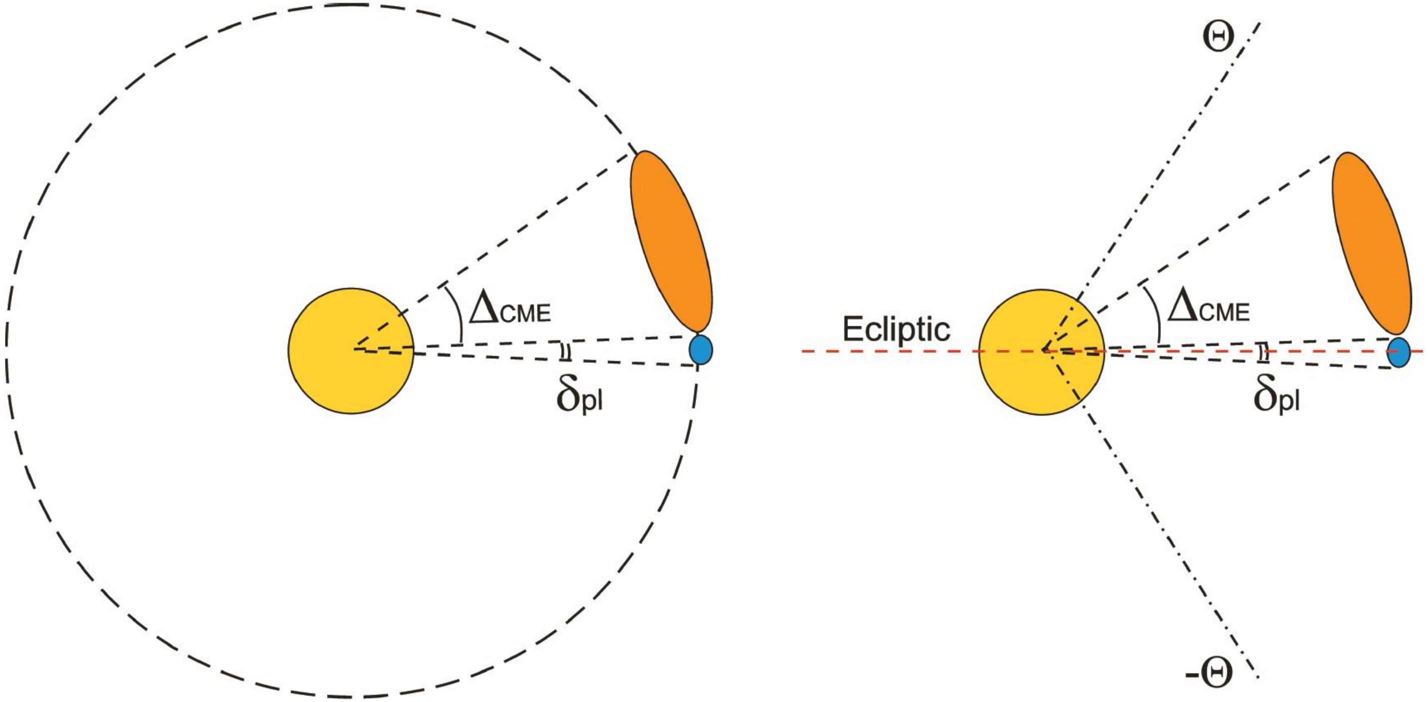


Earth's radiogenic heat release ≈ $20\ TW$



$R = \delta_s$

CME impact model



$$f_{\mathrm{Impact}} = \frac{\Delta_{CME} \sin\left[\left(\Delta_{CME} + \delta_{pl}\right)/2\right]}{2\pi \sin(\Theta)}$$

For $\Theta = 80°$ and $\Delta_{\mathrm{CME}} = 40° - 80°$:

$$\bar{f}_{\mathrm{Impact}} = 0.08$$

Khodachenko et al. 2007

Results

Table 1. Comparison of heating rates (in TW) for different heating mechanisms. Electromagnetic heating was calculated for the layered (Figure 3a) and a homogeneous (100 Ωm) models.

Planet	Ohmic (ICMEs)[1]				Ohmic (stellar field)[2]		Tidal[3]
	Layered		Homogeneous		Layered	Homogeneous	
	Nonmagnetized	Magnetized	Nonmagnetized	Magnetized			
b	2.9	139.2	15.5	379.3	42.9	304.5	N/A
c	1	48.2	5.3	130.5	4.5	19.1	N/A
d	0.16	7.9	0.59	19.4	0.34	0.3	N/A
e	0.1	4.6	0.42	11.9	0.31	1.1	12.2
f	0.05	2.5	0.26	6.8	0.18	1.	17.0
h	0.034	1.6	0.18	4.4	0.11	0.73	0.72

[1] The reported values are geometric means as shown in Figure 4

[2] Values were calculated following the approach of Kislyakova et al. (2017). Note that we used the updated TRAPPIST-1 rotation period of 3.3 days, whereas in Kislyakova et al. (2017) an older estimate of 1.4 days was used. Other parameters are identical.

Conclusions

- Elaborated a physical model for simulating electromagnetic SPI and Ohmic dissipation.
- Showed that EM interactions is a significant source of heat (for compact systems)
- Intrinsic magnetic field acts as an “amplifier”

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