Exoplanetary Atmospheric Escape Driven by Rapid Orbital Motion Through an Extreme Space Environment

Ofer Cohen[1], Alex Glocer[2], Cecilia Garraffo[3], Julian Alvarado-Gomez[4], Jeremy Drake[5], Kristina Monsch[3] (presenter), and Farah Fauth Puigdomenech [6]
[1]UMass Lowell, [2]NASA GSFC, [3]Harvard-Smithsonian CfA, [4]Leibniz Institute for Astrophysics Potsdam, [5]Lockheed Martin, [6]University of Southampton

What are we trying to do?

Exoplanets with short orbit periods reside very close to their host stars. They transition very rapidly between different sectors of the circumstellar space environment along their orbit, leading to large variations of the magnetic field in the vicinity of the planet on short timescales. This rapid change of the magnetic flux through the conducting and resistive layer of the planetary upper atmosphere may drive currents that dissipate in the form of Joule heating (JH). Here, we estimate the amount of JH dissipation in the upper atmosphere of Trappist-1e, and two hypothetical planets orbiting the Sun in close-in orbits.

Simulating the stellar wind conditions along the planetary orbit:

Using the AWSOM 3D MHD model for the solar/stellar corona and the solar/stellar wind, and using solar and ZDI magnetograms, we simulate the stellar wind conditions for the three cases. We extract the magnitude of the stellar wind magnetic field along the orbits of the three cases in order to obtain the orbital variations of the magnetic field.

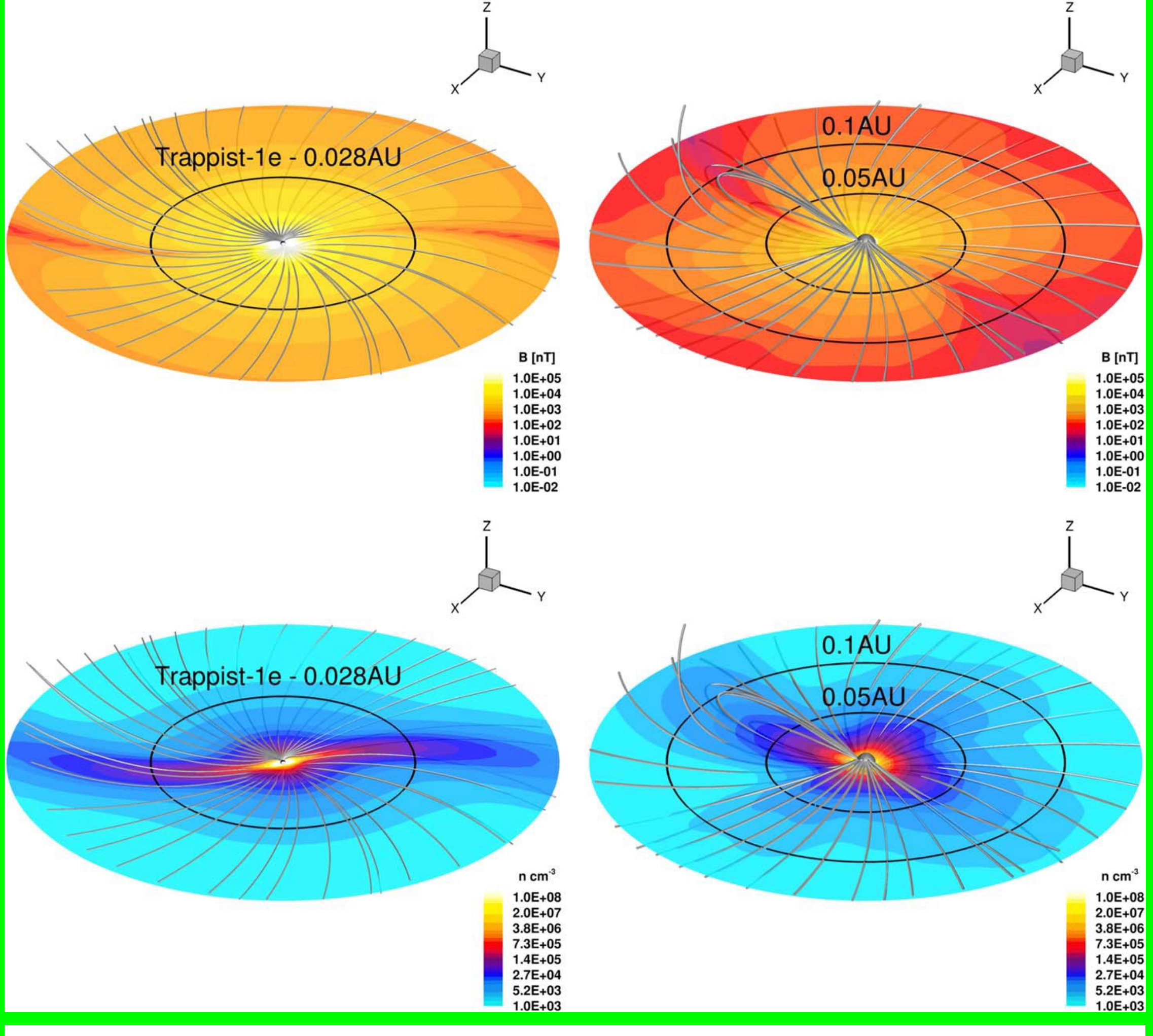

Figure 1. Equatorial slices showing the solar/stellar wind solution for Trappist-1e (left column) and for solar Carrington Rotation 1916 (right column). Color contours are of magnetic field strength (top) and number density (bottom). Also shown is the orbit of Trappist-1e at 0.028 au and the hypothetical orbits at 0.05 and 0.1 au as solid black circles. Selected magnetic field lines are shown in gray.

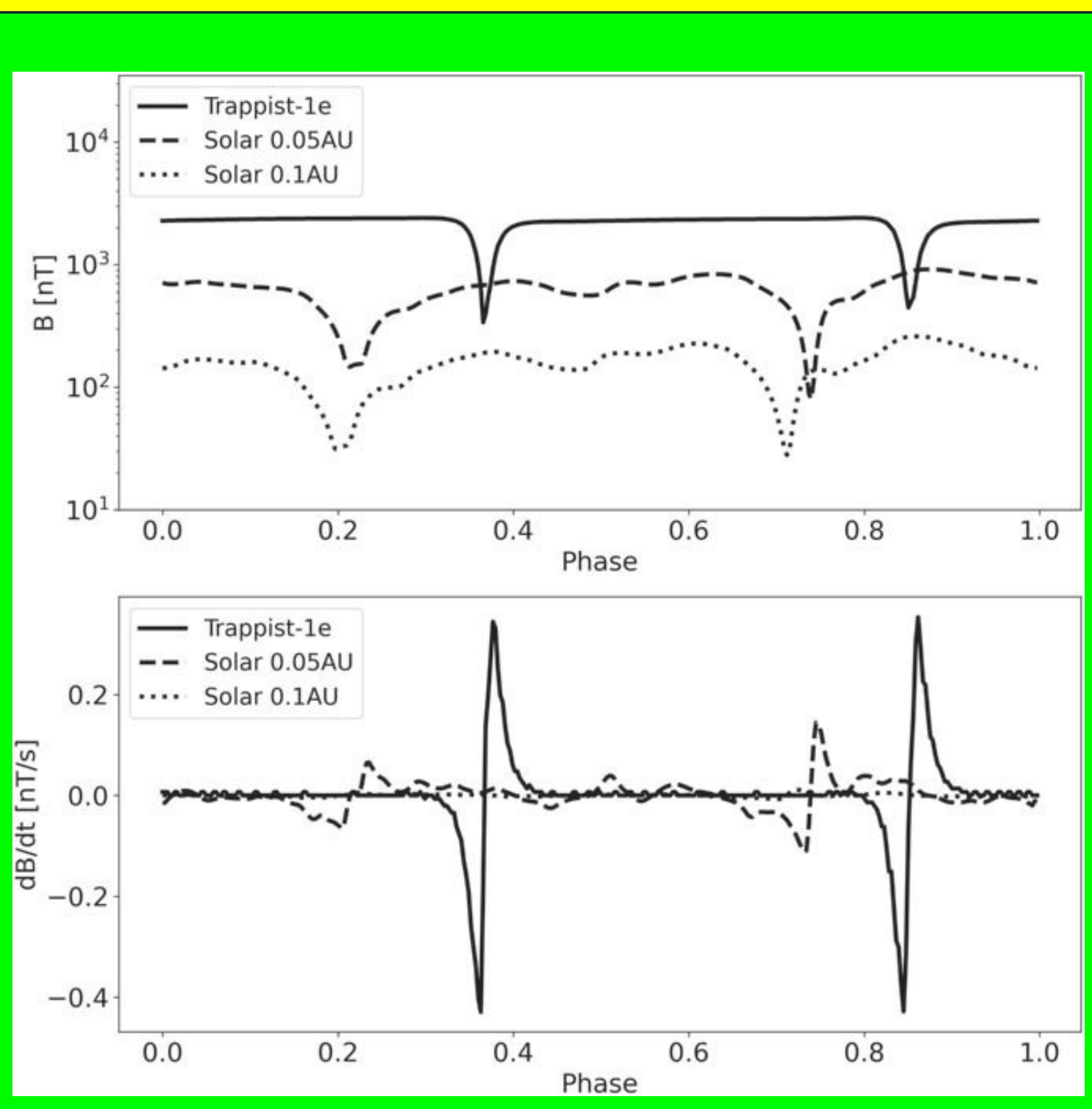

Figure 2. The orbital variations of the magnetic field strength (top) and dB/dt (bottom) as a function of phase for the three simulated data sets. The time derivative accounts for the specific orbital period, which is a function of the specific stellar mass and radius, and the orbital radius.

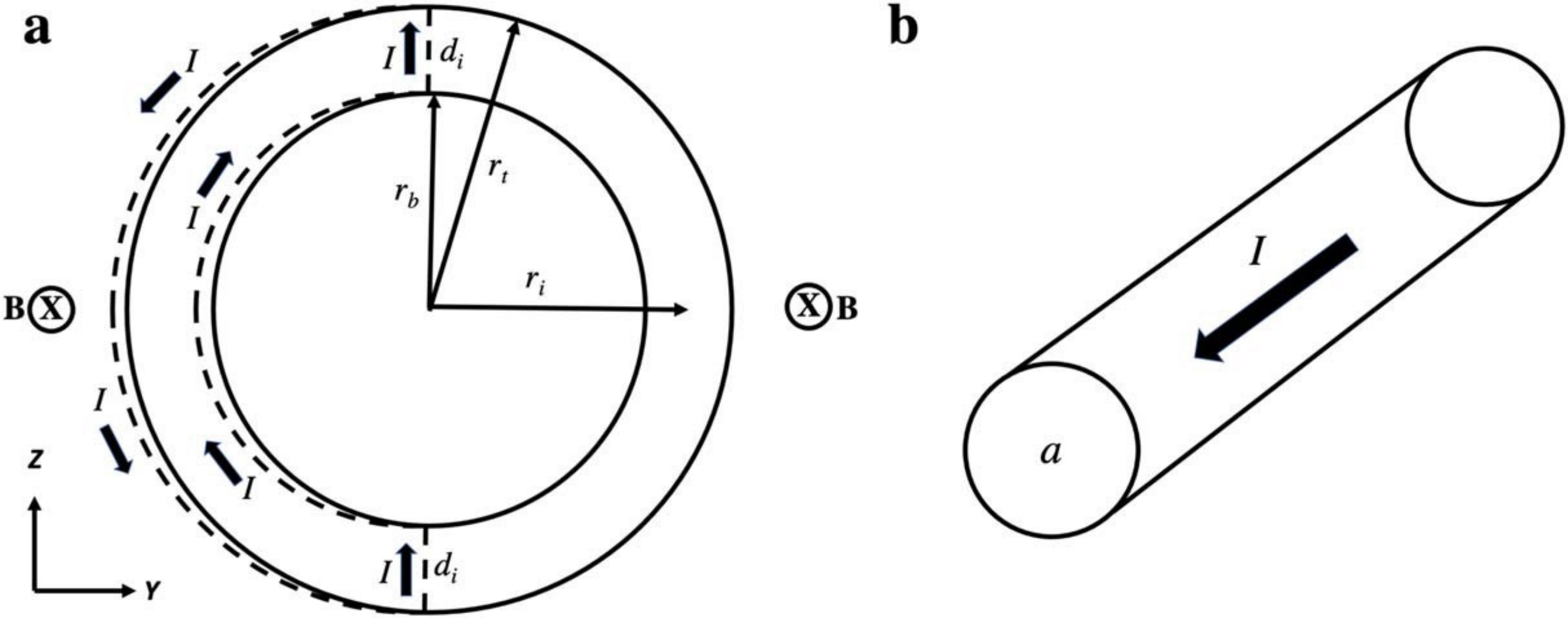

Figure 3. Left: the geometry of the problem. The stellar wind magnetic flux is going through the ionospheric cross section, which is determined by the area bounded between r_b and r_t. The current, I, induced by dB/dt is flowing in a closed loop with an approximated length 2πri (dashed line) and a cross section, a (shown on the right).

Estimating the Joule Heating of the planetary upper atmosphere:

The total heating energy flux, Q, can be calculated from the magnetic field variations, dB/dt, as follows:

$$1.\ -\frac{d\Phi}{dt} = -A\frac{dB}{dt} = \mathcal{E} = IR \quad 2.\ -A\frac{dB}{dt} = IR = aj\frac{l}{a\sigma} = \frac{jl}{\sigma} \quad 3.\ j = -\frac{A\sigma}{l}\frac{dB}{dt} \quad 4.\ j = \sigma E \quad 5.\ q = j\cdot E = j^2/\sigma$$

Shallow ionosphere limit:

$$A = \int_{r_b}^{r_t} 2\pi r dr \approx 2\pi r_i d_i$$

$$j = -\frac{1}{2}\frac{2\pi r_i d_i \sigma}{2\pi r_i}\frac{dB}{dt} = -\frac{d_i\sigma}{2}\frac{dB}{dt}$$

$$Q = q d_i = \frac{d_i^3\sigma}{4}\left(\frac{dB}{dt}\right)^2 \ [\mathrm{W\ m^{-2}}]$$

Extended ionosphere limit:

$$A = \int_{r_b}^{r_t} 2\pi r dr = \pi(r_t^2 - r_b^2) \approx \pi r_t^2 \approx \pi d_i^2$$

$$Q \approx 0.3^2 d_i^3\sigma\left(\frac{dB}{dt}\right)^2 = 0.1 d_i^3\sigma\left(\frac{dB}{dt}\right)^2 \ [\mathrm{W\ m^{-2}}]$$

Results

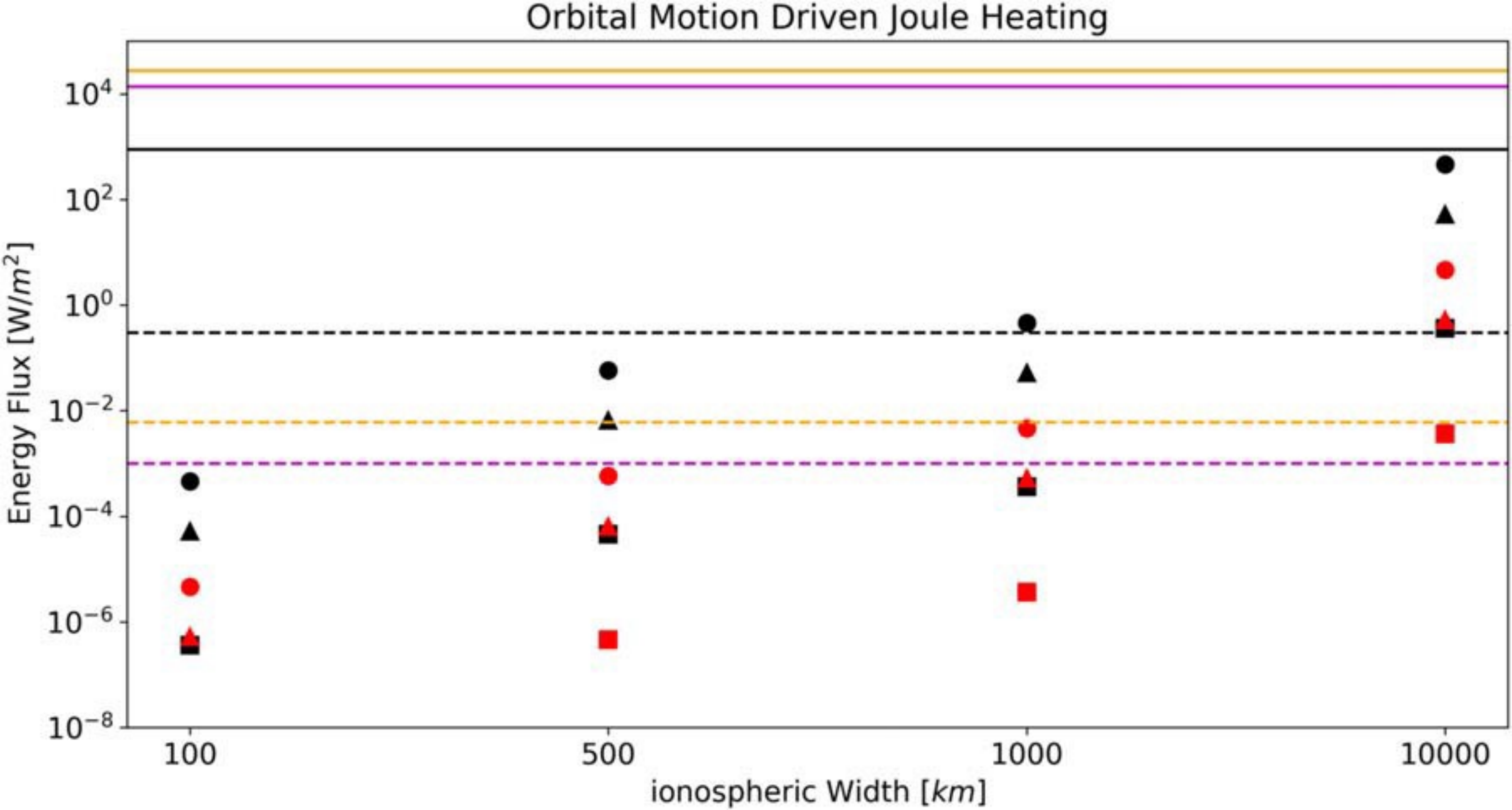

Figure 4. Maximum Joule Heating energy flux in [W/m^2] as a function of ionospheric width using the maximum value of dB/dt for the synthetic data sets of Trappist-1e (circles), the solar case at 0.05 AU (triangles), and the solar case at 0.1 AU (squares). The red markers represent the energy flux using σ = 0.1 [S/m], while the black markers represent the energy flux using σ = 10 [S/m]. Also shown are the reference energy fluxes of the stellar/solar constant radiation (solid lines) and EUV radiation (dashed lines) for the orbits of Trappist-1e (black), 0.05 au (orange), and 0.1 au (magenta).

Conclusions

We present a simple model to estimate JH of the upper atmosphere of short-orbit exoplanets. The JH is the result of a dissipation of electric current, which is driven by the rapidly varying magnetic field along the planetary orbit. We estimate the JH energy flux on the exoplanet Trappist-1e as well as similar planets orbiting the Sun in close-in orbits. We find that the JH energy flux is larger than the anticipated EUV energy flux at the planet, and it may reach a few percent of the stellar constant energy flux. Such an intense heating could drive a strong atmospheric escape and could lead to a rapid loss of the atmosphere. Thus, the rapid orbital motion of short-orbit exoplanets may exhaust a significant portion of their atmospheres over time.

For more information:
Ofer_cohen@uml.edu; **Reference: Cohen et. al, ApJ 962, 157, 2024**