Testing a Martian Magnetic Dipole Shield using Monte Carlo Particle Simulation

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Introduction

- Due to its weak magnetic field, Mars features dangerous exposures to the solar wind and cosmic rays, and its atmosphere suffers from escaping gas (Dong et al. 2015), resulting in a pressure drop that likely evaporated its oceans
- As a potential solution, Green et al. (2017) proposed that it is possible to shield the Martian atmosphere using a 2 Tesla magnetic dipole at the Martian L1 orbit point. Figure 1 shows concept art to demonstrate this idea

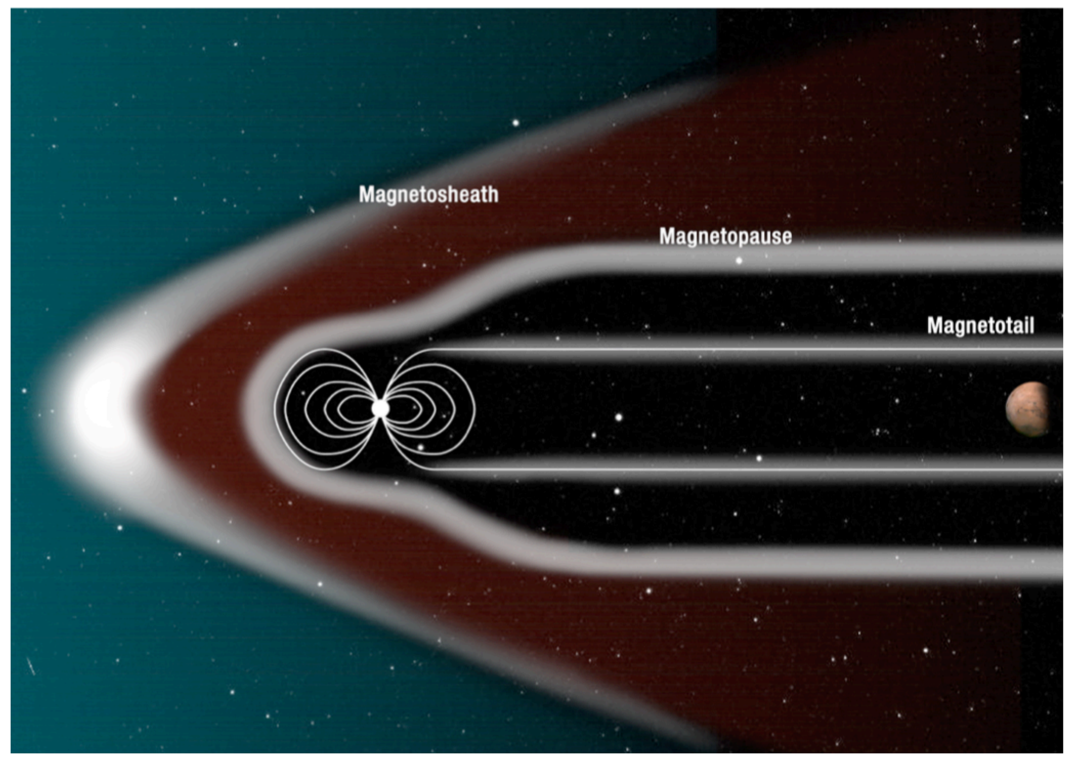

Figure 1: Diagram describing the concept behind the dipole shield. Reprinted from "A Future Mars Environment for Science and Exploration," by Green et al. 2017, *Lunar and Planetary Science Contribution Series*.

- A successful shielding of the atmosphere would reduce the escaping of its gas, allowing atmospheric pressure to rise from outgassing of its interior, which would spark a runaway greenhouse effect that could potentially evaporate the Martian ice caps
- My simulations intend to test the validity of this proposal by testing how strong this dipole would need to be to adequately deflect the wind from Mars

References

Dong, Y., Fang, X., Brain, D. A., McFadden, J. P., Halekas, J. S., Connerney, J. E., Curry, S. M., Harada, Y., Luhmann, J. G., and Jakosky, B. M. (2015), Strong plume fluxes at Mars observed by MAVEN: An important planetary ion escape channel, *Geophys. Res. Lett.*, 42, 8942– 8950, doi:10.1002/2015GL065346.

Evans, R. F. (2018). Magnetic moments, dipoles and fields. In *The European Magnetism Association*. Retrieved from http://magnetism.eu/esm/2018/slides/evans-slides1.pdf

Fitzpatrick, R. (2011, March 31). Interplanetary Magnetic Field. In *University of Texas at Austin*. Retrieved from https://farside.ph.utexas.edu/teaching/plasma/lectures/node68.html

Green, J. L., Hollingsworth, J., Brain, D., Airapetian, V., Glocer, A., Pulkkinen, A., Dong, C., & Bamford, R. (2017). A Future Mars Environment for Science and Exploration. From the *Lunar and Planetary Science Contribution Series*. Retrieved from https://www.hou.usra.edu/meetings/V2050/pdf/8250.pdf (Original work published 2017)

Particle in Cell Consulting, LLC. (2010, November 8). The Electrostatic Particle in Cell (ES-PIC) Method. In *Particle in Cell*. Retrieved from https://www.particleincell.com/2010/es-pic-method/

Methods

- The test was carried out via Monte Carlo (MC) simulations; protons generated at random positions in collision courses with Mars, with a velocity matching that of the solar wind (Fitzpatrick 2011)
- Over iterations of time steps which vary based on the strength of the magnetic field at the particle's location, which was calculated using a dipole approximation summed with the interplanetary magnetic field (IMF)
  - Its motion perpendicular to the magnetic field is determined according to the angular velocity around its gyroradius. The parallel component of the velocity is unaffected by force, so is calculated normally by velocity and time step
- The simulation terminates when the particle escapes the simulation dimensions or if it intercepts Mars

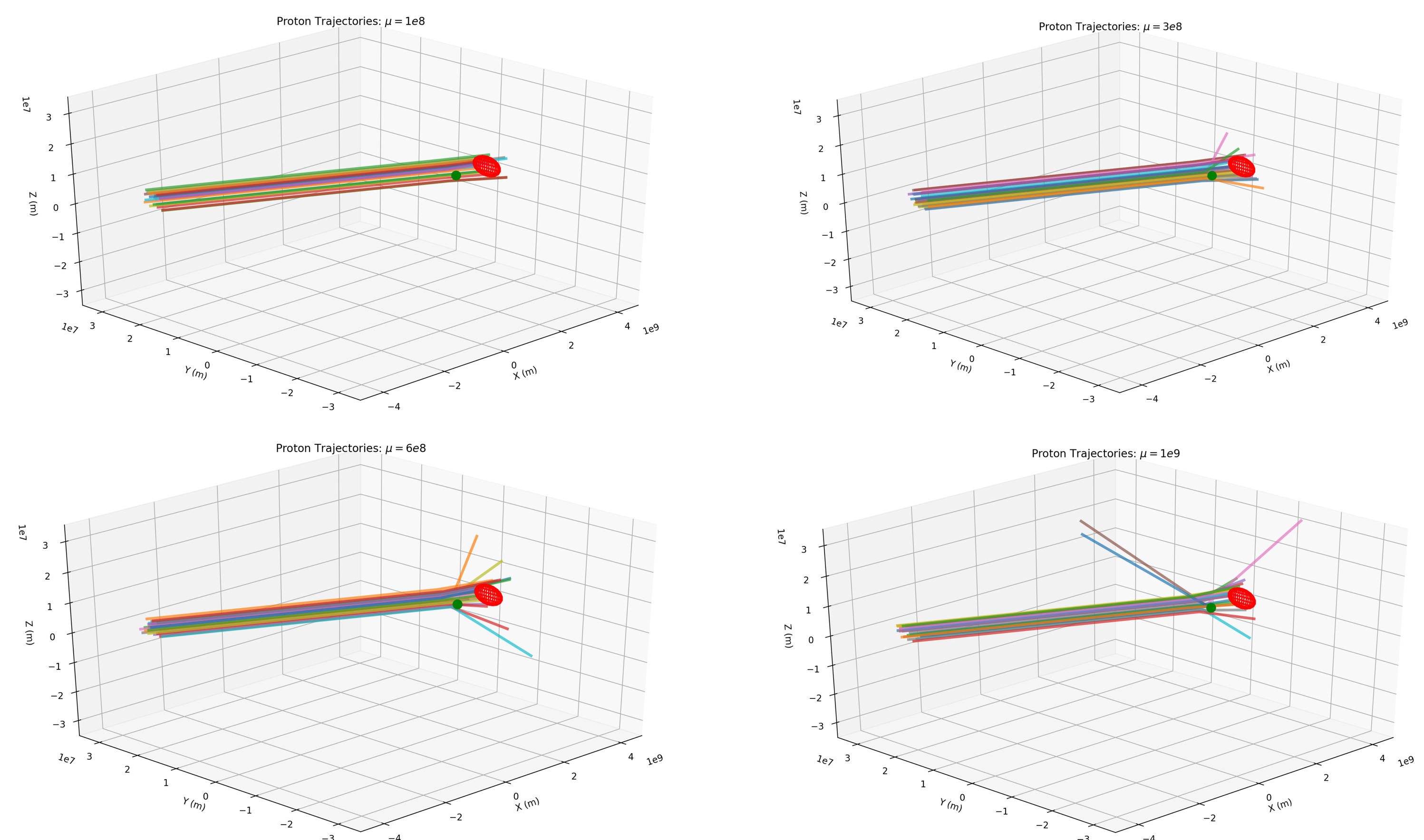

Figure 2: Example particle trajectories for different values of μ, measured in Am$^2\cdot\frac{\mu_0}{4\pi}$. For each of these runs, 25 particles were fired. Mars is plotted as the red spherical mesh, and the magnetic dipole is plotted as a green point.

Method Caveat

Particle simulation only gets part of the picture with simulating the solar wind through magnetic field. The solar wind is a plasma, which will carry with itself internal electric field and magnetic field interactions that will apply pressure and bend the dipole's magnetic field to produce the pattern shown in Figure 1. The IMF approximates this, but the best alternative would have been to run a particle-in-cell (PIC) plasma simulation (Particle in Cell 2010). The reason I stuck with MC simulations is that a PIC for representing this system would have been too complex for the time we had to conduct this project.

Results/Analysis

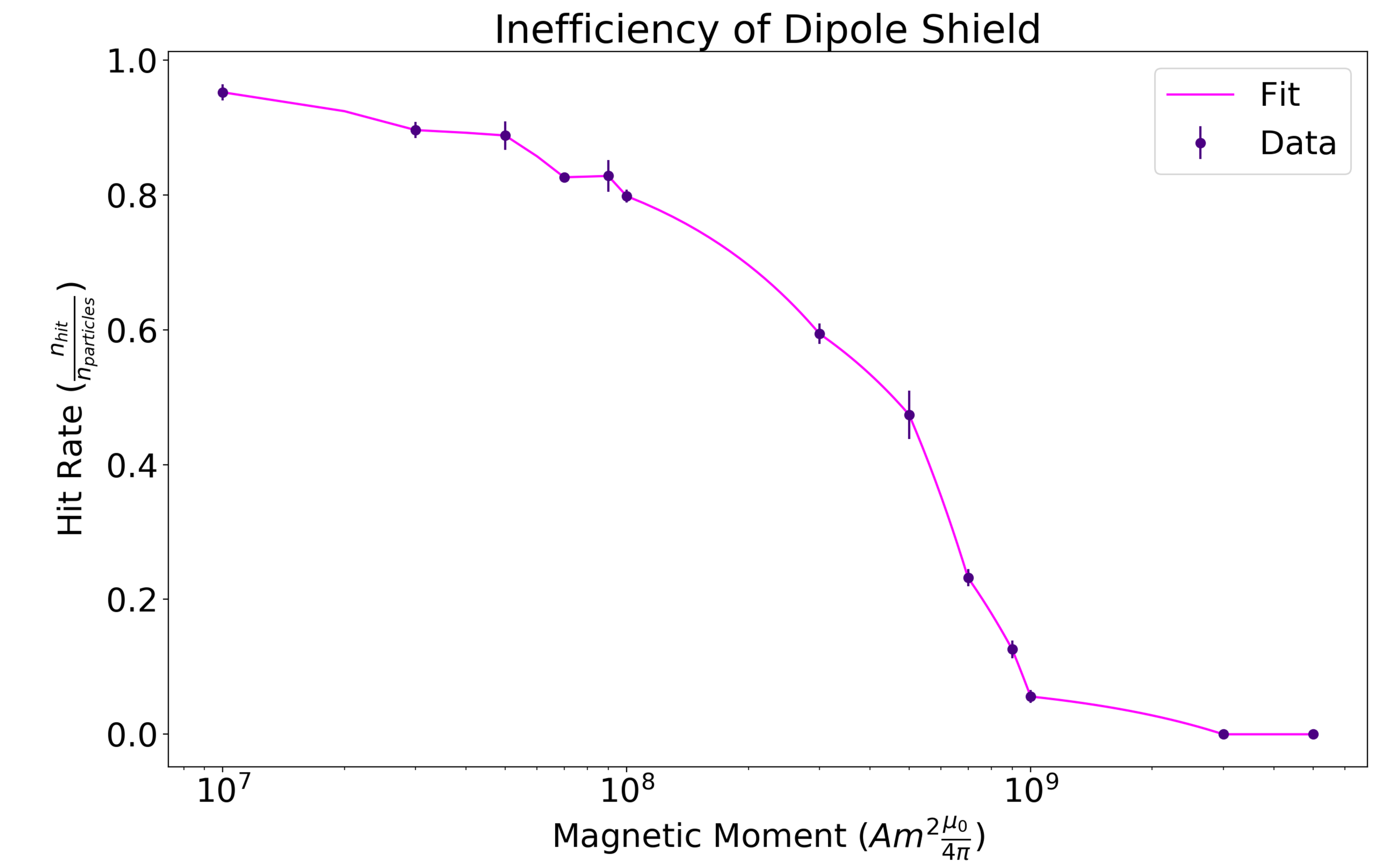

Figure 3: Inefficiency plot for simulations over varying magnetic moments. Inefficiency is defined as the ratio of particles that successfully hit Mars to total particles fired.

- According to the results presented in Figure 3, to have a dipole capable of protecting Mars, it would need to have a magnetic moment at least on the order of 1e9 Am$^2\cdot\frac{\mu_0}{4\pi}$. For comparison, in these units, Earth's dipole approximation has a moment on the order of 1e16 Am$^2\cdot\frac{\mu_0}{4\pi}$ (Evans 2018).
- The inefficiency drops to 0 very rapidly throughout the 1e8–1e9 Am$^2\cdot\frac{\mu_0}{4\pi}$ range. This makes sense: particles examined do not pass directly through the dipole, but graze by it at roughly 1 $R_{♂}$. In a dipole approximation, field strength drops as r^{-3}, so the dipole would need to be very strong to see noticeable effects at this range

Conclusions

- The minimum moment required to see adequately shielded results is very large in magnitude. While not on a planetary scale, it still would require a powerful magnet for production
- It's likely that this estimate is an underestimate. Due to the limitations of a particle model, the effect of the wind on the magnetic field is limited. The dipole would have a weaker effect on a bulk plasma than individual particles
- According to the simulation results, the claim that a 2T magnet can adequately deflect the solar wind from Mars seems questionable. Green et al. (2017) do not follow up with many details about this claim