# THE ROLE OF PLANETARY MAGNETIC FIELDS DURING THE FORMATION OF ICE GIANTS.

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**Introduction:** Giant-planet formation can be generally described by the core accretion model: a core of ~10 Earth masses ($M_{Earth}$) forms in the protoplanetary disk, experiences runaway accretion and stops growing when the gas in the disk dissipates [1]. While Jupiter and Saturn have most of their masses located within their gas envelopes, that is not the case for Uranus and Neptune, suggesting that the ice giants might not have experienced runaway accretion.

A potential mechanism that could have played a role in planetary formation, including in the case of the ice giants, is the presence of magnetic fields in the cores of protoplanets. Previous work has suggested that planetary magnetic fields of ~2000 µT can provide enough pressure against the nebular gas resulting in significantly less accretion of gas to the protoplanet [2]. For reference, the strength of present-day Earth's magnetic field at the top of the core is ~4000 µT [3], implying that it is plausible that the core of Uranus sustained a magnetic field of at least similar strength. Here, we aim to determine: (1) the strength of the magnetic field at the surface of the proto-core of a giant-planet, just before it goes into runaway accretion, and (2) if the strength of this field is enough to hinder accretion of gas and play an important role during planetary formation.

**Model:** Fig. 1 illustrates the model used here. At the start of the simulation, we defined the planetesimal size, composition, spatial and temporal grid sizes, and run time. During the simulation we grew the planetesimal to ~10 $M_{Earth}$ through impacts, with the frequency and size of impactors defined at the beginning of the run. The planetesimal and the impactors modeled here are composed of iron, silicate, water, and ice, with planetesimal and impactors having the same composition during the simulations.

As the planet evolved, we solved the heat conduction equation, assuming heating from $^{26}$Al and impacts, to determine the thermal evolution of the planetesimal. After an impact happened during the simulation, we added the same amount of material from the impactor to the planetesimal and interpolated the temperature profile.

We conducted a parameter space survey by varying the amount of mass in the iron core, impactor frequency, impactor size and simulation run time. The end-member values of iron core sizes were determined based on the current amount of metal in chondrites [4] and in the proposed present size of the iron cores of giant planets [5-7]. The water and ice layer sizes were kept constant (i.e., 10% of the planetesimal size each) while we varied the silicate and iron fractions (i.e., remaining 80% of the planetesimal size). Values of impactor frequency ranged from 0.02 to 0.1 million years (Myr) while the values for impactor size ranged from 0.01 to 0.1 $M_{Earth}$. The simulation running times ranged from 1 to 3 Myr, as this is likely to be within the lifetime of protoplanetary disks [8, 9] and the relevant period during which the proto-planet core is likely to reach its critical mass prior to runway accretion. We used planetary interior properties values from ref. [10].

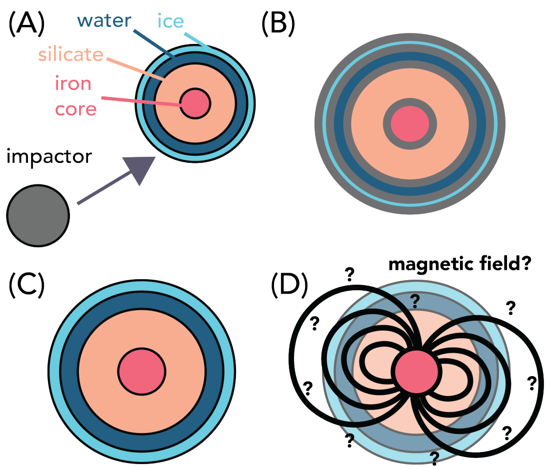

**Figure 1: Overview of the evolution of the model used to determine the strength of the magnetic field at the surface of a planetesimal. (A)** At the start of the model, we defined planet size, planet composition, spatial and temporal grid sizes, impactor size and frequency of impacts. **(B)** After impacts, we added the same amount of material from the impactor to the planetesimal and interpolated the temperature profile. **(C)** The model ran for millions of years as we solve the heat conduction in a sphere, assuming that heat is produced by $^{26}$Al decay and impacts. We repeated (A), (B) and (C) until the ending time of the simulation is reached. **(D)** At the end, we calculated the temperature gradient across all layers and used a scaling law considering a MAC balance to determine the strength of the magnetic field at the surface of the planetesimal.

At the end of the run, the temperature gradients across all layers were calculated, and we used a scaling law considering the balance between magnetic, buoyant and Coriolis forces ("MAC") to calculate the magnetic field generated at the surface of the planetesimal [10, 11]. We only calculated the magnetic field in the iron and silicate regions that had fluid motion (i.e., where the heat flux across a region is greater than the adiabatic

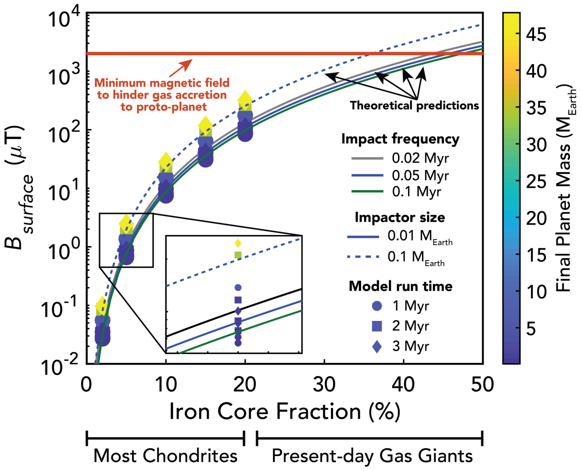

**Figure 2: Results of the simulations showing magnetic field as a function of iron core fraction, impact frequency, impactor size and model run time.** The color scale represents the final planet mass in $M_{Earth}$. Distinct model run times are shown using circles, squares, and diamonds, with some of them including variations in impact frequency and impactor size. For clarity, impact frequency and impactor size variations are represented by the different lines computed using a power-law, with impact frequency variations represented by different colors and impactor size variations represented with solid and dashed lines. The orange line represents the minimum magnetic fields necessary to hinder accretion of gas to the protoplanet from ref. [2]. We also included for reference expected iron core fractions in planetesimals based on chondritic materials [4] and the iron core size of ice giants assuming a range of water fractions [5-7].

heat flux) and where the magnetic Reynolds number across the region was > $O(10)$.

**Results:** Fig. 2 summarizes our results, showing the magnetic field at the surface of the planetesimal as a function of the core mass fraction with respect to the size of the planetesimal, model run time, impactor size and impactor frequency. The orange line indicates the minimum magnetic field strength at the surface of the planetesimal that would hinder accretion of gas to the protoplanet's core. We also computed first-order power-law fits to our current results to stablish a potential scaling between magnetic field strength and core size.

Overall, our models are mostly dependent on the composition of the planetesimal, with impactor frequency, impactor size and model run having little effect on the final strength of the magnetic field at the surface. Planetesimals composed of chondritic materials (i.e., < 20% iron core fraction) will produce magnetic fields ranging from ~0.01 to 100 µT. Alternatively, if our extrapolation to larger core fractions is correct, planetesimals with core fractions > 45% will generate magnetic fields at the surface of the planetesimal > 2000 µT.

**Discussion:** Planetesimals that are composed of purely chondritic material will generate magnetic fields that are below the ~2000 µT threshold and are unlikely to produce magnetic fields that play a role on the final size of giant planets. On the other hand, planetesimals that have core sizes > 45% in size will generate magnetic fields that are greater than the ~2000 µT threshold.

If we assume that the iron silicate ratio of the giant planets stayed the same since planetary growth in the protoplanetary disk, we can calculate iron core fractions for these planets using present-day density profiles. We find iron core fractions of ~30-50% for the ice giants [5] and ~20-30% for the gas giants [6, 7], depending on the fraction of water included in the calculation. While the ice giants could have sustained strong planetary magnetic fields that hindered accretion of gas to their proto-cores, the calculated estimates indicate that it is unlikely that the gas giants sustained such strong fields. This could explain the size difference between the gas envelopes of the giant planets and suggests that planetary magnetic fields could have played an important role in regulating the amount of gas accreted to giant planets.

Overall, planetary formation will depend on several factors, including gas availability, impactor frequency and composition of planetesimals. While the solar system contained chondritic material with metal fractions < 20%, it is possible that exoplanets in other planetary systems were built from materials that have higher metal fractions. In this case, the role of magnetic fields in controlling planetary gas accretion could have been pervasive.

**Future work:** We will further test the scaling law between magnetic field at the surface and core fraction by running simulations with larger core sizes. We will also investigate planetesimals with varying water layer sizes and the possibility of the water layers producing magnetic fields. Finally, we want to investigate the iron-core fraction size differences between the gas giants and the ice giants to determine if planetary magnetic fields could explain their gas accretion difference.

**References:** [1] Pollack J. B. et al. (1996) *Icarus*, 124. [2] Owen J. E. and Menou K. (2016) *ApJ*, 819. [3] Gillet N. (2010) *Nature*, 465, 7294. [4] Scott E. R. D. and Krot A. N. (2013) *Treatise on Geochemistry*, pp. 66-137. [5] Helled R. and Fortney J. J. (2020) *Philos. Trans. R. Soc., A*, 378, 2187. [6] Helled R. et al (2022) *Icarus*, 378. [7] Mankovich C. R. and Fuller J. (2021) *Nature Astronomy*, 5, 11. [8] Borlina C. S. et al. (2022) *JGR: Planets*, 127, 7. [9] Weiss B. P. et al. (2021) *Sci. Adv.*, 7. [10] Sterenborg M. G. and Crowley J. W. (2013) *Phys. Earth Planet. Inter.*, 214. [11] Christensen U. R. et al. (2009) *Nature*, 457, 7226.