Stellar and Planetary Dynamos and their Implications for Exoplanets

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Physics 486
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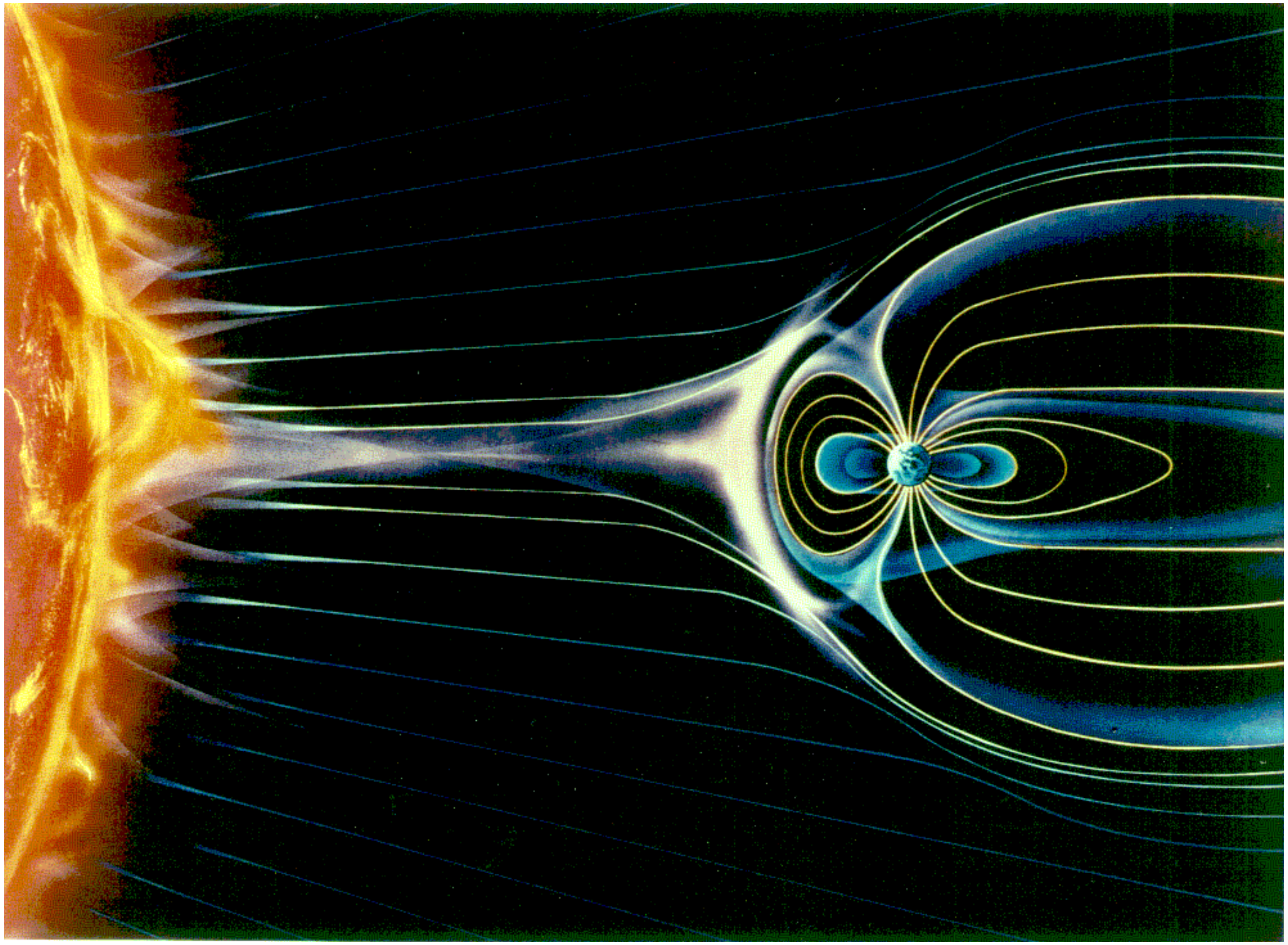
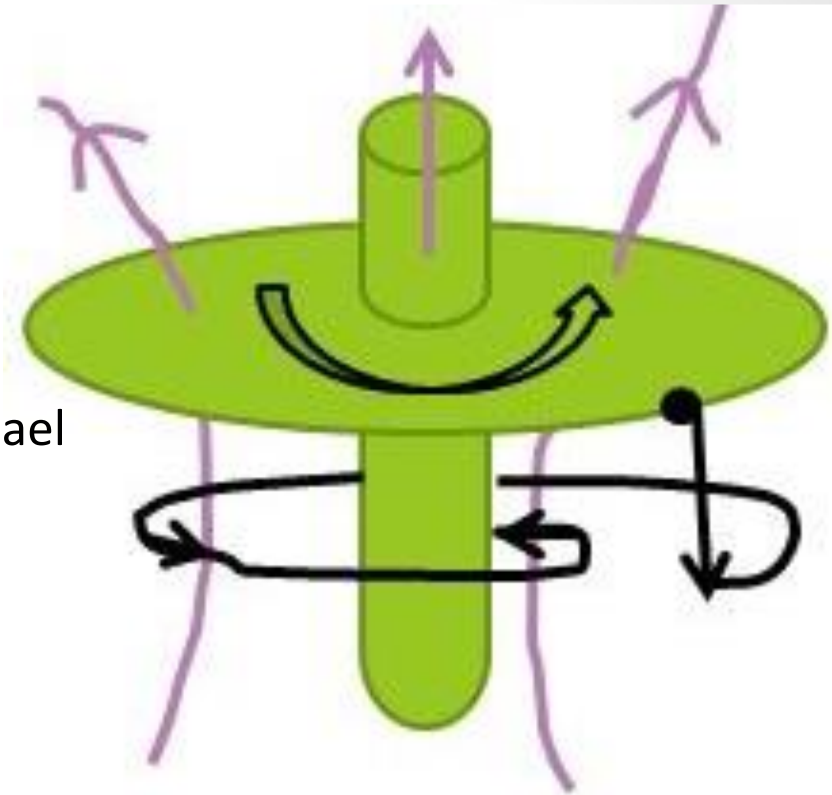
Overview

- Part I: Stellar and Planetary Dynamos
  - Dynamos
  - The Sun
  - The Earth
  - Four categories of fields in our Solar system's planets and moons
- Part II: Implications for Exoplanets
  - Define Exoplanet
  - Intersections with study of Magnetic fields
- Conclusions

Part I: Stellar and Planetary Dynamos



Dynamos



- Mechanical dynamo:
  - disk dynamo developed by Michael Faraday 1831
  - Faraday's Law:

$$\mathcal{E} = -\frac{d\Phi_B}{dt},$$

  - Ampere's Law:

$$\oint B \cdot dl = \mu_0 I$$

- Magnetohydrodynamic dynamo Theory:
  - Astrophysical bodies which possess high magnitude long lasting magnetic fields also contain highly conducting fluids. Motion of these fluids creates currents which maintain the magnetic field.
  - Requires specific orientation and relative motions just like the mechanical dynamo analog

Basic Development of Mean-field Electrodynamics and Magnetohydrodynamics:

- Maxwell and Ohm:

$$\nabla \times E = -\partial_t B\,, \quad \nabla \times B = \mu J$$
$$\nabla \cdot B = 0 \quad J = \sigma(E + U \times B)$$

- Induction equation:

$$\eta \nabla^2 B + \nabla \times (U \times B) - \partial_t B = 0$$

- Take Means + Mass/momentum balance:

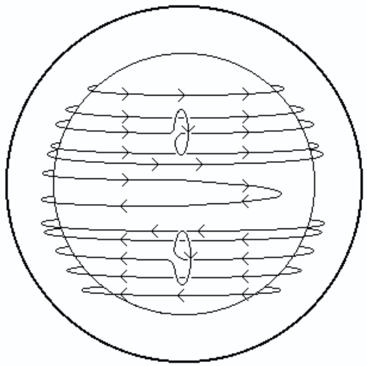
$$\eta \nabla^2 b + \nabla \times (\overline{U} \times b + \epsilon) - \partial_t b = -\nabla \times (u \times \overline{B})$$
$$\epsilon = u \times b - \overline{u \times b}\,, \quad \nabla \cdot b = 0\,.$$

- Net emf from turbulence:

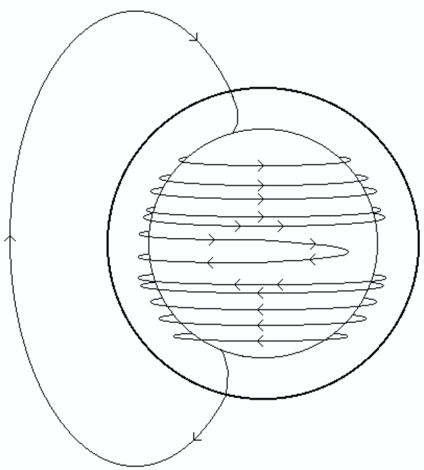
$$\mathcal{E} = \alpha_1 (g \cdot \Omega)\overline{B} + \alpha_2 g(\Omega \cdot \overline{B}) + \alpha_3 \Omega(g \cdot \overline{B}) + \gamma g \times \overline{B}$$
$$-\beta \nabla \times \overline{B} - \delta \Omega \times (\nabla \times \overline{B}) - \delta_* \nabla(\Omega \cdot \overline{B}) \qquad (26)$$

- Magnetic Reynolds Number:

$$Rm = UL/\eta$$

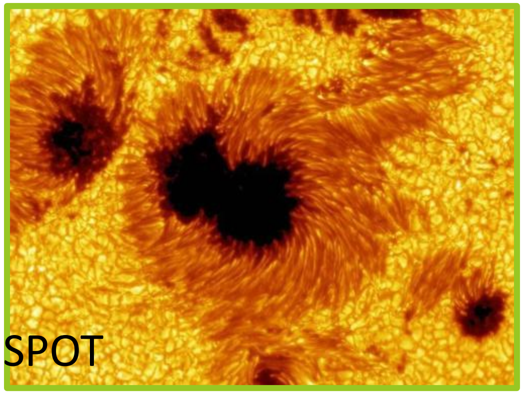


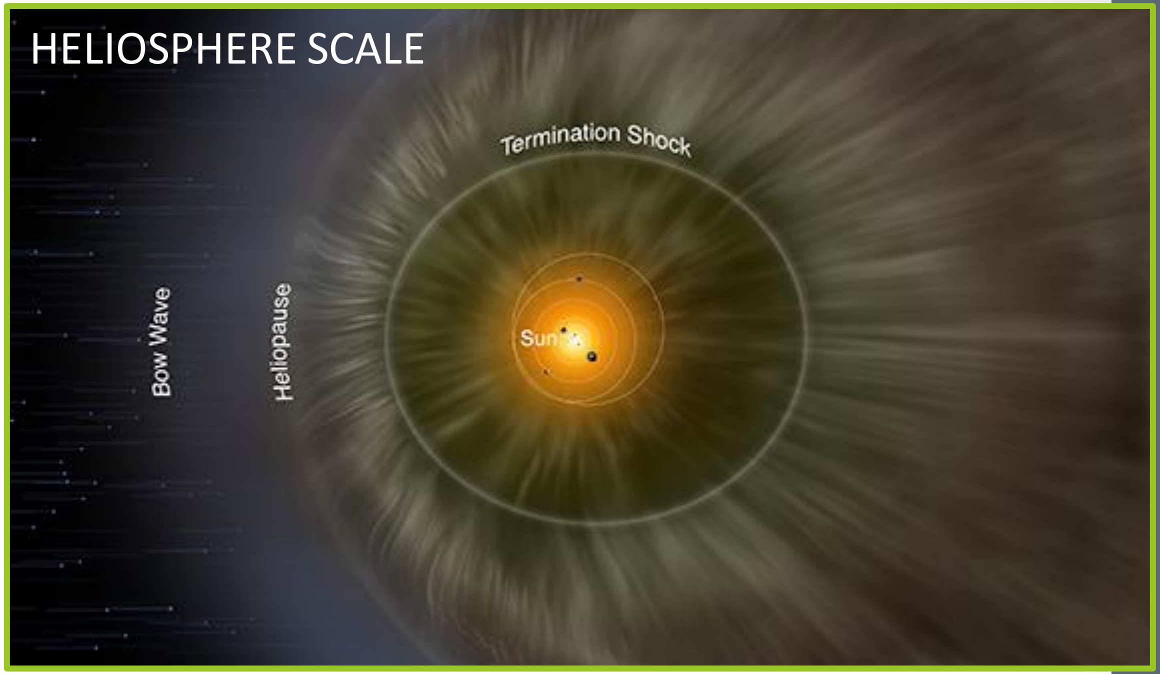
The α-effect

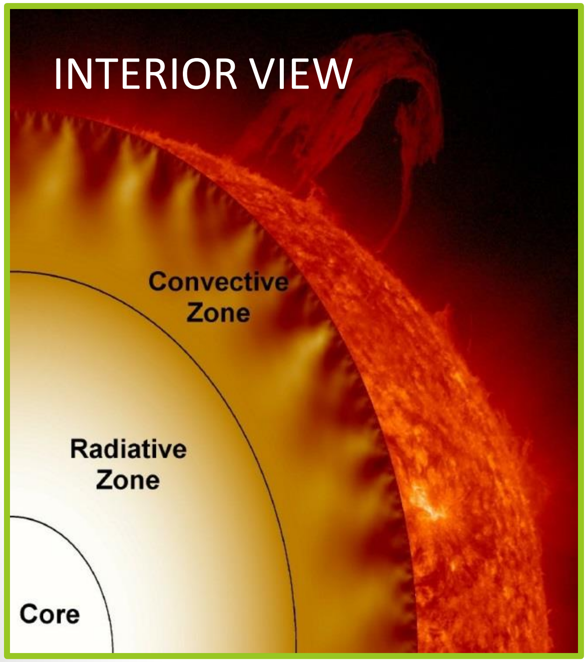


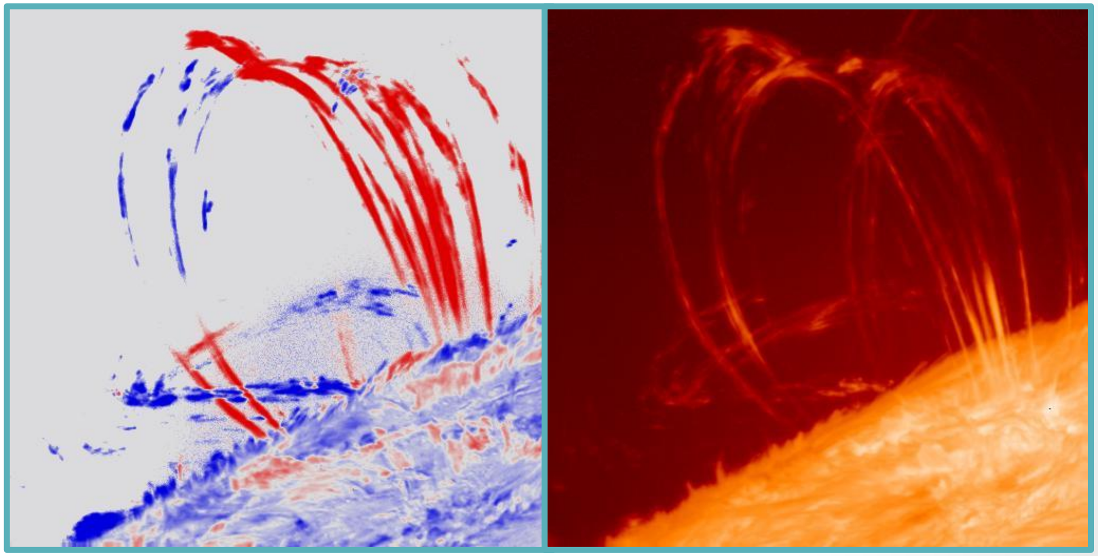
The ω-effect

The Sun





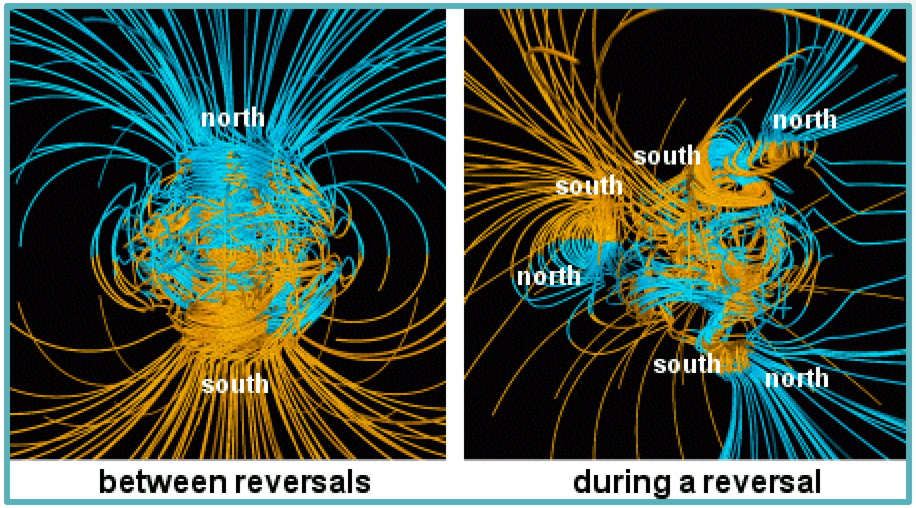


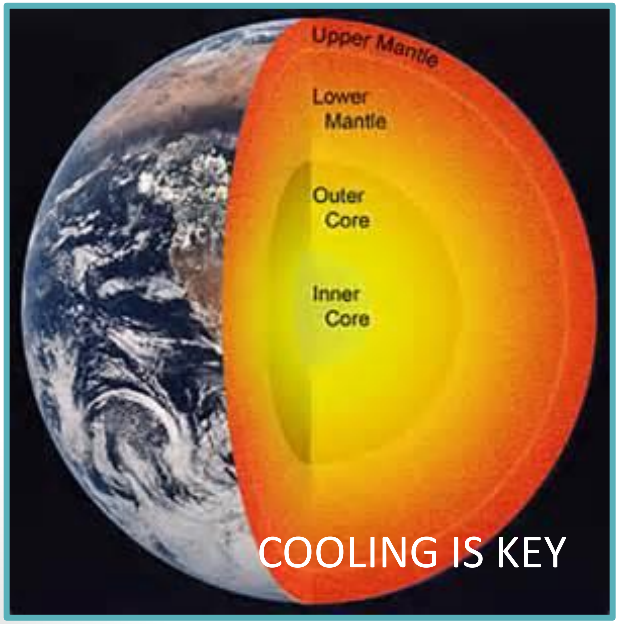


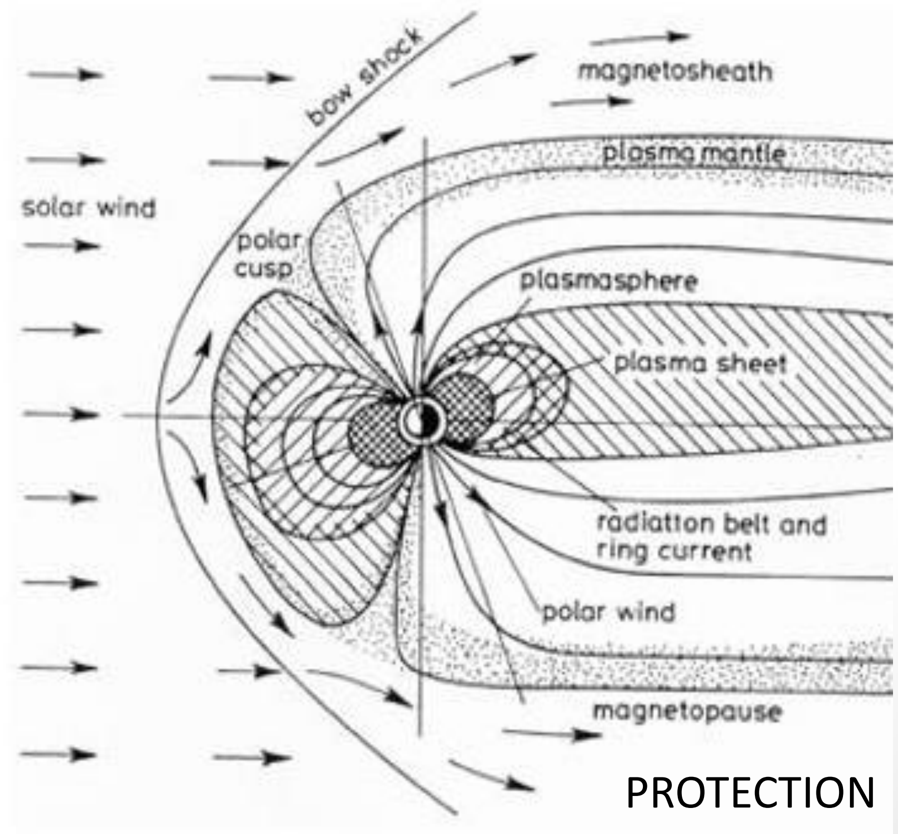
FIELD LINES

Earth

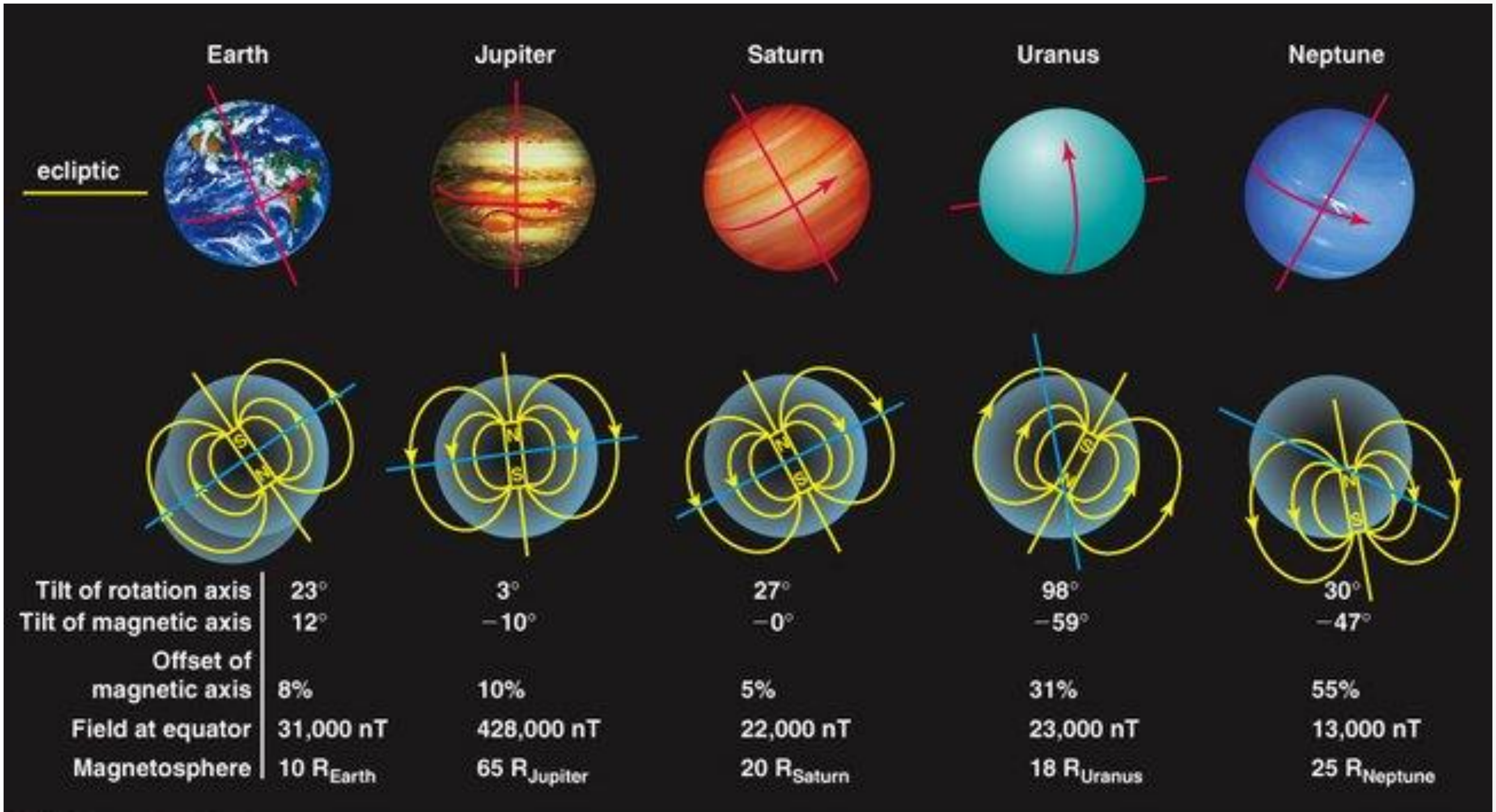
REVERSALS





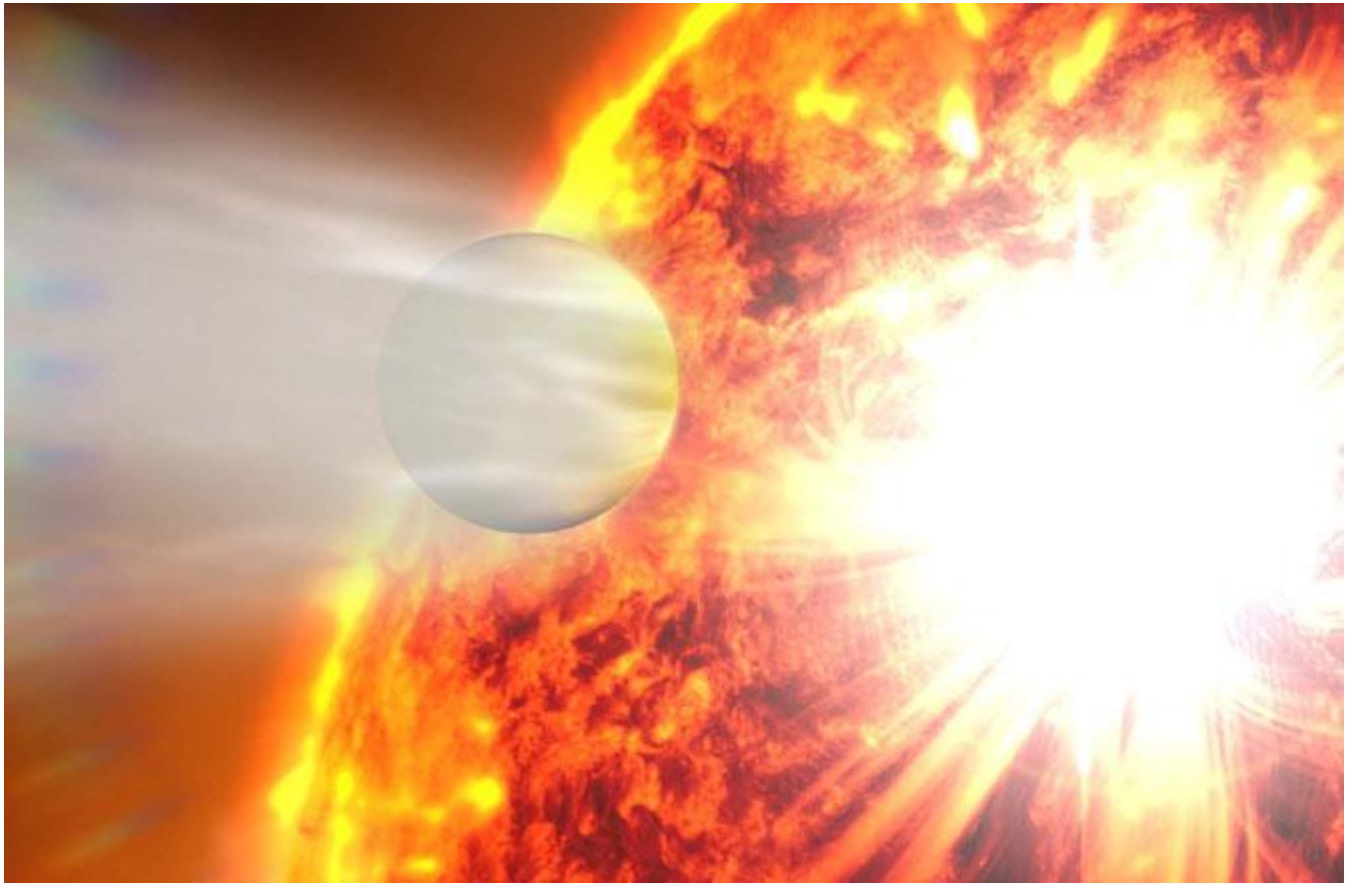


Fields in our solar system



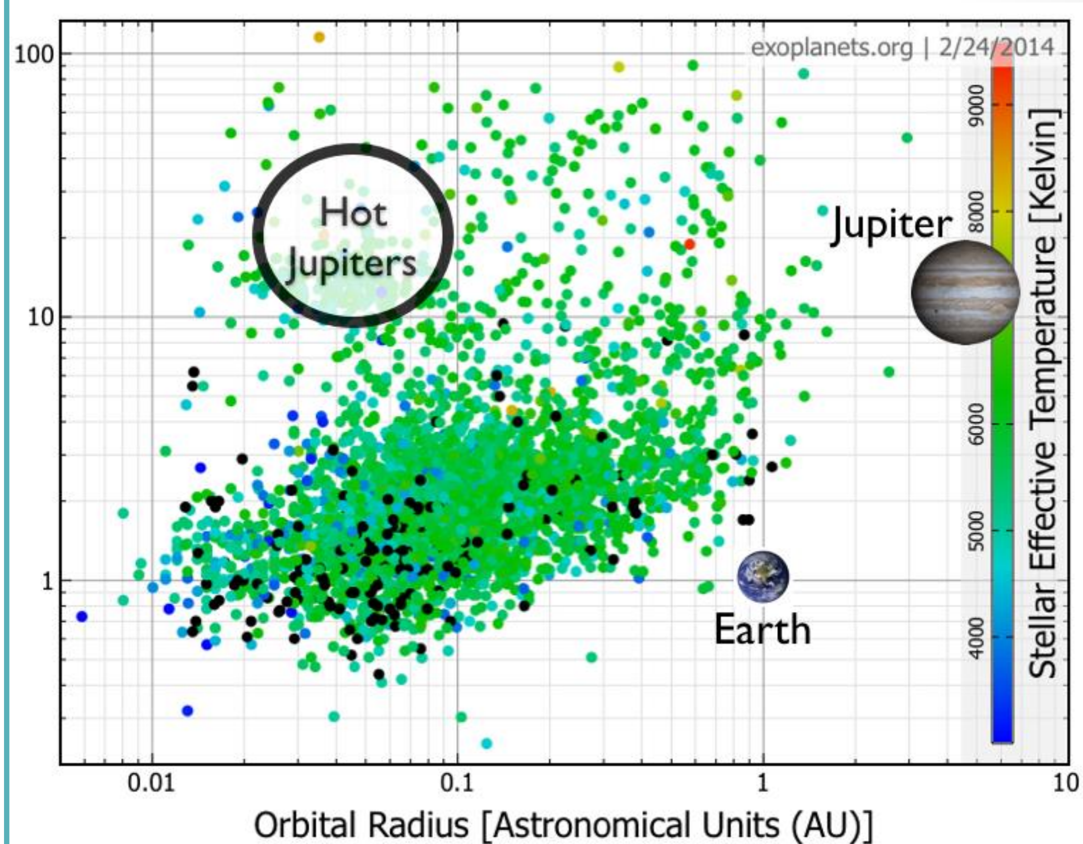
DIVERSITY

Part II: Implications for Exoplanets



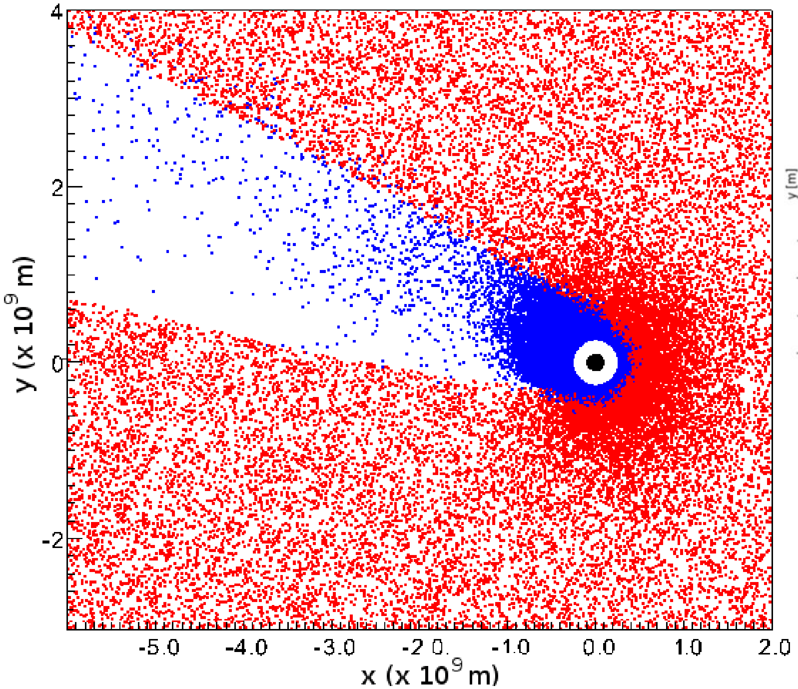
Exoplanets

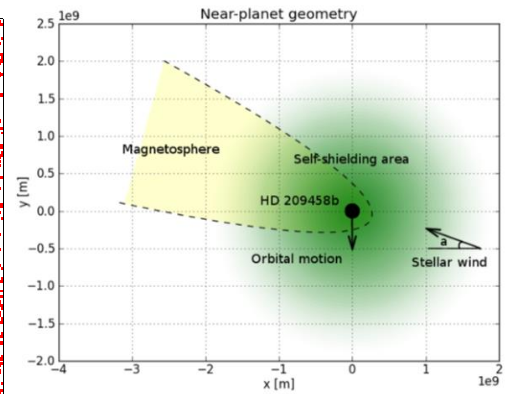
- 1523 total confirmed planets
- 3303 unconfirmed Kepler candidates
- Detection methods
  - Radial velocity
  - Transits
  - Transit timing variations
  - Gravitational lensing
  - Direct imaging
- Lots of surprises
- Habitability

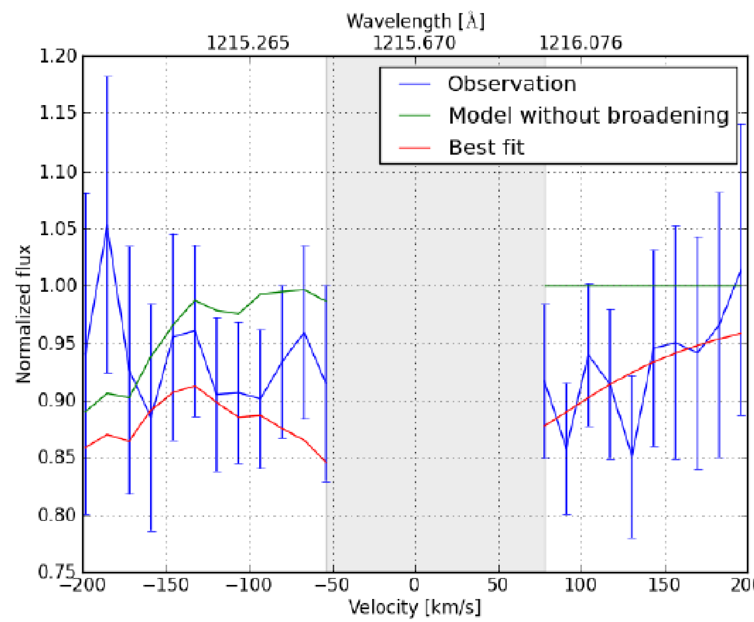


Exoplanet.org

How can we measure the magnetic fields of distant exoplanets…



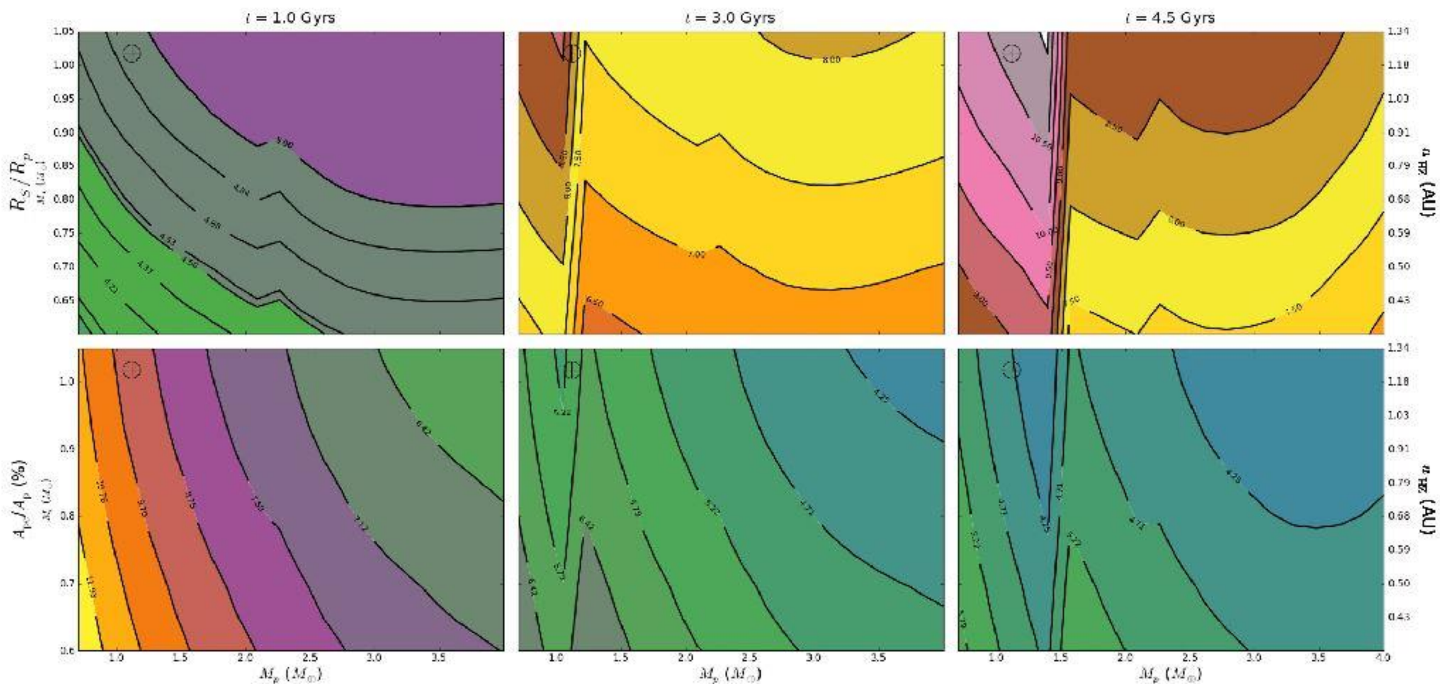




$$\mathcal{M} = \left(\frac{8\pi^2 R_{\rm s}^6 \rho_{\rm sw} v_{\rm rel}^2}{\mu_0 f_0^2} \right)^{1/2}$$

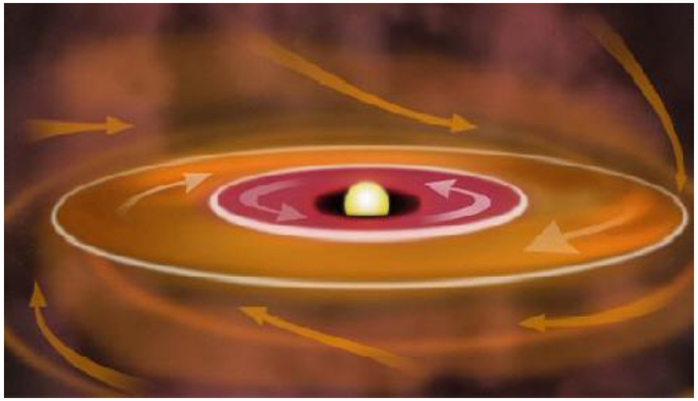
Magnetic Forces and Habitability

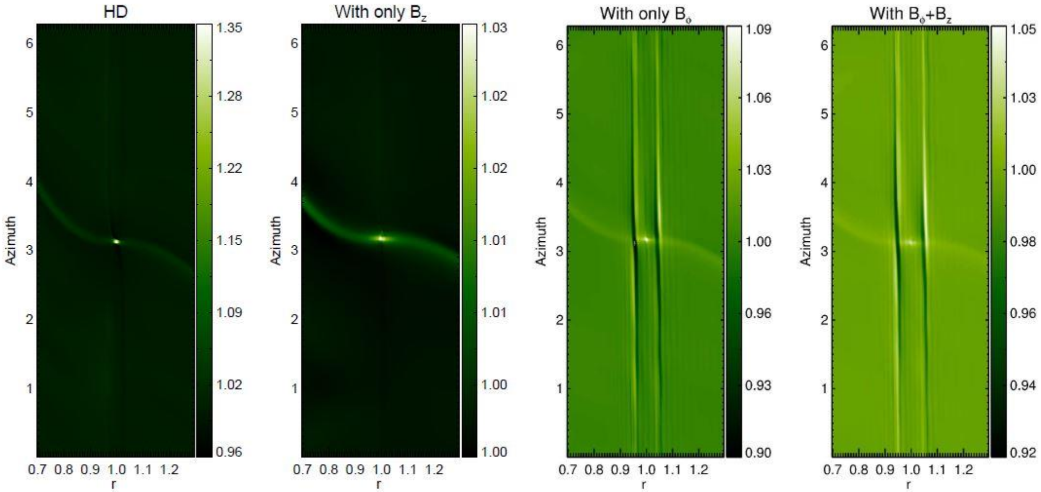
- Finding a habitable world is always in the mind of exoplanet specialists
- Magnetic fields protect atmospheres and lifeforms from stellar activity
- Hence an important factor to consider in determining habitability (along with temperature and surface)
- Modeling lifetimes of geodynamos in potentially habitable exoplanets



Magnetic forces in Formation

- Magnetic character of disks inform understanding of migration and accretion processes
- **Type I Migration Models**
- **Semarkona Meteorite**





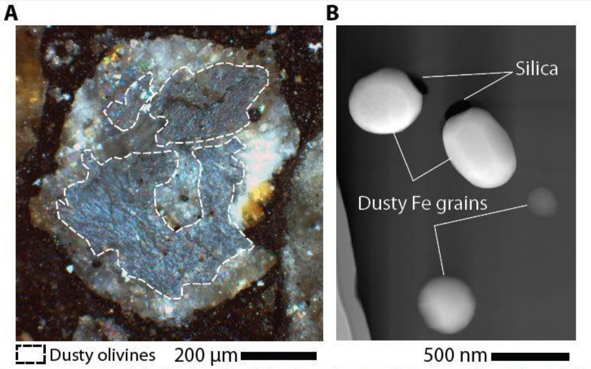
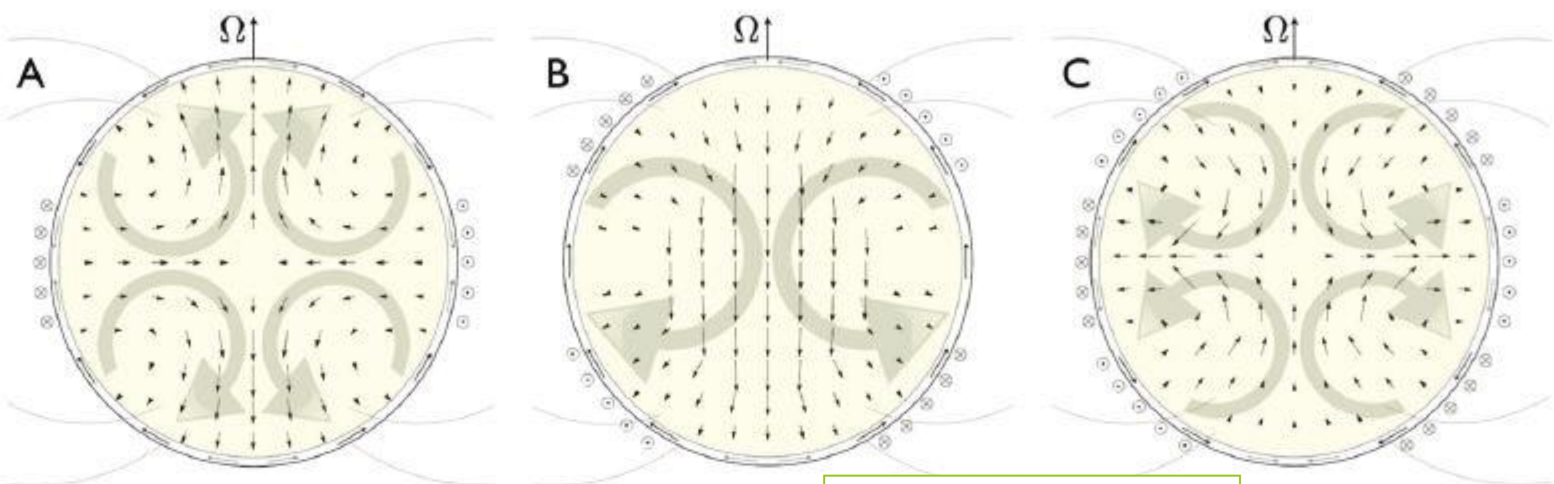


Figure 1. Dusty olivine-bearing chondrules from the Semarkona meteorite. **(A)** Optical photomicrograph of chondrule DOC4 showing the location of dusty olivine grains. Image taken in reflected light with crossed polarizers. **(B)** Annular dark field scanning transmission electron microscope (STEM) image of four dusty olivine Fe grains from chondrule DOC5. Brightness in image reflects column-averaged atomic number; darker grains are smaller in size, implying a higher relative abundance of olivine at their location and hence a lower mean atomic number. Note the euhedral morphology and chemical homogeneity of the Fe grains, which indicate the lack of secondary recrystallization and alteration. Such Fe grains are the primary carriers of pre-accretional magnetization in Semarkona chondrules.

Magnetic Forces and Characterization

- Potentially help establish whether exoplanets have cores or interior structure
- Implications for atmospheres…
- **Explaining the anomalous radii of some Hot Jupiters**



$$Q \propto I^2 \cdot R \cdot t$$

Conclusions

- Magnetic fields generated by dynamo actions ubiquitous in Solar System and likely through out the universe
- Our understanding of the criteria for internally generated magnetic fields in rocky planets and planets in general are not fully understood, but probably close to those for convection
- The earth's magnetic field is key in making it habitable in light of the Sun's activity
- Exoplanets are everywhere!
- Magnetic fields of host stars and exoplanets themselves play a role in formation of the system and provide a tool for detecting and characterizing planets as well as posing one more necessary criteria for habitability– thus the study of magnetic effects impact most aspects of exoplanet field
- Exoplanets can perhaps test and fill in our theory of magnetic dynamos

References

- General Dynamos and our Solar System:
  - K.-H. Radler, *Mean-field dynamos: the old concept and some recent developments.* *http://adsabs.harvard.edu/abs/2014AN....335..459R*
  - David Stevenson , *Magnetic Fields in Solar System Planets.* https://www.youtube.com/watch?v=F488kOmhu9Q **(**talk at Keck Institute for Space Studies, August 12, 2013 part of series titled Magnetic Fields: A Window to a Planet's Interior and Habitability)
  - *NASA Solar Physics.* http://solarscience.msfc.nasa.gov/
- Exoplanets:
  - Jorge I. Zuluaga, Pablo A. Cuartas-Restrepo, *Evolution of Magnetic Protection in Potentially Habitable Terrestrial Planets.* http://arxiv.org/pdf/1204.0275v1.pdf
  - Ana Uribe, Alissa Bans, and Arieh Kongil. , *Type I Planet Migration in a Magnetized Disk I. Effect of Large-Scale Vertical and Azimuthal Field Components.* *http://adsabs.harvard.edu/abs/2015arXiv150102742U*
  - Konstantin Batygin, David J. Stevenson, Peter H. Bodenheimer, *Evolution of Ohmically Heated Hot Jupiters***.** http://adsabs.harvard.edu/abs/2012arXiv1204.0275Z
  - R.R. Fu, B.P. Weiss, E.A. Lima, R.J. Harrison, X.-N. Bai, et al. *Solar Nebula Magnetic Fields Recorded in the Semarkona Meteoriite*. http://dx.doi.org/10.1126/science.1258022
  - Kristina G. Kislyakova, Mats Holmstr¨om, Helmut, *Magnetic moment and plasma environment of HD 209458b as determined from Ly observations.* *httpp://adsabs.harvard.edu/abs/2014Sci...346..981K*

Questions

Neutron star dynamos if y'all were still curious after Ray's presentation on compact objects…

- Entropy driven convection allows alpha-omega dynamo action for a time, gets imprinted in crust, contributes to "spin down" rate
- http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1993ApJ...408..194T&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf