Planetary Magnetic Fields

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Tilts and Obliquities

Rotation axis
Magnetic axis

Earth 11°
Saturn 0°

Jupiter -9.6°
Uranus -59°
Neptune -47°

Offset Tilted Dipole Approximation
Magnetic Potential

3-D harmonics

\[ V = R_p \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left( \frac{R_p}{r} \right)^{n+1} P_n^m(\cos \theta) \left( g_n^m \cos m\lambda + h_n^m \sin m\lambda \right), \quad (7.1) \]

functions

- \( P_0^0(\cos \theta) = 1 \)
- \( P_1^0(\cos \theta) = \cos \theta \)
- \( P_1^1(\cos \theta) = -\sin \theta \)
- \( P_2^0(\cos \theta) = \frac{1}{2} (3 \cos^2 \theta - 1) \)
- \( P_2^1(\cos \theta) = -3 \cos \theta \sin \theta \)
- \( P_2^2(\cos \theta) = 3 \sin^2 \theta \)
- \( P_3^0(\cos \theta) = \frac{1}{2} (5 \cos^3 \theta - 3 \cos \theta) \)

\[ \mathbf{B} = -\nabla V \]
Same technique used to model cosmic microwave background or interior of Sun with Helioseismology...

Earth - International Geomagnetic Reference Field

Complexity

Time

4 pages later.....

g 13 13
http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html

h 13 13
1. From accurate measurement of surface field:

2. Extrapolate to core-mantle boundary = dynamo

3. Derive core flows

4. Secular variation & reversals.....

\[ \frac{\partial B_r}{\partial t} = -\nabla_h \cdot (u_u B_r) \]

\( h = \) horizontal
\( r = \) radial

Hulot et al. 2010
What's the difference between Magnetic and Geomagnetic Poles?

Geomagnetic = best fit dipole
Magnetic = where \( B = B_r \)

Secular variation

Dipole dropped by 9% since 1840
Reconstructions of core field morphology 1590 - now
Fluctuations of non-dipole parts on time scales 50 – 400 yrs
Stability of high-latitude flux lobes
Westward drift in Atlantic / Africa
Br through a reversal

Hulot et al. 2010
Pavlov & Gallet 2005

Polarity reversals:
1. variable in duration and
2. rate

![Graph showing reversal rates and ages](image)
Power spectra of the field of internal origin for the Earth (after Olsen et al. 2009a and Maus et al. 2008), Mars (after Cain et al. 2003), Jupiter, Mercury (after Connerney 2008) and the Moon (after Purucker 2008) at their respective surface reference radius. Also shown are theoretical crustal spectra (thin curves, Voorhies et al. 2002) for the Earth, Mars and the Moon.

- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.
**Planetary Dynamos**

Volume of electrically conducting fluid which is convecting and rotating

All planetary objects probably have enough rotation - the presence (or not) of a global magnetic field tells us about 1 and 2.

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<table>
<thead>
<tr>
<th>Planet</th>
<th>Dynamo</th>
<th>$R_c/R_p$</th>
<th>$B_o$ [nT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>Yes (?)</td>
<td>0.75</td>
<td>195</td>
</tr>
<tr>
<td>Venus</td>
<td>No</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>Yes</td>
<td>0.55</td>
<td>31,000</td>
</tr>
<tr>
<td>Moon</td>
<td>No</td>
<td>0.2?</td>
<td>31,000</td>
</tr>
<tr>
<td>Mars</td>
<td>No, but in past</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Ganymede</td>
<td>Yes</td>
<td>0.3?</td>
<td>720</td>
</tr>
</tbody>
</table>

What drives dynamos in tiny Mercury & Ganymede?

Why don't Venus or Mars have dynamos?
Why Don't Venus or Mars have Dynamos?

- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?
  1. If...Mantle convection controls heat flow from core.
     Then...Lack of plate tectonics suggests less efficient cooling of interior and lower heat flux from core
  2. No inner core means no latent heat of solidification and no enhancement of lighter material in the outer core

Stevensen 2010
**Mercury & Ganymede**

What drives convection in these small bodies?

“They test of a good theorist is the ability to explain any outcome, even when the data are wrong”

- David Stevenson

Jupiter

- Molecular state
- ~2.5 Mbar phase transition

Saturn

- Saturn has lower mass
  - lower pressures
  - smaller region of metallic hydrogen
  - weaker magnetic field

Rc/Rp = 0.84

Rc/Rp = 0.6
Uranus and Neptune have much less mass

- Lower pressures
- No metallic hydrogen
- Weak & irregular magnetic fields produced in water layer, deep below gas envelope

### Table: Relative Magnetic Field Strengths

<table>
<thead>
<tr>
<th>Planet</th>
<th>Rc/Rp</th>
<th>Bo [μT]</th>
<th>Tilt</th>
<th>Quad/Dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.55</td>
<td>31</td>
<td>+9.92°</td>
<td>0.04</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.84</td>
<td>428</td>
<td>-9.6°</td>
<td>0.10</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.6</td>
<td>21</td>
<td>&lt;-1°</td>
<td>0.02</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.7</td>
<td>23</td>
<td>-59°</td>
<td>1.3</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.8</td>
<td>14</td>
<td>-47°</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Stanley & Bloxham 2006

Modeling Uranus' & Neptune's non-dipolar fields with a thin-shell dynamo over a stratified core

Even with the Best Equation of State – Still lots of unknowns

Juno
Launched Aug. 5th
Arrives Jul. 2016

Guillot et al. 2004
Current knowledge of Jupiter is limited to $n < 4$

Earth dynamo at $n > 14$ is hidden by crustal field

Juno will measure out to $n \sim 20$

Determine spectral shape, dynamo radius, and secular variations

Now we have magnetic fields.... what about magnetospheres?
\[ \frac{R_{\text{Chapman-Ferraro}}}{R_p} \sim \left\{ \frac{B_0^2}{2 \mu_0 \rho_{\text{sw}} V_{\text{sw}}^2} \right\}^{1/6} \]

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_0 ) Gauss</td>
<td>.003</td>
<td>.31</td>
<td>4.28</td>
<td>.22</td>
<td>.23</td>
<td>.14</td>
</tr>
<tr>
<td>( R_{\text{CF Calc.}} )</td>
<td>1.4 ( R_M )</td>
<td>10 ( R_E )</td>
<td>42 ( R_J )</td>
<td>19 ( R_S )</td>
<td>25 ( R_U )</td>
<td>24 ( R_N )</td>
</tr>
<tr>
<td>( R_M ) Obs.</td>
<td>1.4-1.6 ( R_M )</td>
<td>8-12 ( R_E )</td>
<td>60-90 ( R_J )</td>
<td>16-22 ( R_S )</td>
<td>18 ( R_U )</td>
<td>23-26 ( R_N )</td>
</tr>
</tbody>
</table>

**Magnetospheres scaled by stand-off distance of dipole field**

<table>
<thead>
<tr>
<th></th>
<th>M/M_\oplus</th>
<th>( M_{\text{dipole}} )</th>
<th>( M_{\text{mean}} )</th>
<th>( M_{\text{range}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>( \sim 8 \times 10^3 )</td>
<td>1.4 ( R_M )</td>
<td>1.4 ( R_M )</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
<td>10 ( R_E )</td>
<td>10 ( R_E )</td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>600</td>
<td>20 ( R_S )</td>
<td>24 ( R_S )</td>
<td>22-27° ( R_S )</td>
</tr>
<tr>
<td>Jupiter</td>
<td>20,000</td>
<td>46 ( R_J )</td>
<td>75 ( R_J )</td>
<td>63-92° ( R_J )</td>
</tr>
</tbody>
</table>

*Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS*

Note bimodal average locations
* Achilleos et al. 2008  # Joy et al. 2002
**Mercury & Ganymede**

**Mercury - Magnetic field**
detected by *Mariner 10* in 1974

**Ganymede - Magnetic field**
detected by *Galileo* in 1996

\[ B_{\text{surface}} \sim \frac{1}{100} \text{ Earth} \]
Ganymede

- Highly asymmetric,
- Highly non-dipolar
- Complex transport (SW + rotation)
- Multiple plasma sources (ionosphere + solar wind + satellites)

Uranus

- Highly asymmetric,
- Highly non-dipolar
- Complex transport (SW + rotation)
- Multiple plasma sources (ionosphere + solar wind + satellites)
Neptune

Similarly complex as Uranus

Zieger et al.
Juno arrives at Jupiter July 4th 2016

Juno

Microwave Radiometer (JPL)
Magnetometer (GSFC/JPL)
Energetic Particle Detector (APL)
Plasma (SwRI)
Waves (Iowa)
UV Spectrometer (SwRI)
IR Spectral Imager (Rome)
Visible Camera (Malin)

Launch 2011
Arrive 2016
Launch: August 2011

5 year cruise

Baseline mission:
- 32 polar orbits
- Perijove ~5000 km
- 11 day period
- Spinner
- Solar-powered

Science Objectives:
- Origin of Jupiter
- Interior Structure
- Atmosphere Composition & Dynamics
- Polar Magnetosphere

Probing Jupiter's Deep Interior

Microwaves tell us about the outer weather layers
- the amount of water

Magnetic and Gravity Fields tell us about the deep interior
Juno passes directly through auroral field lines

Measures particles precipitating into atmosphere creating aurora

Plasma/radio waves reveal processes responsible for particle acceleration

UV & IR images provides context for in-situ observations