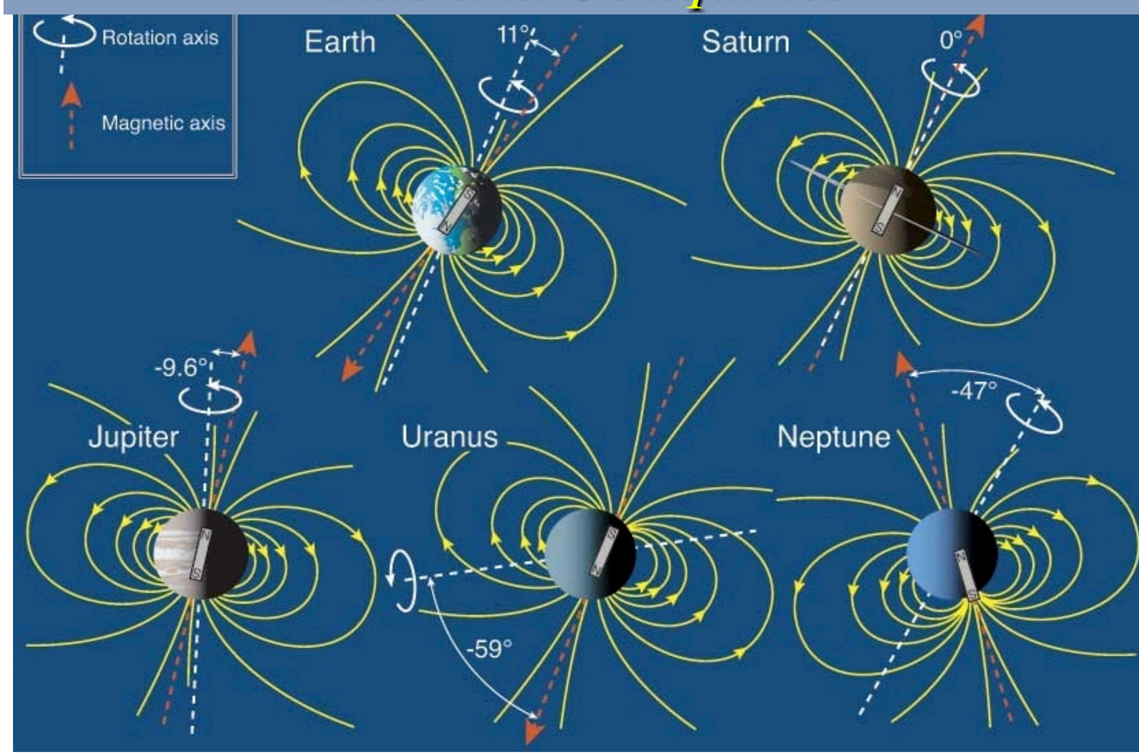
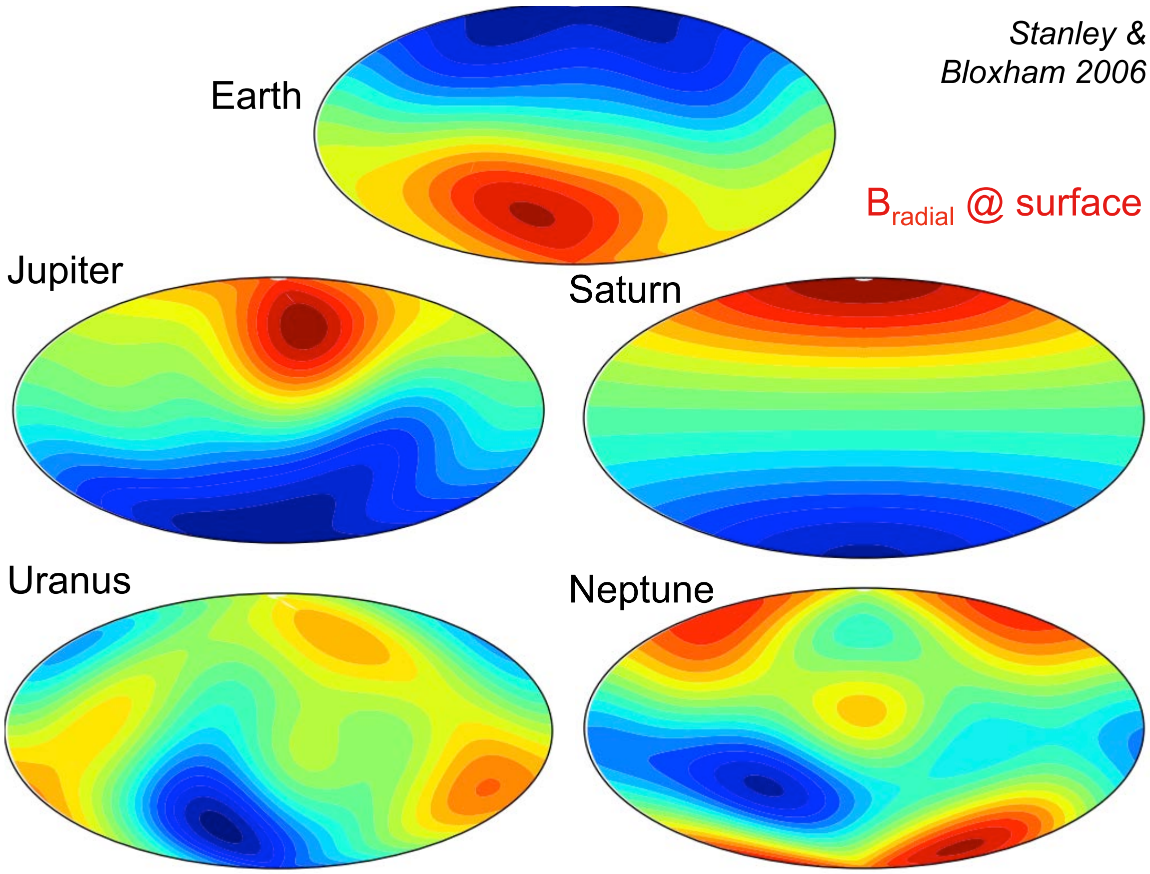
Tilts and Obliquities



Offset Tilted Dipole Approximation



Magnetic Potential 3-D harmonics

$$\mathbf{B} = -grad\ V$$

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

coefficients - constants

functions

$P_0^0(\cos\theta) = 1$

$P_1^0(\cos\theta) = \cos\theta$

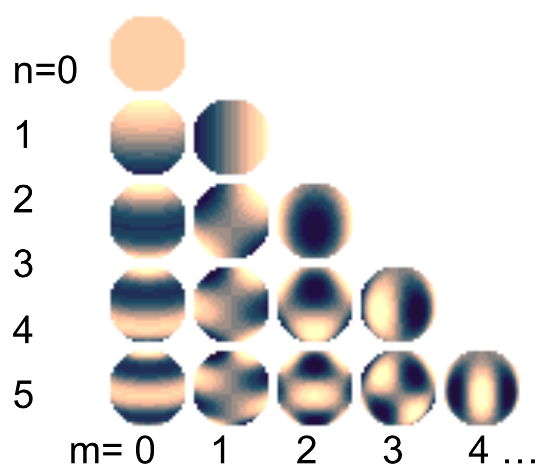
$P_1^1(\cos\theta) = -\sin\theta$

$P_2^0(\cos\theta) = \frac{1}{2}(3\cos^2\theta - 1)$

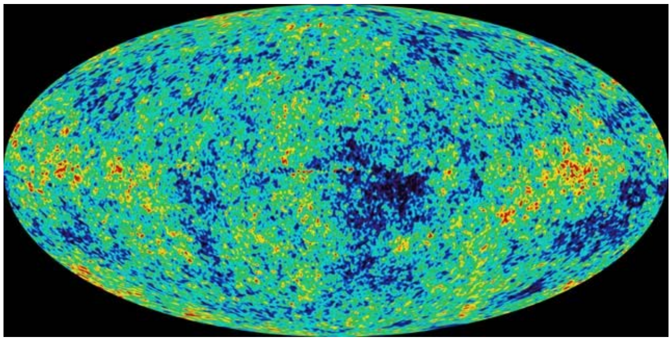
$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$

$P_2^2(\cos\theta) = 3\sin^2\theta$

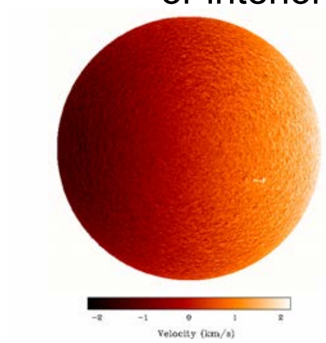
$P_3^0(\cos\theta) = \frac{1}{2}(5\cos^3\theta - 3\cos\theta)$

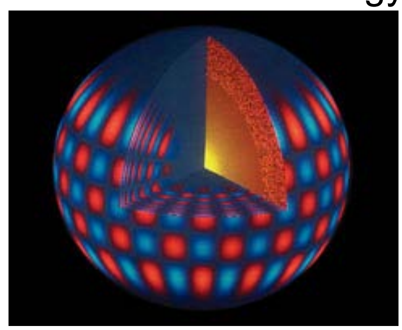


Same technique used to model cosmic microwave background



or interior of Sun with Helioseismology…





Earth - International Geomagnetic Reference Field

11th Generation International Geomagnetic Reference Field Schmidt semi-normalised spherical harmonic coefficients, degree n=1,13
in units nanoTesla for IGRF and definitive DGRF main-field models (degree n=1,8 nanoTesla/year for secular variation (SV))

			IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	IGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	DGRF	IGRF	SV
g/h	n	m	1900.0	1905.0	1910.0	1915.0	1920.0	1925.0	1930.0	1935.0	1940.0	1945.0	1950.0	1955.0	1960.0	1965.0	1970.0	1975.0	1980.0	1985.0	1990.0	1995.0	2000.0	2005.0	2010.0	2010-15
g	1	0	-31543	-31464	-31354	-31212	-31060	-30926	-30805	-30715	-30654	-30594	-30554	-30500	-30421	-30334	-30220	-30100	-29992	-29873	-29775	-29692	-29619.4	-29554.63	-29496.5	11.4
g	1	1	-2298	-2298	-2297	-2306	-2317	-2318	-2316	-2306	-2292	-2285	-2250	-2215	-2169	-2119	-2068	-2013	-1956	-1905	-1848	-1784	-1728.2	-1669.05	-1585.9	16.7
h	1	1	5922	5909	5898	5875	5845	5817	5808	5812	5821	5810	5815	5820	5791	5776	5737	5675	5604	5500	5406	5306	5186.1	5077.99	4945.1	-28.8
g	2	0	-677	-728	-769	-802	-839	-893	-951	-1018	-1106	-1244	-1341	-1440	-1555	-1662	-1781	-1902	-1997	-2072	-2131	-2200	-2267.7	-2337.24	-2396.6	-11.3
g	2	1	2905	2928	2948	2956	2959	2969	2980	2984	2981	2990	2998	3003	3002	2997	3000	3010	3027	3044	3059	3070	3068.4	3047.69	3026.0	-3.9
h	2	1	-1061	-1086	-1128	-1191	-1259	-1334	-1424	-1520	-1614	-1702	-1810	-1898	-1967	-2016	-2047	-2067	-2129	-2197	-2279	-2366	-2481.6	-2594.50	-2707.7	-23.0
g	2	2	924	1041	1176	1309	1407	1471	1517	1550	1566	1578	1576	1581	1590	1594	1611	1632	1663	1687	1686	1681	1670.9	1657.76	1668.6	2.7
h	2	2	1121	1065	1000	917	823	728	644	586	528	477	381	291	206	114	25	-68	-200	-306	-373	-413	-458.0	-515.43	-575.4	-12.9
g	3	0	1022	1037	1058	1084	1111	1140	1172	1206	1240	1282	1297	1302	1302	1297	1287	1276	1281	1296	1314	1335	1339.6	1336.30	1339.7	1.3
g	3	1	-1469	-1494	-1524	-1559	-1600	-1645	-1692	-1740	-1790	-1834	-1889	-1944	-1992	-2038	-2091	-2144	-2180	-2208	-2239	-2267	-2288.0	-2305.83	-2326.3	-3.9
h	3	1	-330	-357	-389	-421	-445	-462	-480	-494	-499	-499	-476	-462	-414	-404	-366	-333	-336	-310	-284	-262	-227.6	-198.86	-160.5	8.6
g	3	2	1256	1239	1223	1212	1205	1202	1205	1215	1232	1255	1274	1288	1289	1292	1278	1260	1251	1247	1248	1249	1252.1	1246.39	1231.7	-2.9
h	3	2	3	34	62	84	103	119	133	146	163	186	206	216	224	240	251	262	271	284	293	302	293.4	269.72	251.7	-2.9
g	3	3	572	635	705	778	839	881	907	918	916	913	896	882	878	856	838	830	833	829	802	759	714.5	672.51	634.2	-8.1
h	3	3	523	480	425	360	293	229	166	101	43	-11	-46	-83	-130	-165	-196	-223	-252	-297	-352	-427	-491.1	-524.72	-536.8	-2.1
g	4	0	876	880	884	887	889	891	896	903	914	944	954	958	957	957	952	946	938	936	939	940	932.3	920.55	912.6	-1.4
g	4	1	628	643	660	678	695	711	727	744	762	776	792	796	800	804	800	791	782	780	780	780	786.8	797.96	809.0	2.0
h	4	1	195	203	211	218	220	216	205	188	169	144	136	133	135	148	167	191	212	232	247	262	272.6	282.07	286.4	0.4
g	4	2	660	653	644	631	616	601	584	565	550	544	528	510	504	479	461	438	398	361	325	290	250.0	210.65	166.6	-8.9
h	4	2	-69	-77	-90	-109	-134	-163	-195	-226	-252	-276	-278	-274	-278	-269	-266	-265	-257	-249	-240	-236	-231.9	-225.23	-211.2	3.2
g	4	3	-361	-380	-400	-416	-424	-426	-422	-415	-405	-421	-408	-397	-394	-390	-395	-405	-419	-424	-423	-418	-403.0	-379.86	-357.1	4.4
h	4	3	-210	-201	-189	-173	-153	-130	-109	-90	-72	-55	-37	-23	3	13	26	39	53	69	84	97	119.8	145.15	164.4	3.6
g	4	4	134	146	160	178	199	217	234	249	265	304	303	290	269	252	234	216	199	170	141	122	111.3	100.00	89.7	-2.3
h	4	4	-75	-65	-55	-51	-57	-70	-90	-114	-141	-178	-210	-230	-255	-269	-279	-288	-297	-297	-299	-306	-303.8	-305.36	-309.2	-0.8
g	5	0	-184	-192	-201	-211	-221	-230	-237	-241	-241	-253	-240	-229	-222	-219	-216	-218	-218	-214	-214	-214	-218.8	-227.00	-231.1	-0.5
g	5	1	328	328	327	327	326	326	327	329	334	346	349	360	362	358	359	356	357	355	353	352	351.4	354.41	357.2	0.5
h	5	1	-210	-193	-172	-148	-122	-96	-72	-51	-33	-12	3	15	16	19	26	31	46	47	46	46	43.8	42.72	44.7	0.5
g	5	2	264	259	253	245	236	226	218	211	208	194	211	230	242	254	262	264	261	253	245	235	222.3	208.95	200.3	-1.5
h	5	2	53	56	57	58	58	58	60	64	71	95	103	110	125	128	139	148	150	150	154	165	171.9	180.25	188.9	1.5
g	5	3	5	-1	-9	-16	-23	-28	-32	-33	-33	-20	-20	-23	-26	-31	-42	-59	-74	-93	-109	-118	-130.4	-136.54	-141.2	-0.7
h	5	3	-33	-32	-33	-34	-38	-44	-53	-64	-75	-67	-87	-98	-117	-126	-139	-152	-151	-154	-153	-143	-133.1	-123.45	-118.1	0.9
g	5	4	-86	-93	-102	-111	-119	-125	-131	-136	-141	-142	-147	-152	-156	-157	-160	-159	-162	-164	-165	-166	-168.6	-168.05	-163.1	1.3
h	5	4	-124	-125	-126	-126	-125	-122	-118	-115	-113	-119	-122	-121	-114	-97	-91	-83	-78	-75	-69	-55	-39.3	-19.57	0.1	3.7
g	5	5	-16	-26	-38	-51	-62	-69	-74	-76	-76	-82	-76	-69	-63	-62	-56	-49	-48	-46	-36	-17	-12.9	-13.55	-7.7	1.4
h	5	5	3	11	21	32	43	51	58	64	69	82	80	78	81	81	83	88	92	95	97	107	106.3	103.85	100.9	-0.6
g	6	0	63	62	62	61	61	61	60	59	57	59	54	47	46	45	43	45	48	53	61	68	72.3	73.60	72.8	-0.3
g	6	1	61	60	58	57	55	54	53	53	54	57	57	57	58	61	64	66	66	65	65	67	68.2	69.56	68.6	-0.3
h	6	1	-9	-7	-5	-2	0	3	4	4	4	6	-1	-9	-10	-11	-12	-13	-15	-16	-16	-17	-17.4	-20.33	-20.8	-0.1
g	6	2	-11	-11	-11	-10	-10	-9	-9	-8	-7	6	4	3	1	8	15	28	42	51	59	68	74.2	76.74	76.0	-0.3
h	6	2	83	86	89	93	96	99	102	104	105	100	99	96	99	100	100	99	93	88	82	72	63.7	54.75	44.2	-2.1
g	6	3	-217	-221	-224	-228	-233	-238	-242	-246	-249	-246	-247	-247	-237	-228	-212	-198	-192	-185	-178	-170	-160.9	-151.34	-141.4	1.9
h	6	3	2	4	5	8	11	14	19	25	33	16	33	48	60	68	72	75	71	69	69	67	65.1	63.63	61.5	-0.4
g	6	4	-58	-57	-54	-51	-46	-40	-32	-25	-18	-25	-16	-8	-1	4	2	1	4	4	3	-1	-5.9	-14.58	-22.9	-1.6
h	6	4	-35	-32	-29	-26	-22	-18	-16	-15	-15	-9	-12	-16	-20	-32	-37	-41	-43	-48	-52	-58	-61.2	-63.53	-66.3	-0.5
g	6	5	59	57	54	49	44	39	32	25	18	21	12	7	-2	1	3	6	14	16	18	19	16.9	14.58	13.1	-0.2
h	6	5	36	32	28	23	18	13	8	4	0	-16	-12	-12	-11	-8	-6	-4	-2	-1	1	1	0.7	0.24	3.1	0.8
g	6	6	-90	-92	-95	-98	-101	-103	-104	-106	-107	-104	-105	-107	-113	-111	-112	-111	-108	-102	-96	-93	-90.4	-86.36	-77.9	1.8
h	6	6	-69	-67	-65	-62	-57	-52	-46	-40	-33	-39	-30	-24	-17	-7	1	11	17	21	24	36	43.8	50.94	54.9	0.5

.... 4 pages later.....

g	13	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	-0.10	-0.3	0.0
h	13	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	-0.57	-0.5	0.0
g	13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	-0.18	-0.3	0.0
h	13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.9	-0.82	-0.8	0.0

Complexity ↓

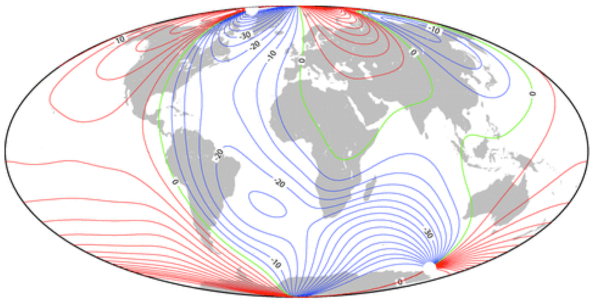
Time →

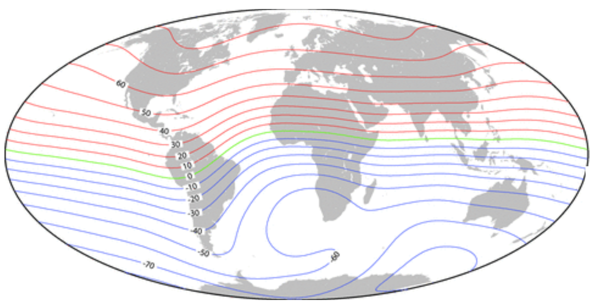
g 13 13
h 13 13

http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-246X.2010.04804.x/full

International Geomagnetic Reference Field 2010

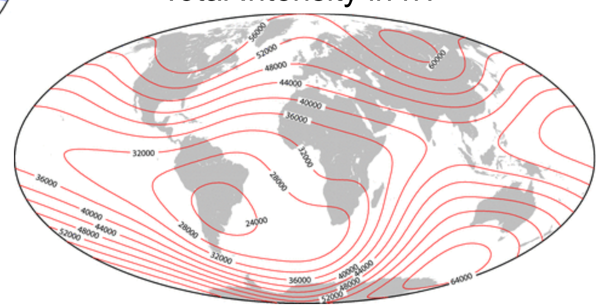
Declination in degrees



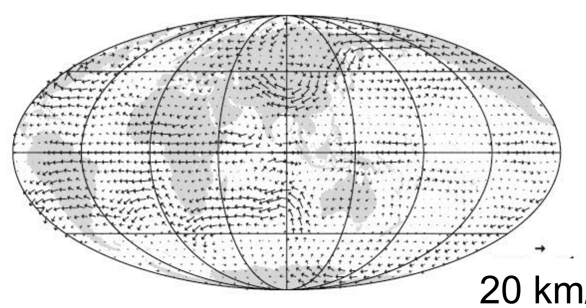


Inclination in degrees

Total Intensity in nT

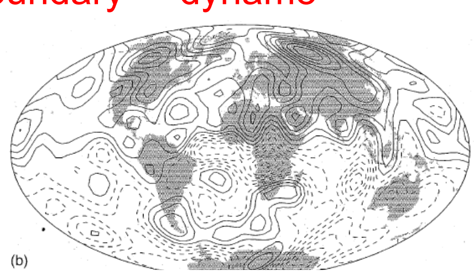


Br surface



20 km/yr

1. From accurate measurement of surface field:
2. Extrapolate to core-mantle boundary = dynamo



Br core-mantle boundary

3. Derive core flows
4. Secular variation & reversals.....

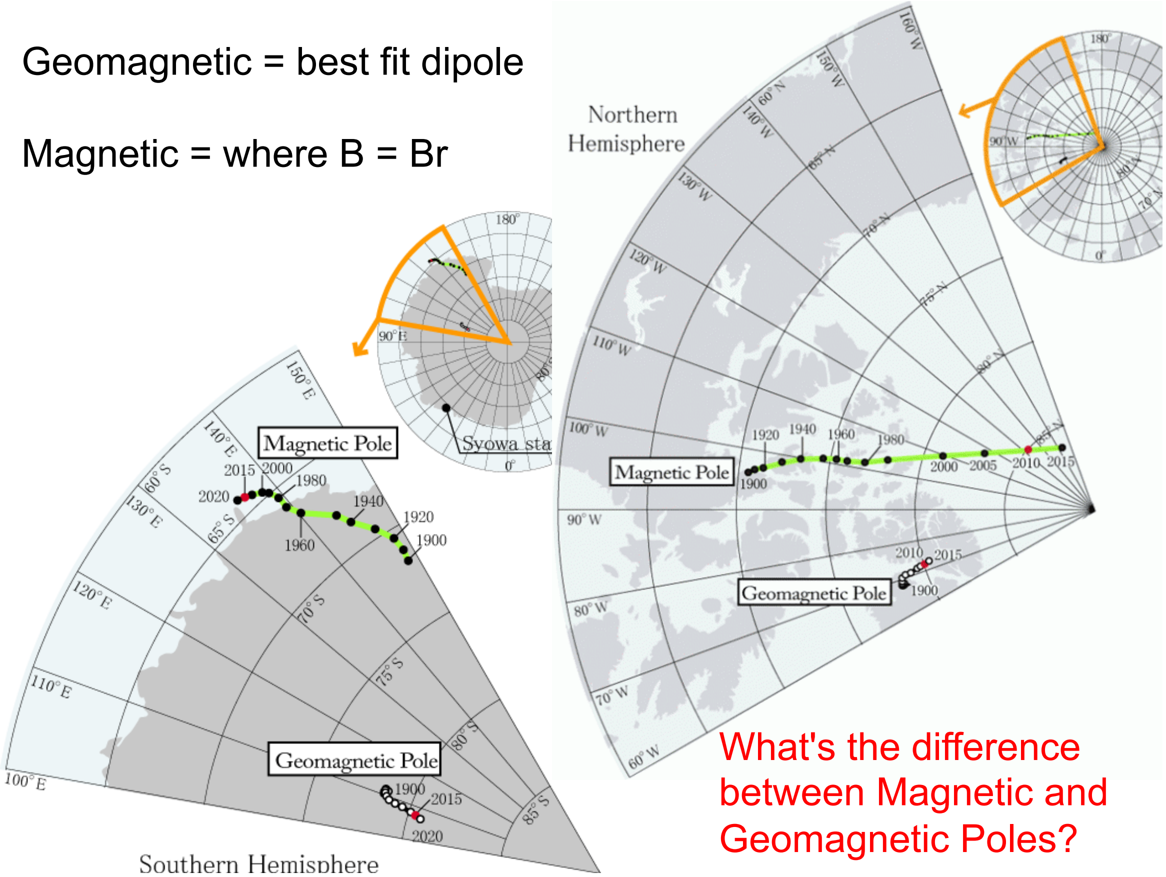
$$\frac{\partial B_r}{\partial t} = -\nabla_h \bullet (\mathbf{u}_h B_r)$$

h=horizontal
r=radial

Hulot et al. 2010

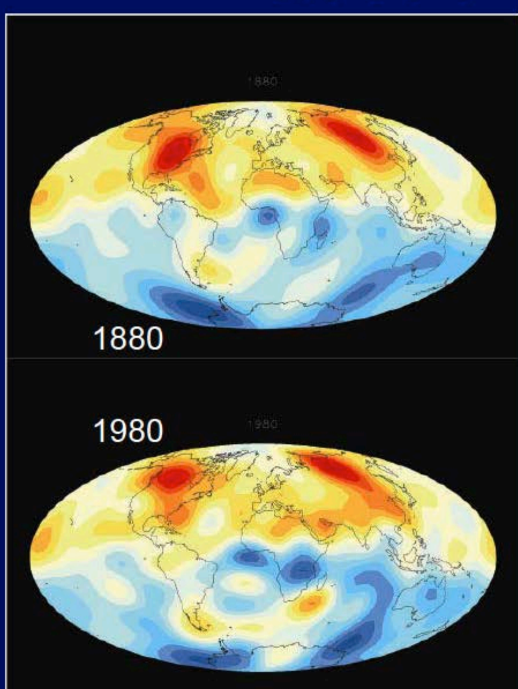
Geomagnetic = best fit dipole

Magnetic = where B = Br

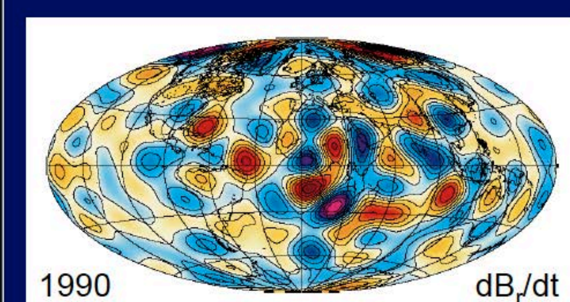


What's the difference between Magnetic and Geomagnetic Poles?

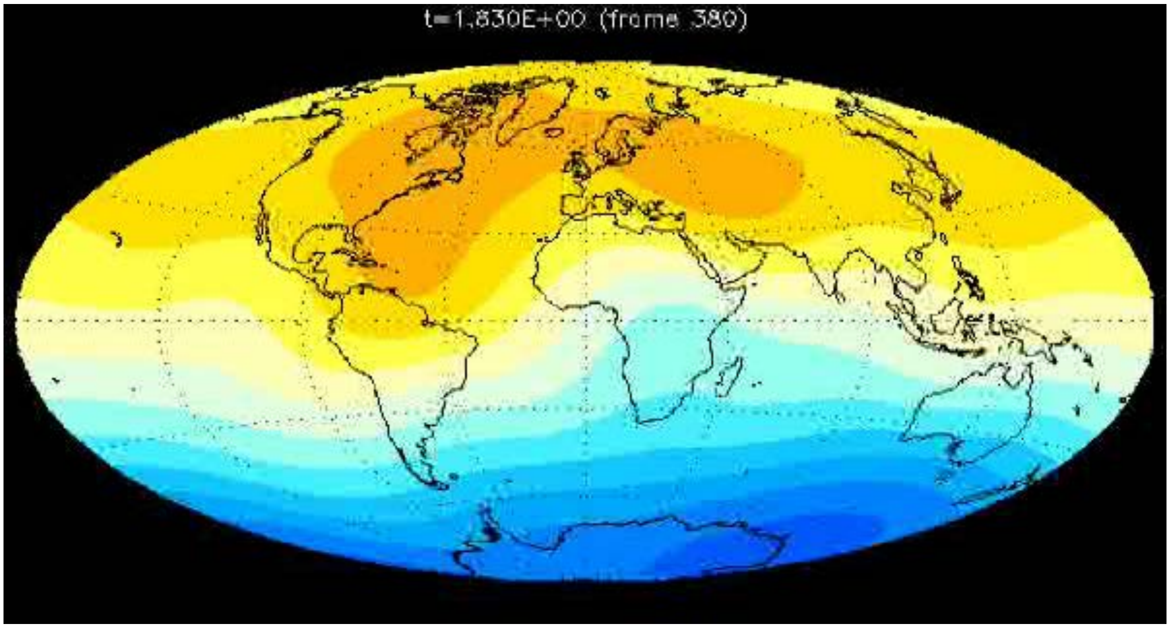
Secular variation



- 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



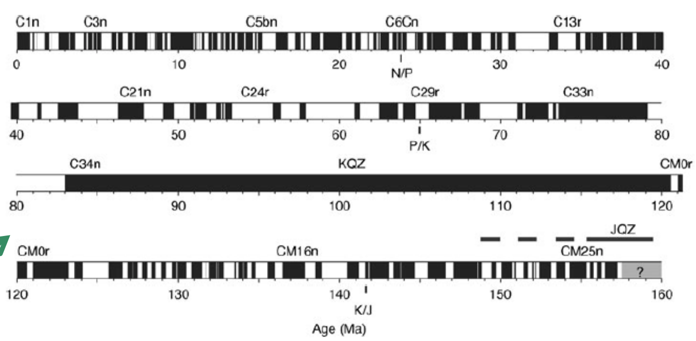
Br through a reversal

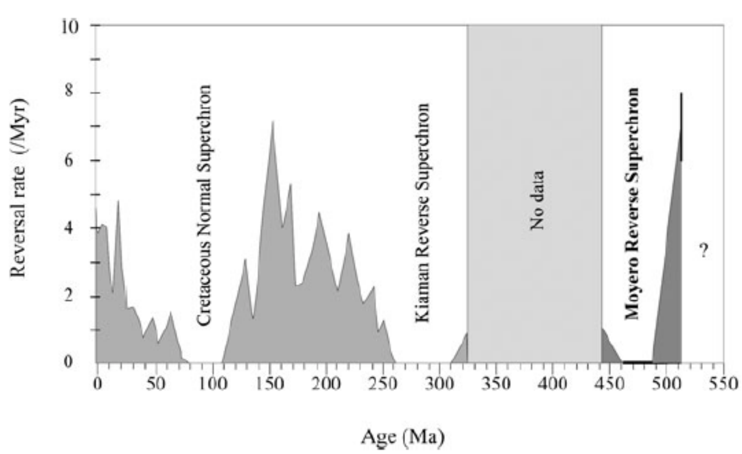


Hulot et al. 2010
Pavlov & Gallet 2005

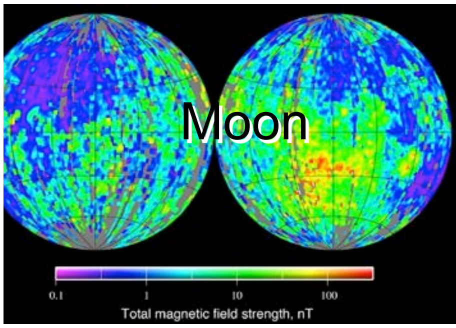
Polarity reversals:

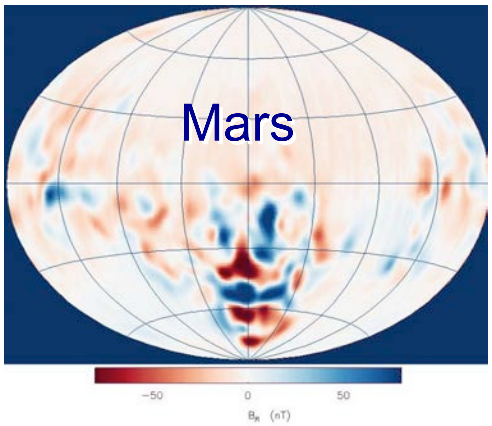
1. variable in duration and
2. rate

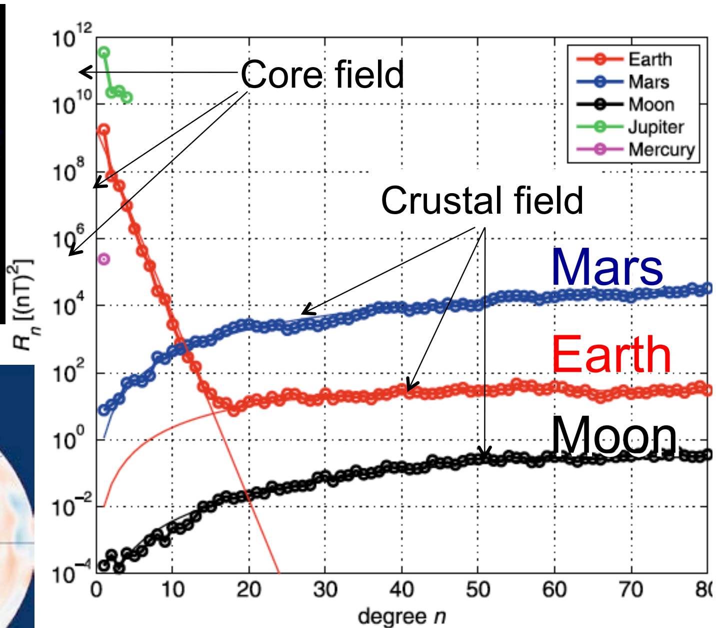




Moon & Mars: All Crustal Remanent Magnetization

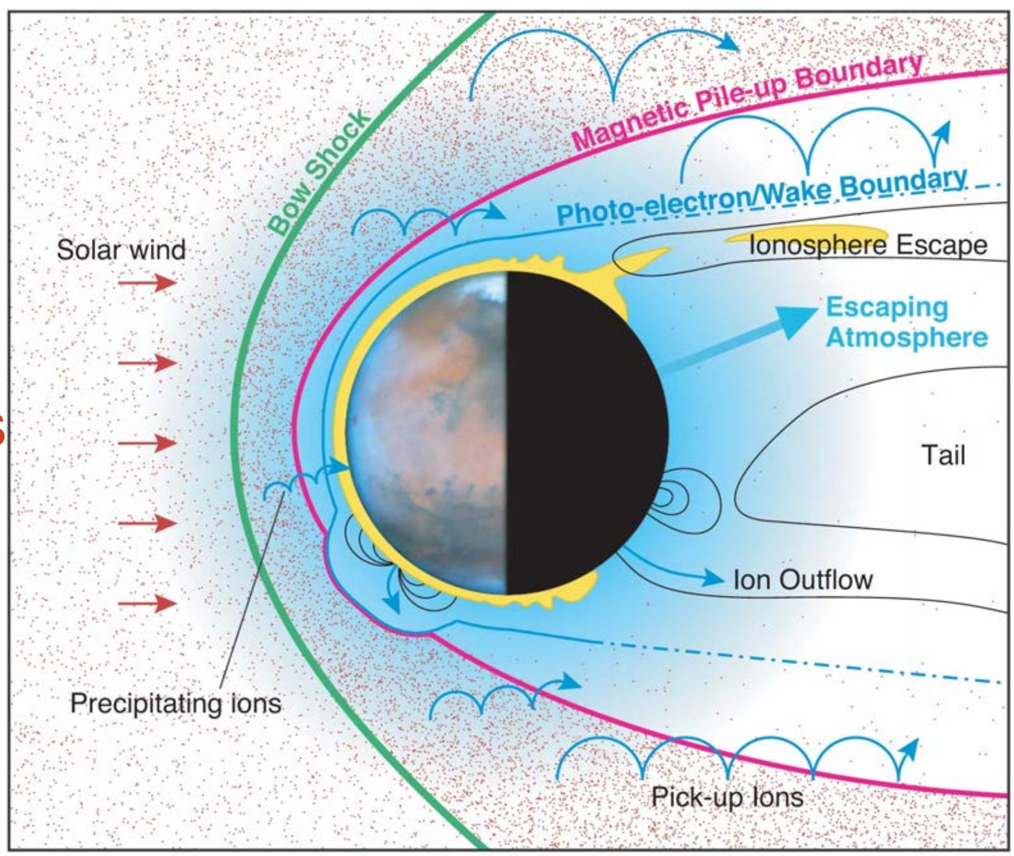






- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

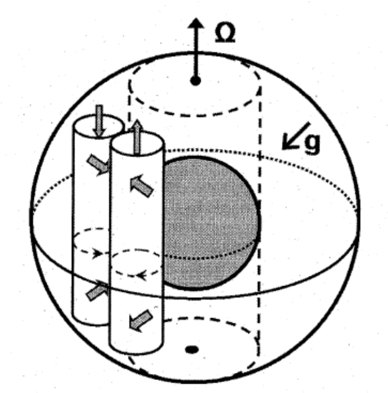
Mars



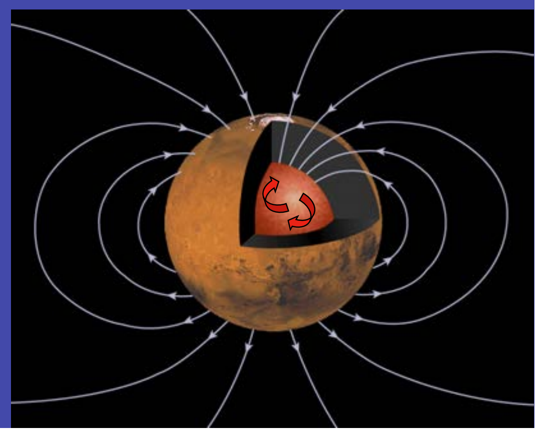
Stanley & Glatzmeier 2010; Christensen 2010

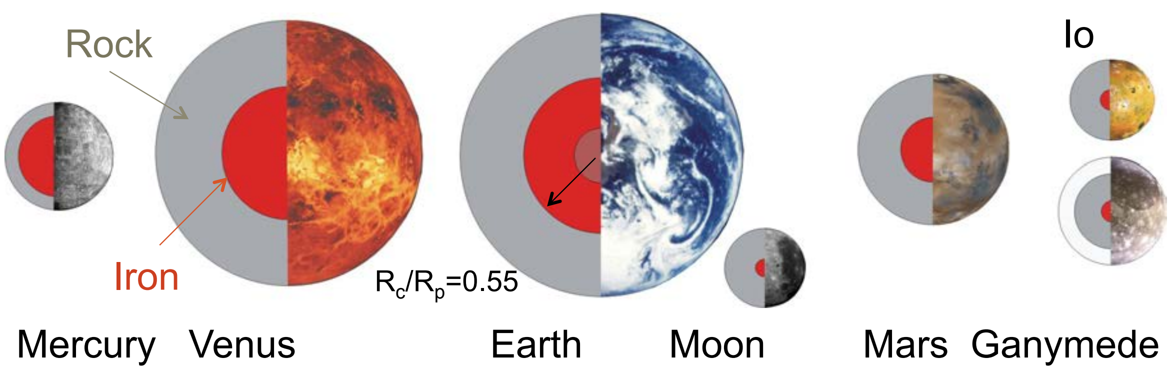
Planetary Dynamos

Volume of electrically conducting fluid (1) which is convecting (2) and rotating



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

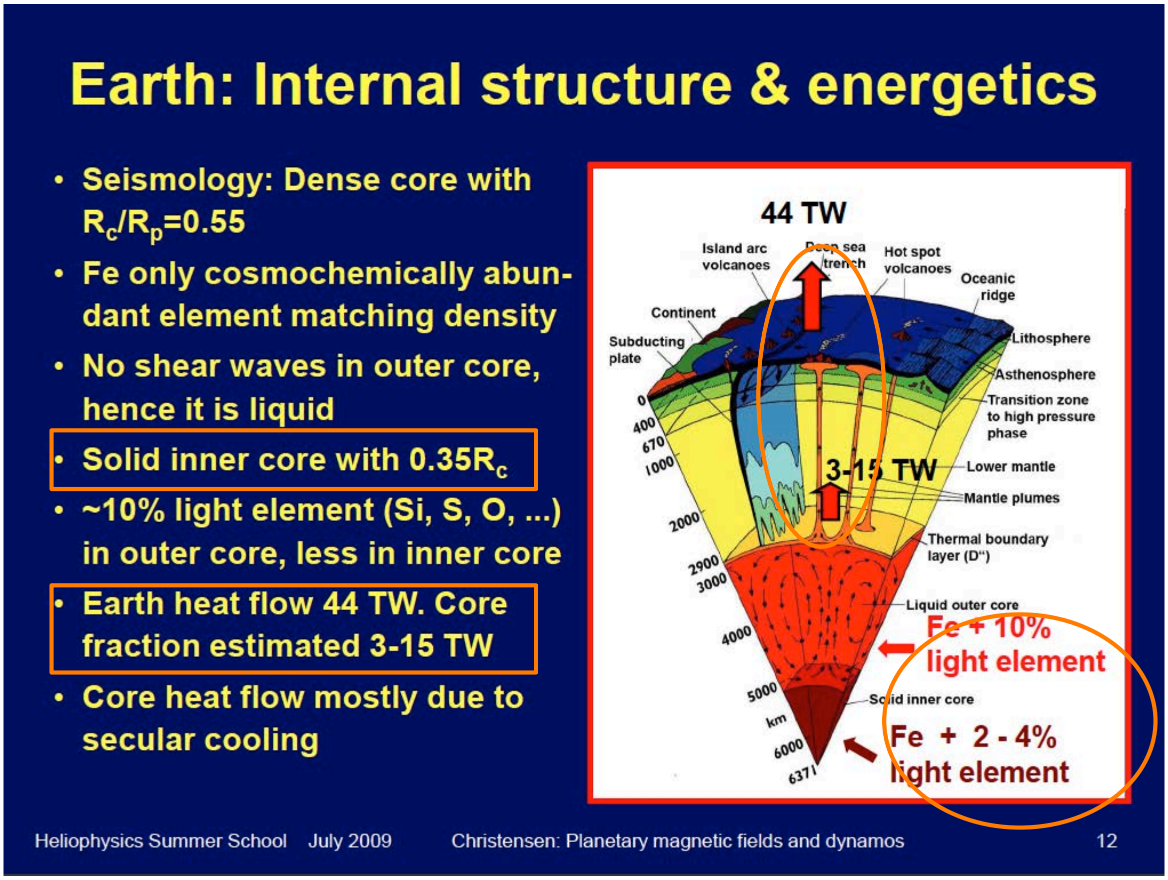


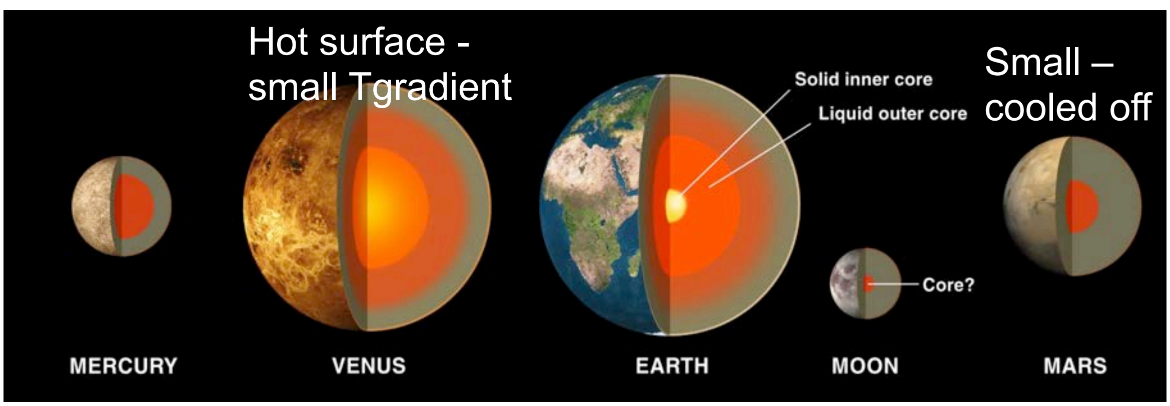


Planet	Dynamo	R_c/R_p	B_o [nT]
Mercury	Yes (?)	0.75	195
Venus	No	0.55	
Earth	Yes	0.55	31,000
Moon	No	0.2?	
Mars	No, but in past	0.5	
Ganymede	Yes	0.3?	720

What drives dynamos in tiny Mercury & Ganymede?

Why don't Venus or Mars have dynamos?





Why Don't Venus or Mars have Dynamos?

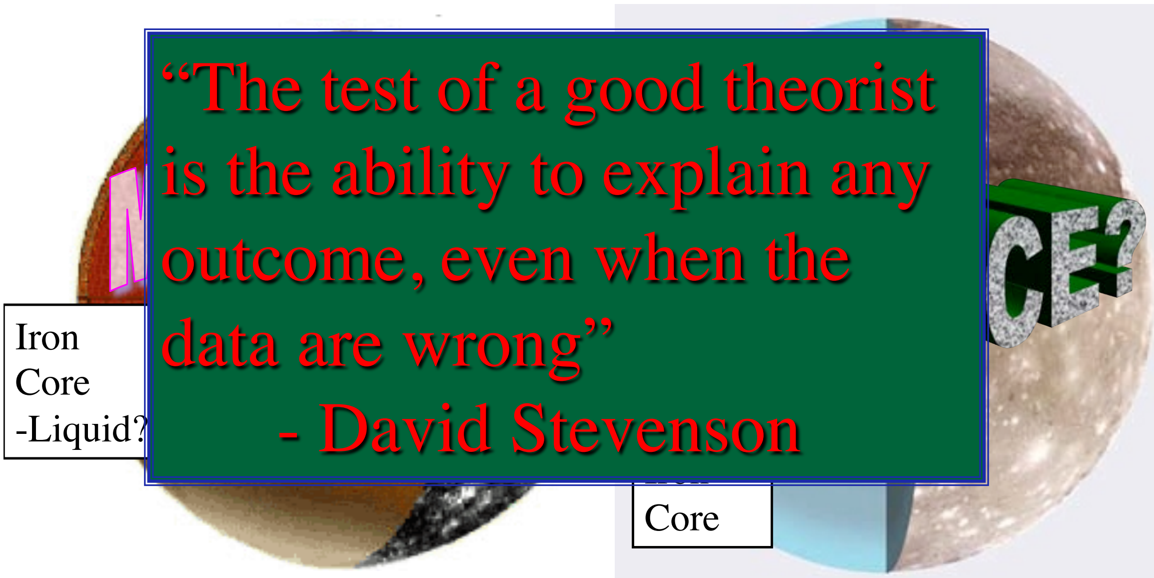
Stevensen 2010

- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?

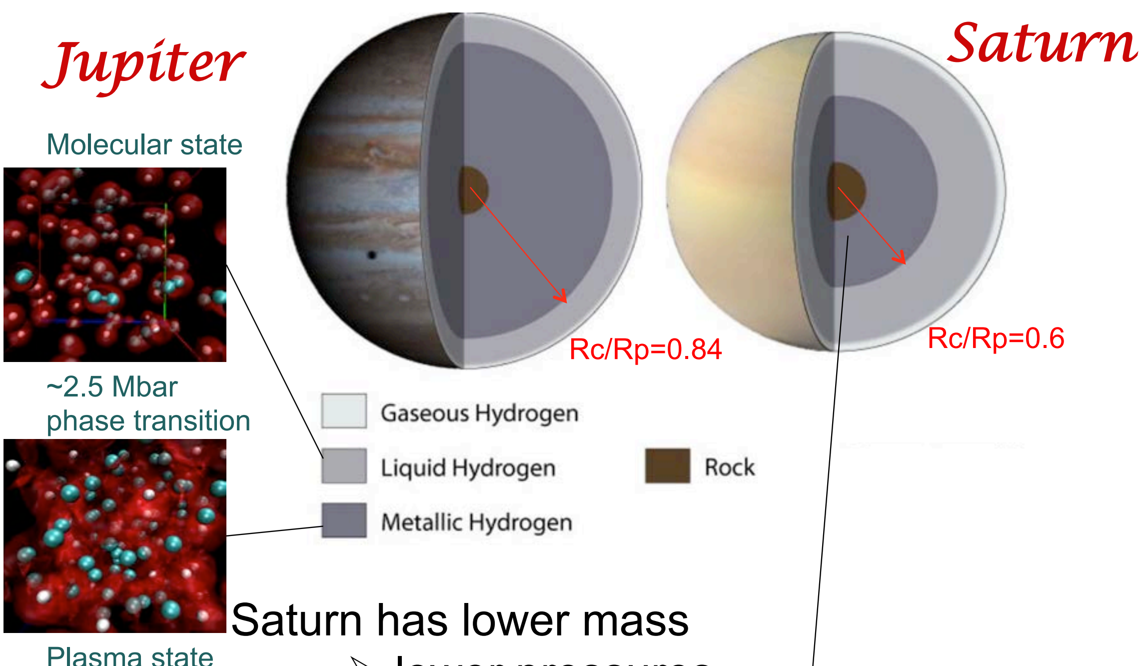
1. If....Mantle convection controls heat flow from core. Then....Lack of plate tectonics suggests less efficient cooling of interior and lower heat flux from core
2. No inner core means no latent heat of solidification and no enhancement of lighter material in the outer core

Mercury & Ganymede

What drives convection in these small bodies?

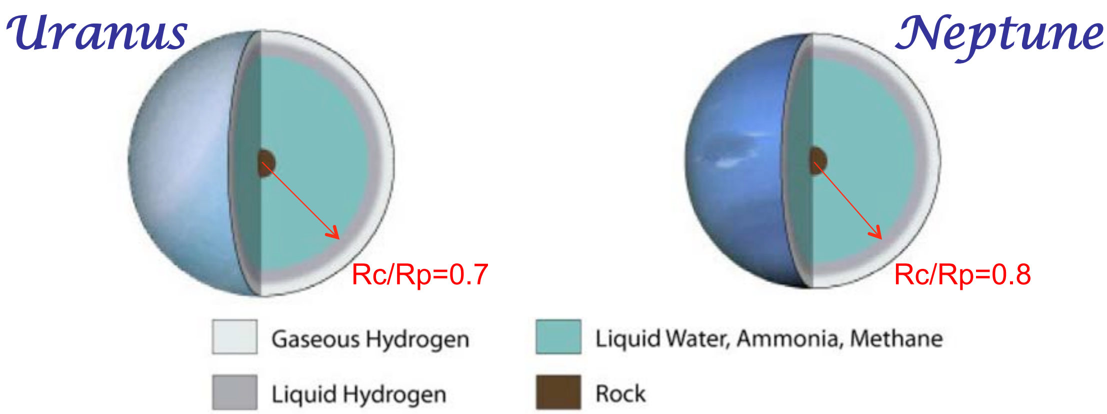


"The test of a good theorist is the ability to explain any outcome, even when the data are wrong"
- David Stevenson



Saturn has lower mass

- lower pressures
- smaller region of metallic hydrogen
- weaker magnetic field



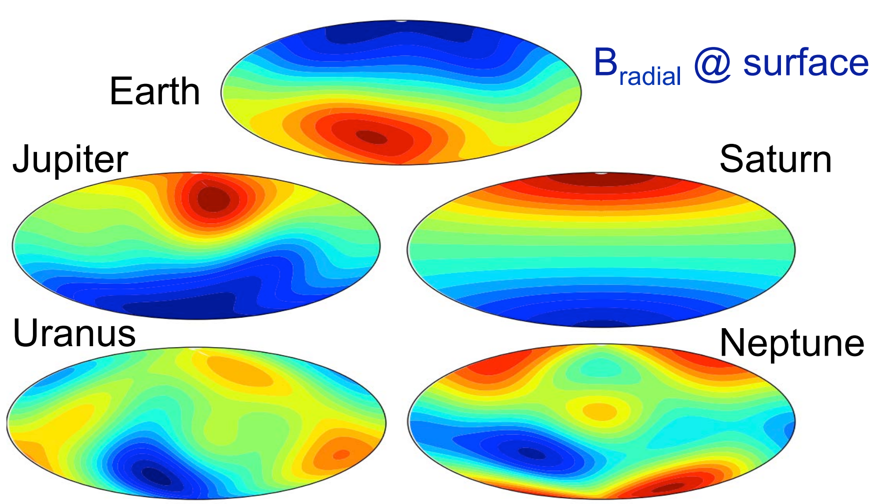
Uranus and Neptune have much less mass

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

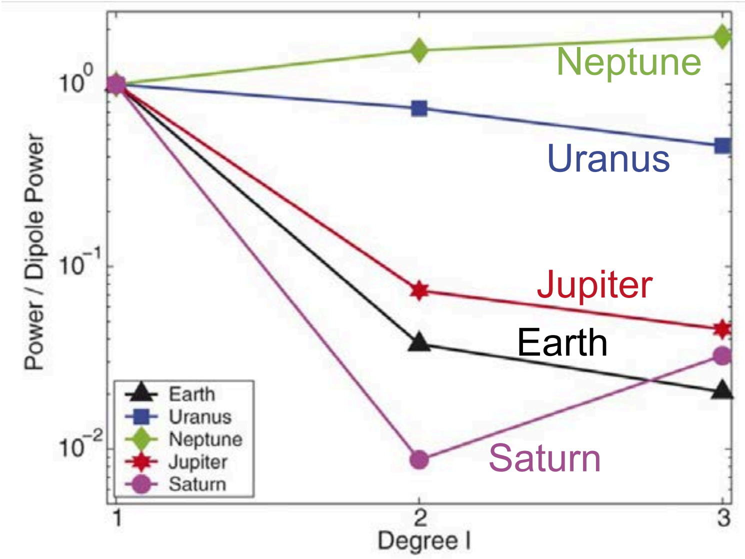
Planet	Rc/Rp	Bo [μT]	Tilt	Quad/ Dipole
Earth	0.55	31	+9.92°	0.04
Jupiter	0.84	428	-9.6°	0.10
Saturn	0.6	21	<-1°	0.02
Uranus	0.7	23	-59°	1.3
Neptune	0.8	14	-47°	2.7

Dipolar (Earth, Saturn)

Irregular (Uranus, Neptune)

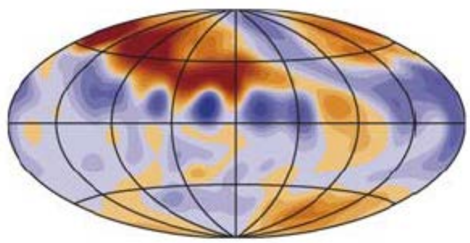


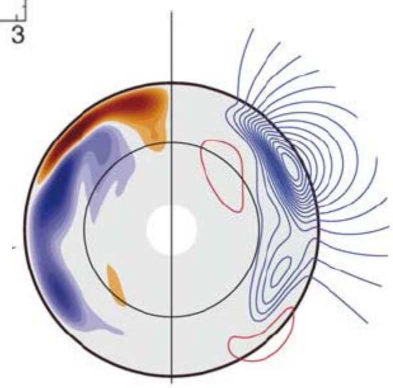
Stanley & Bloxham 2006



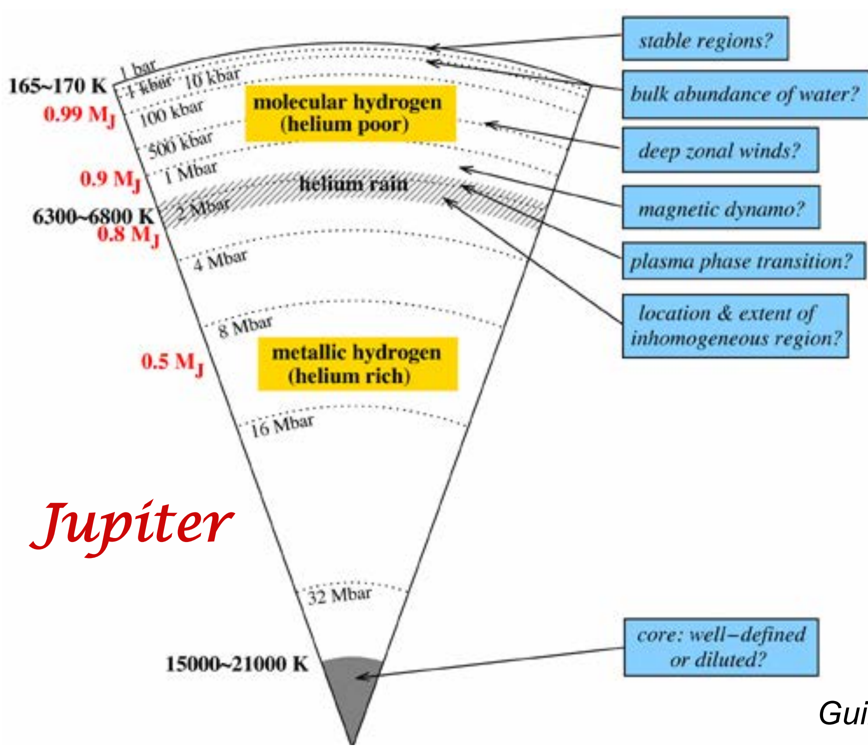
Stanley & Bloxham 2006

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



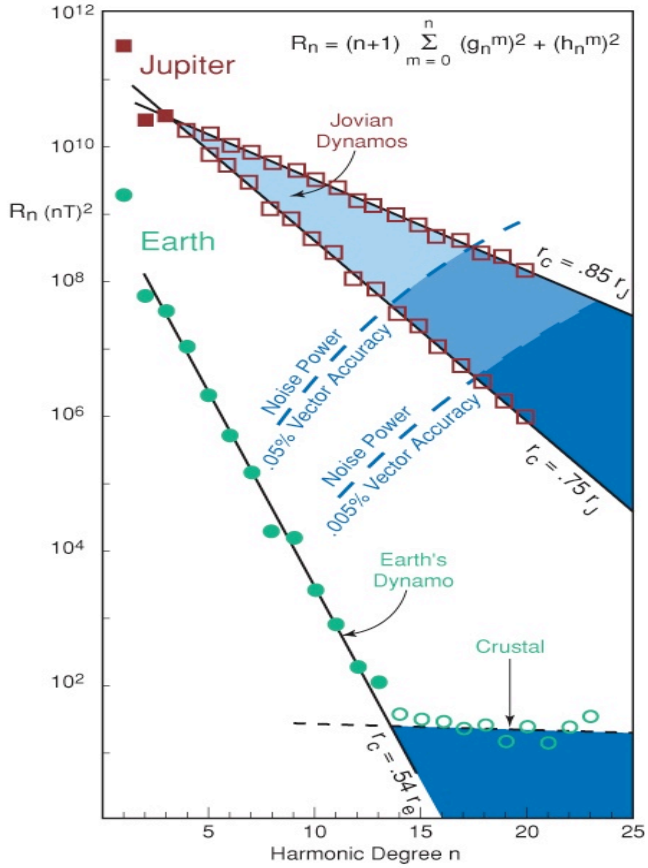
Juno

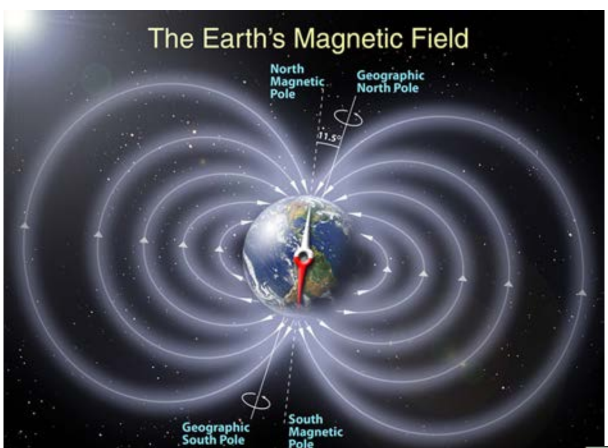
Launched Aug. 5th
Arrives Jul. 2016

Guillot et al. 2004

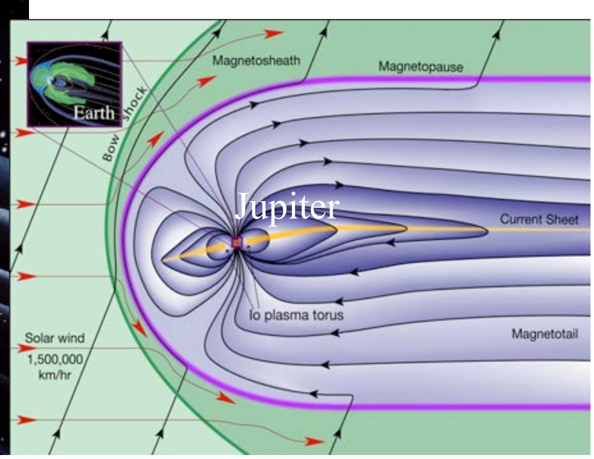
Magnetic Spectra of Earth and Jupiter

- 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 ~ 20
- Determine spectral shape, dynamo radius, and secular variations





Now we have magnetic fields.... what about magnetospheres?



$$R_{\mathbf{Chapman\text{-}Ferraro}}/R_p \sim \{\mathbf{B_o}^2 / 2\,\mu_o\, \rho_{\mathbf{sw}}\, V^2_{\mathbf{sw}}\}^{1/6}$$

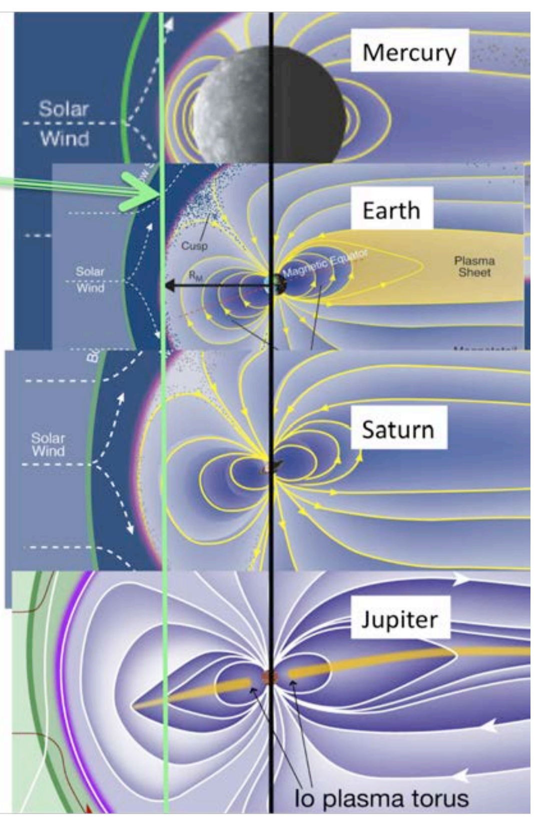
	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o Gauss	.003	.31	4.28	.22	.23	.14
R_{CF} Calc.	1.4 R_M	10 R_E	42 R_J	19 R_S	25 R_U	24 R_N
R_M Obs.	1.4-1.6 R_M	8-12 R_E	60-90 R_J	16-22 R_S	18 R_U	23-26 R_N

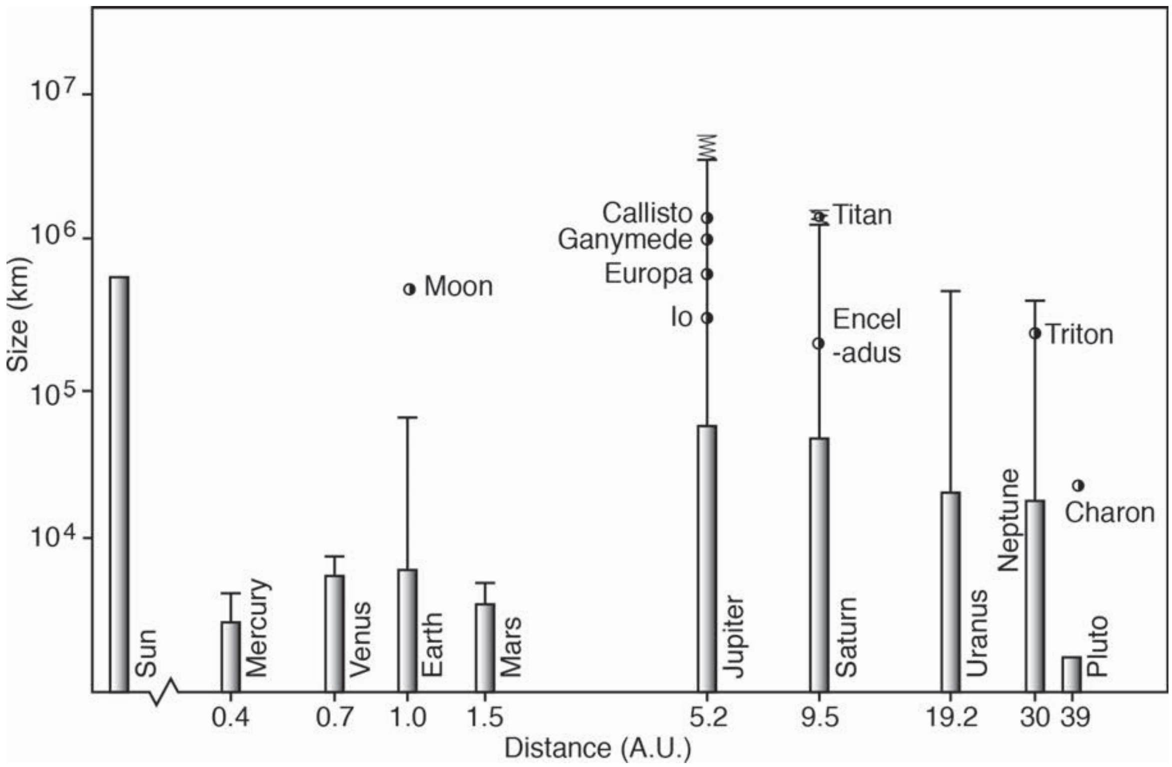
Magnetospheres scaled by stand-off distance of dipole field

	M/M_E	MP_{Dipole}	MP_{mean}	MP_{Range}
Mercury	~8×10^{-3}	1.4 R_M	1.4 R_M	
Earth	1	10 R_E	10 R_E	
Saturn	600	20 R_S	24 R_S	22-27* R_S
Jupiter	20,000	46 R_J	75 R_J	63-92# R_J

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

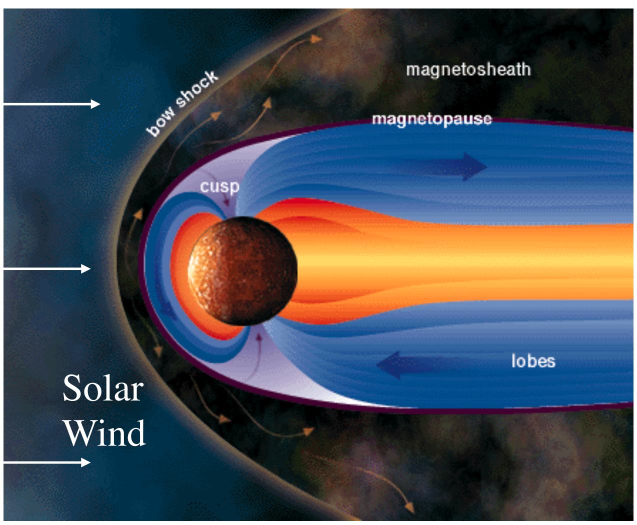
Note bimodal average locations
* *Achilleos et al. 2008* # *Joy et al. 2002*



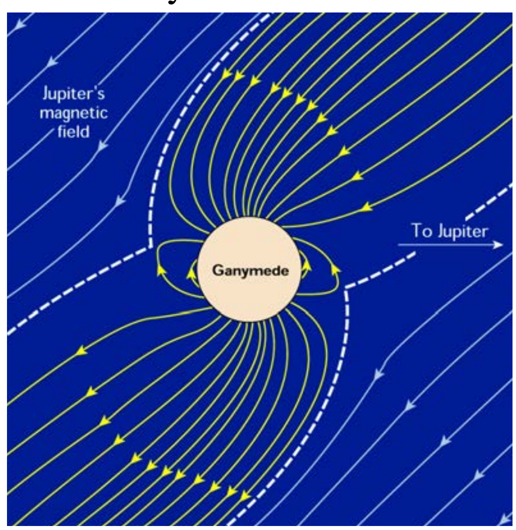


Mercury & Ganymede

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

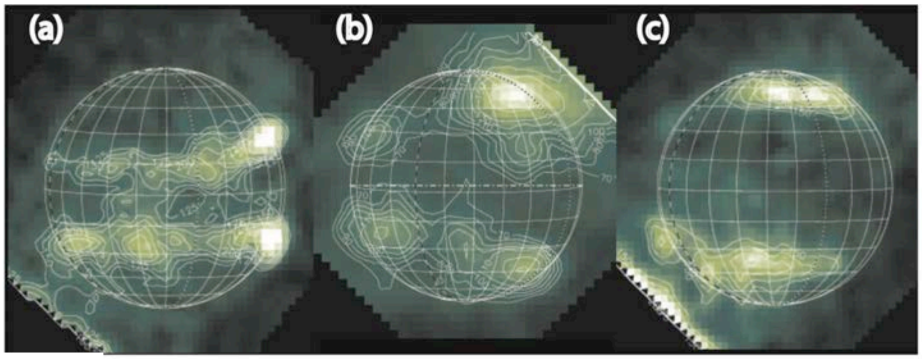


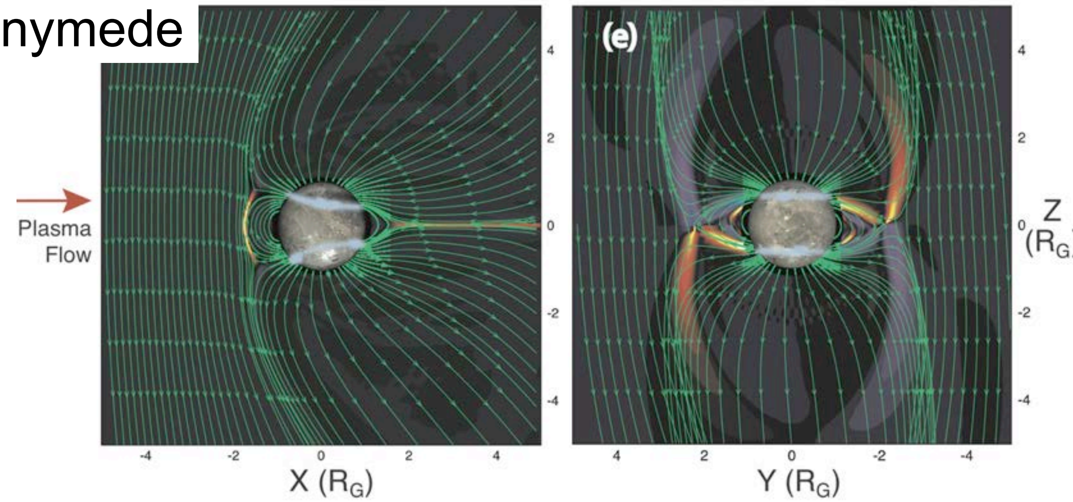
Ganymede - Magnetic field detected by *Galileo* in 1996



$B_{surface}$ ~ 1/100 Earth **Diameter of Earth**

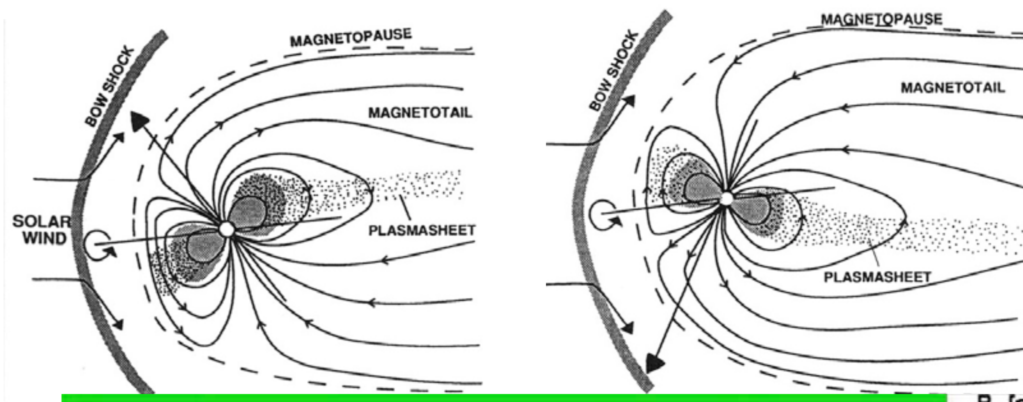
Ganymede

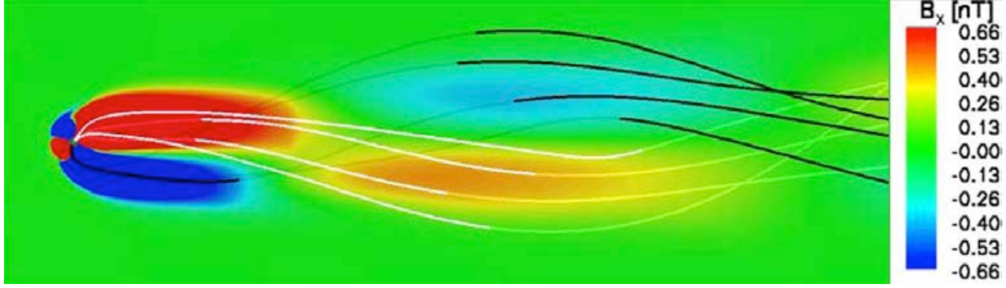




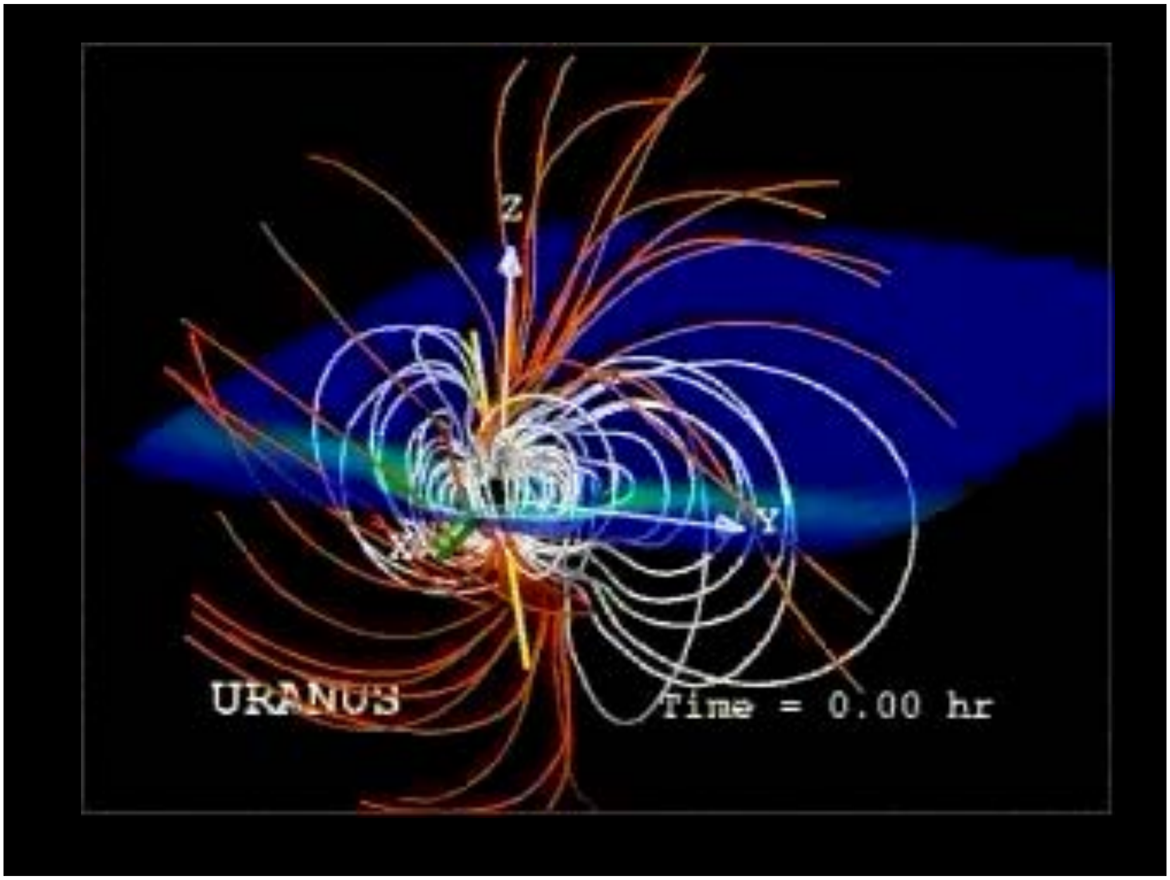
Uranus

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



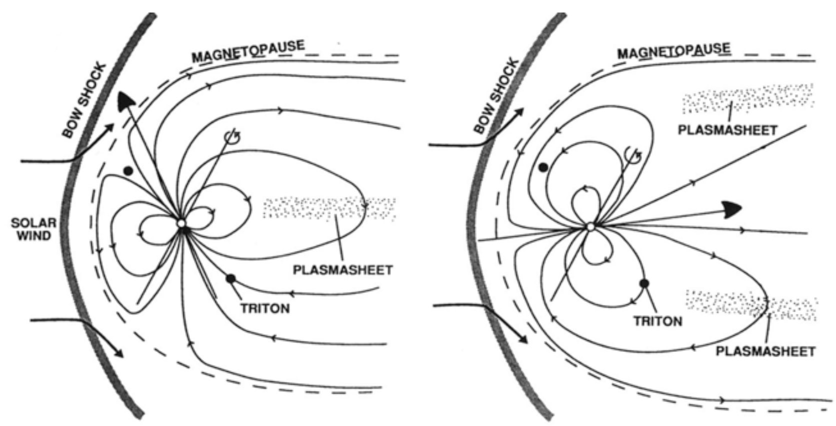


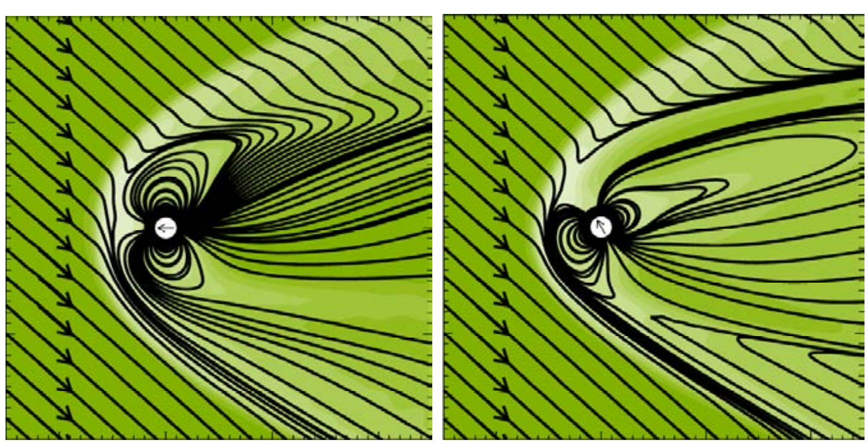
Toth et al.



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 Spectal Imager (Rome)
Visible Camera (Malin)
Launch 2011
Arrive 2016

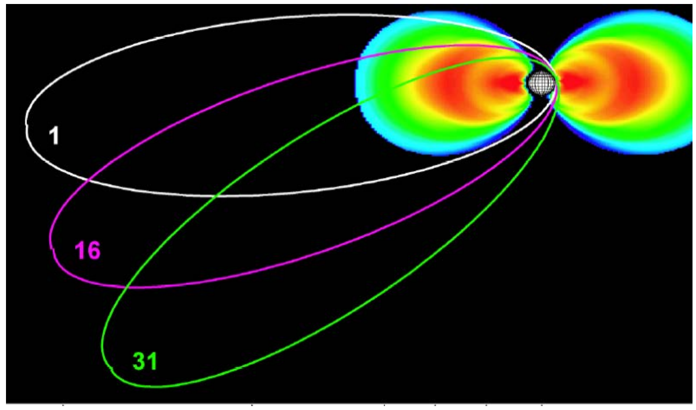
Juno Mission Design

Launch: August 2011

5 year cruise

Baseline mission:

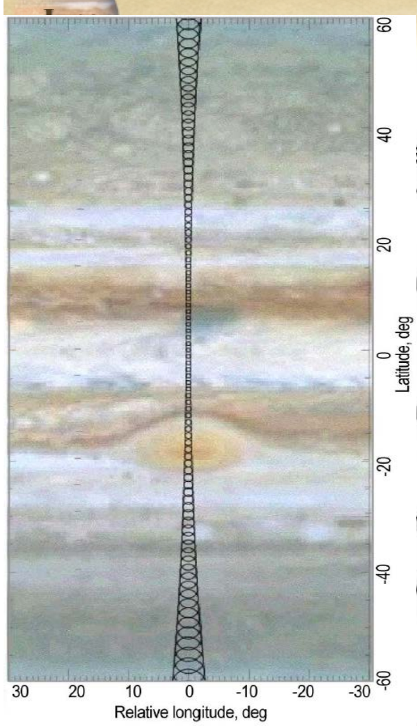
- 32 polar orbits
- Perijove ~5000 km
- 11 day period
- Spinner
- Solar-powered

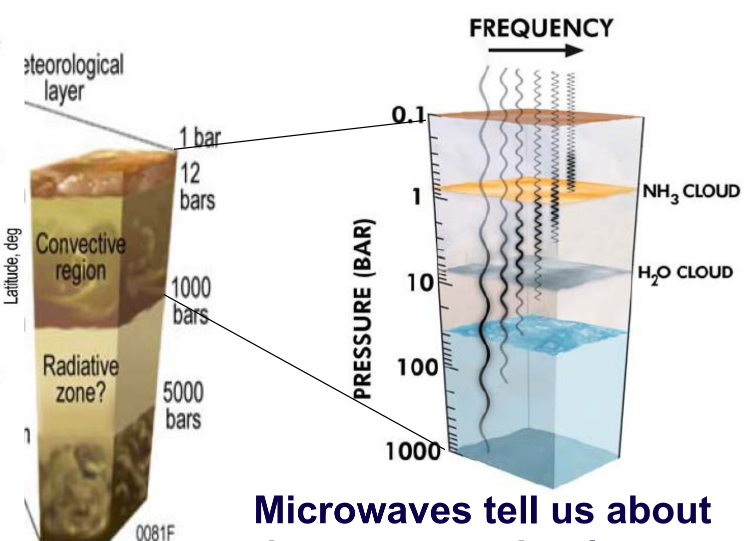


Science Objectives:

- 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

Polar Magnetosphere

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