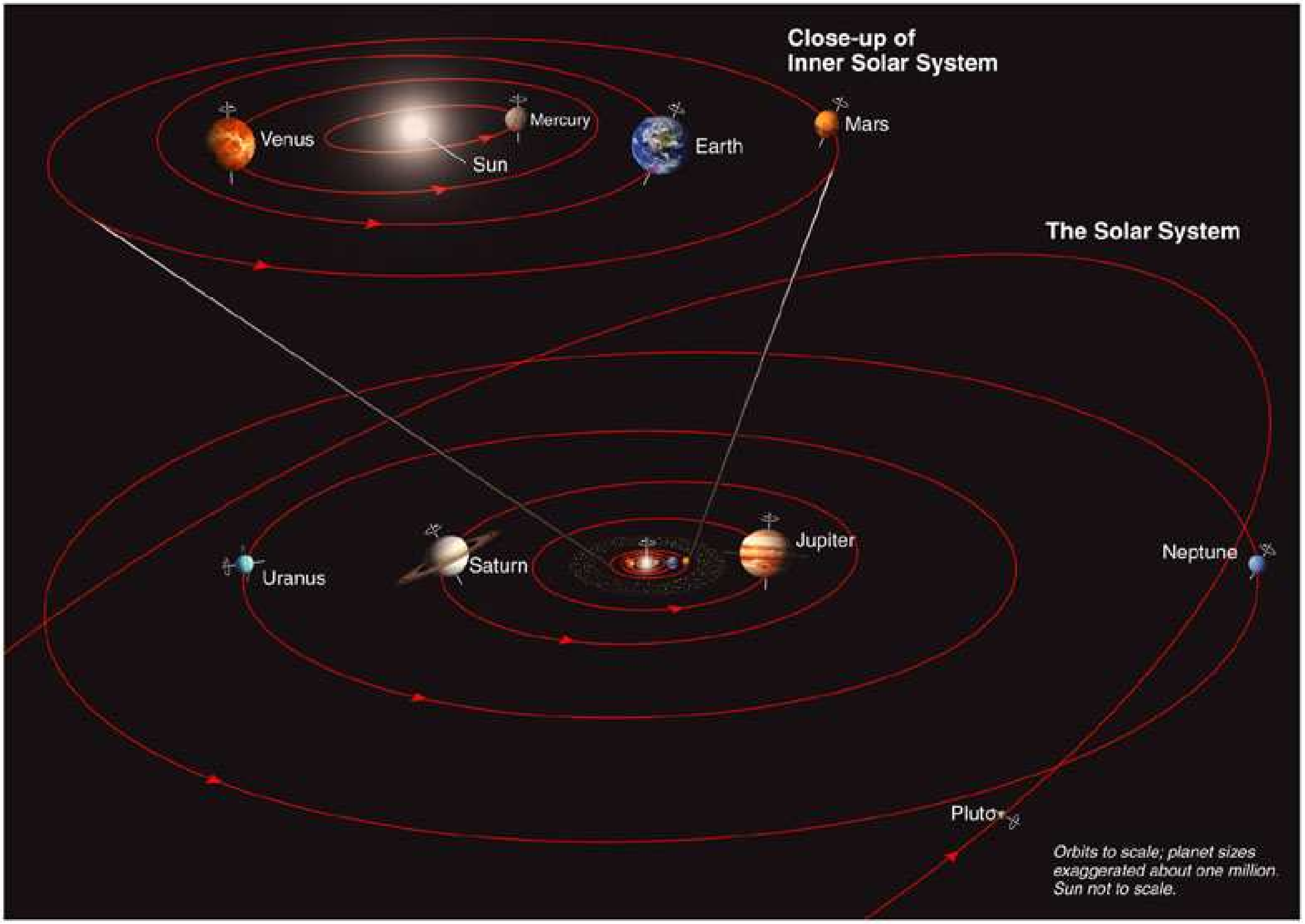
Solar System overview

1) inventory
2) spin/orbit/shape
3) heated by the Sun
4) how do we find out



Inventory

1 star
  (99.9% of M)

8 planets
  (99.9% of L)

- Terrestrial:
  - Mercury
  - Venus
  - Earth
  - Mars
- Giant:
  - Jupiter
  - Saturn
  - Uranus
  - Neptune

Lots of small bodies incl. dwarf planets
  - Ceres
  - Pluto
  - Eris

Inventory (cont'd)

Many moons & rings

Mercury: 0
Venus: 0
Earth: 1 (1700km)
Mars: 2 (~10km)

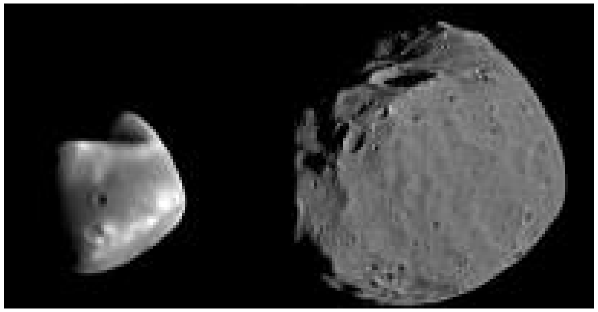
Jupiter: 63 + rings
Saturn: 60 + rings
Uranus: 27 + rings
Neptune: 13 + rings

Even among dwarf planets, asteroids, Kuiper belt objects, and comets. E.g.,

Pluto: 3
Eris: 1

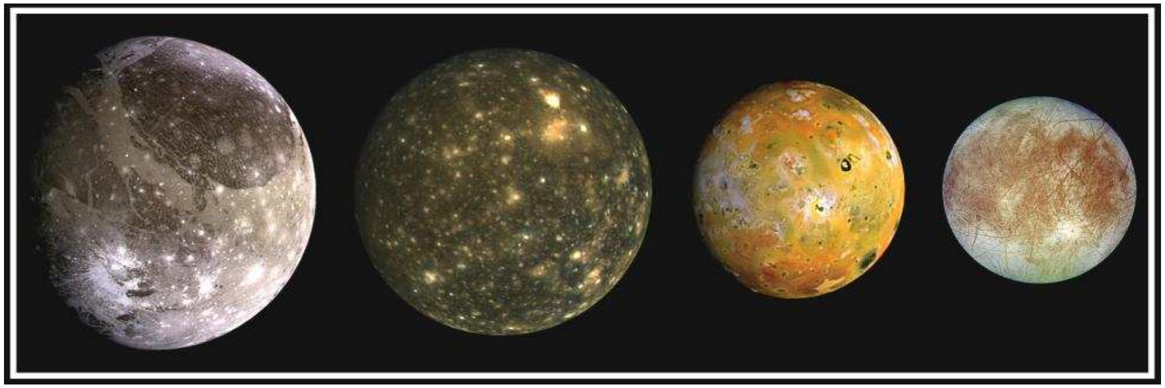
Moons of Mars:

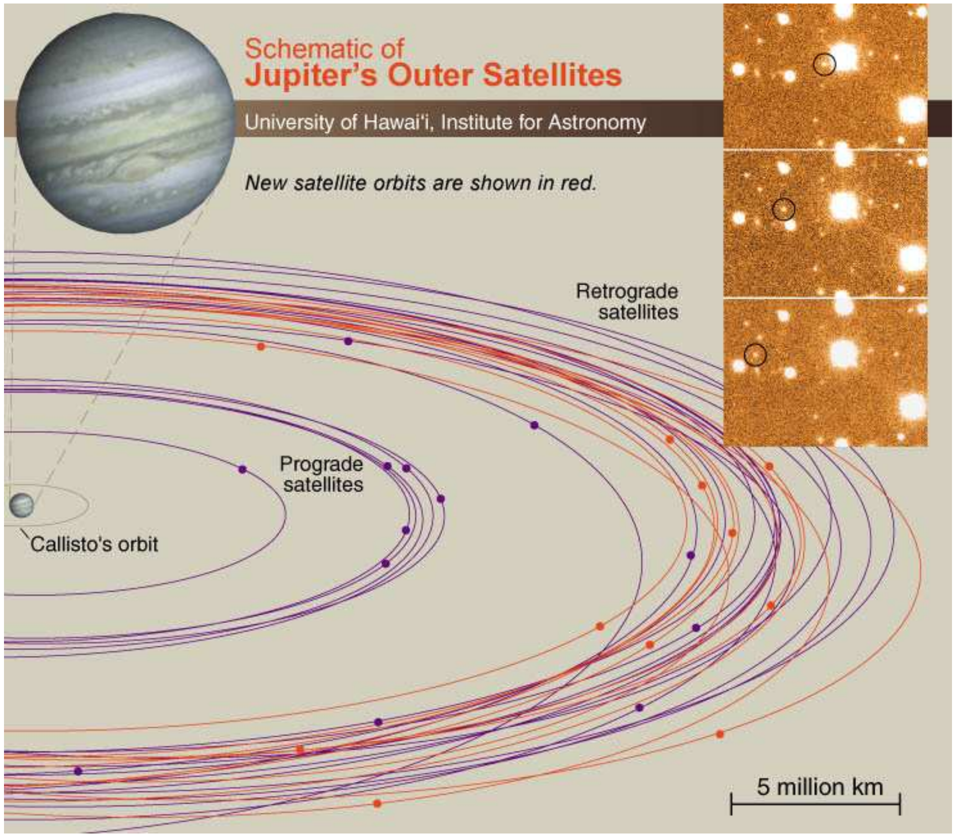
Deimos & Phobos, ~10km



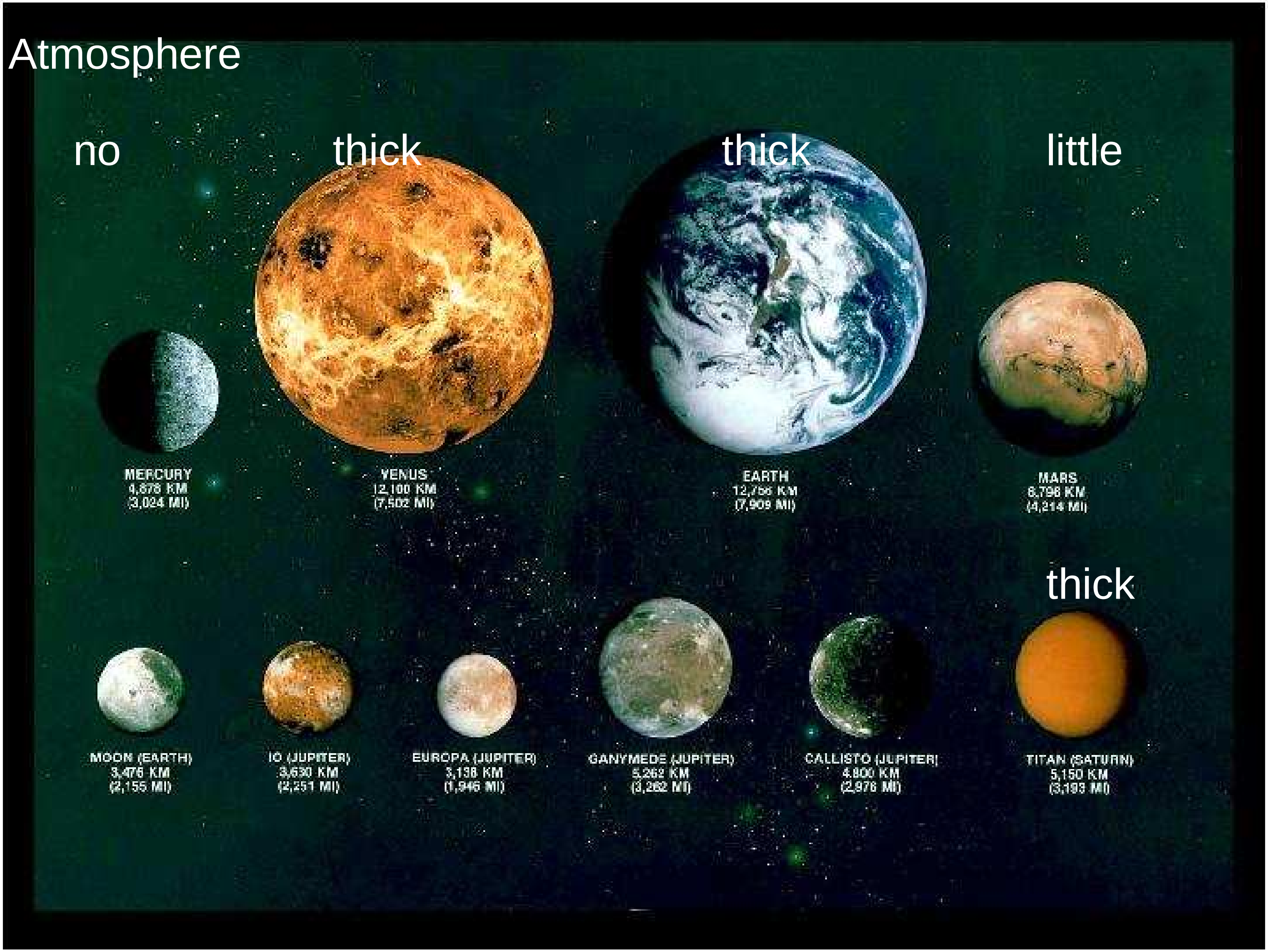
Moons of Jupiter

4 Galilean satellites (Ganymede, Callisto, Io & Europa), ~10^3 km (close to Jupiter, likely primordial)





2001J3: 4km


Atmosphere
no
thick
thick
little
MERCURY
4,878 KM
(3,024 MI)
VENUS
12,100 KM
(7,502 MI)
EARTH
12,756 KM
(7,909 MI)
MARS
6,796 KM
(4,214 MI)
thick
MOON (EARTH)
3,476 KM
(2,155 MI)
IO (JUPITER)
3,630 KM
(2,251 MI)
EUROPA (JUPITER)
3,138 KM
(1,946 MI)
GANYMEDE (JUPITER)
5,262 KM
(3,262 MI)
CALLISTO (JUPITER)
4,800 KM
(2,976 MI)
TITAN (SATURN)
5,150 KM
(3,193 MI)

Inventory (cont'd)

~10^5 known small objects in the

- Asteroid belt
(Ceres ~300 km)

- Kuiper belt
(Eris, Pluto, Sedna, Quaoar, ~1000 km)

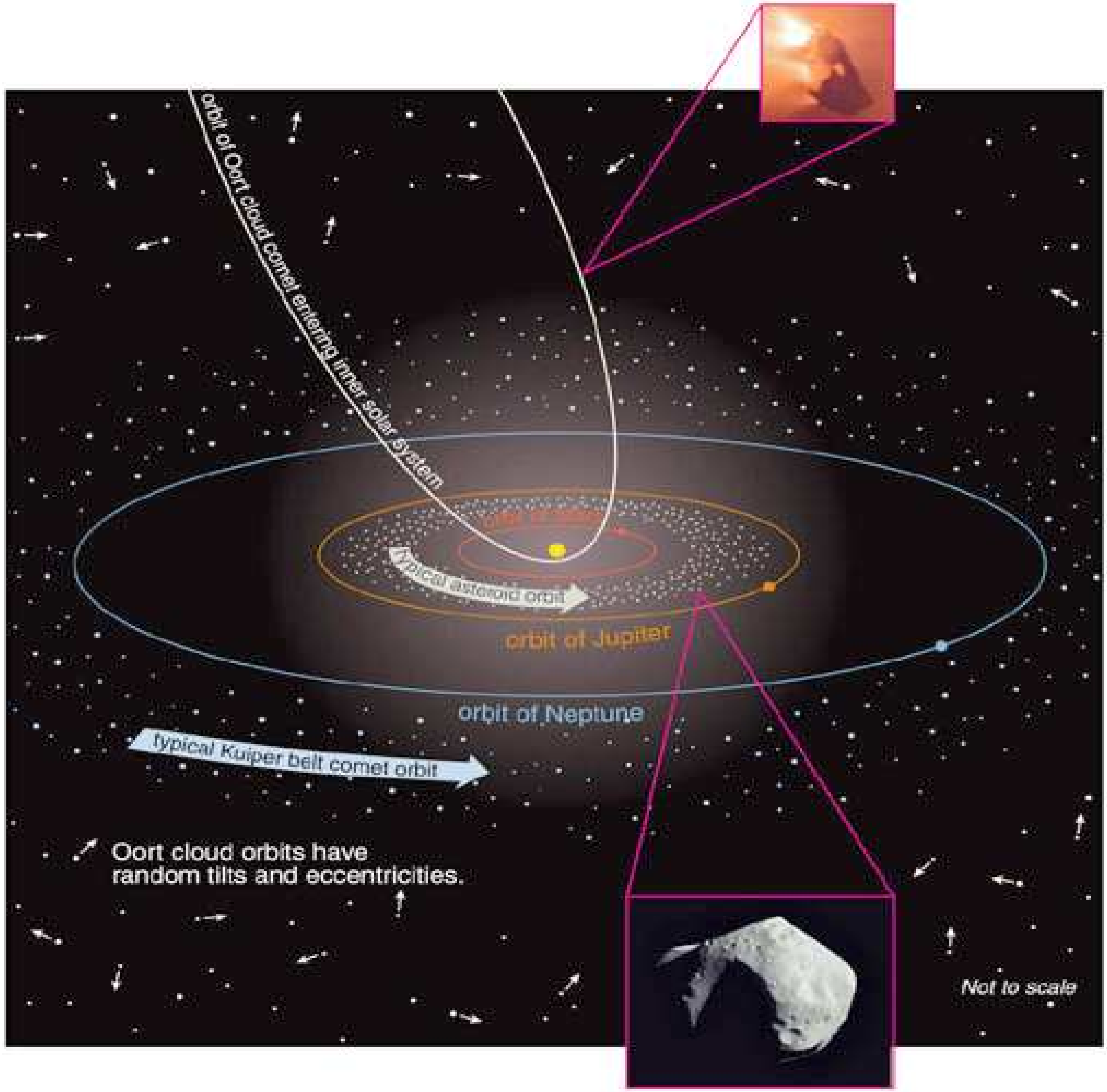
Estimated: ~10^{12} comets in the

- Oort cloud
(~ 10^4 AU)

Associated:

- zodiacal dust

(fire-works on the sky: comets & meteorites)

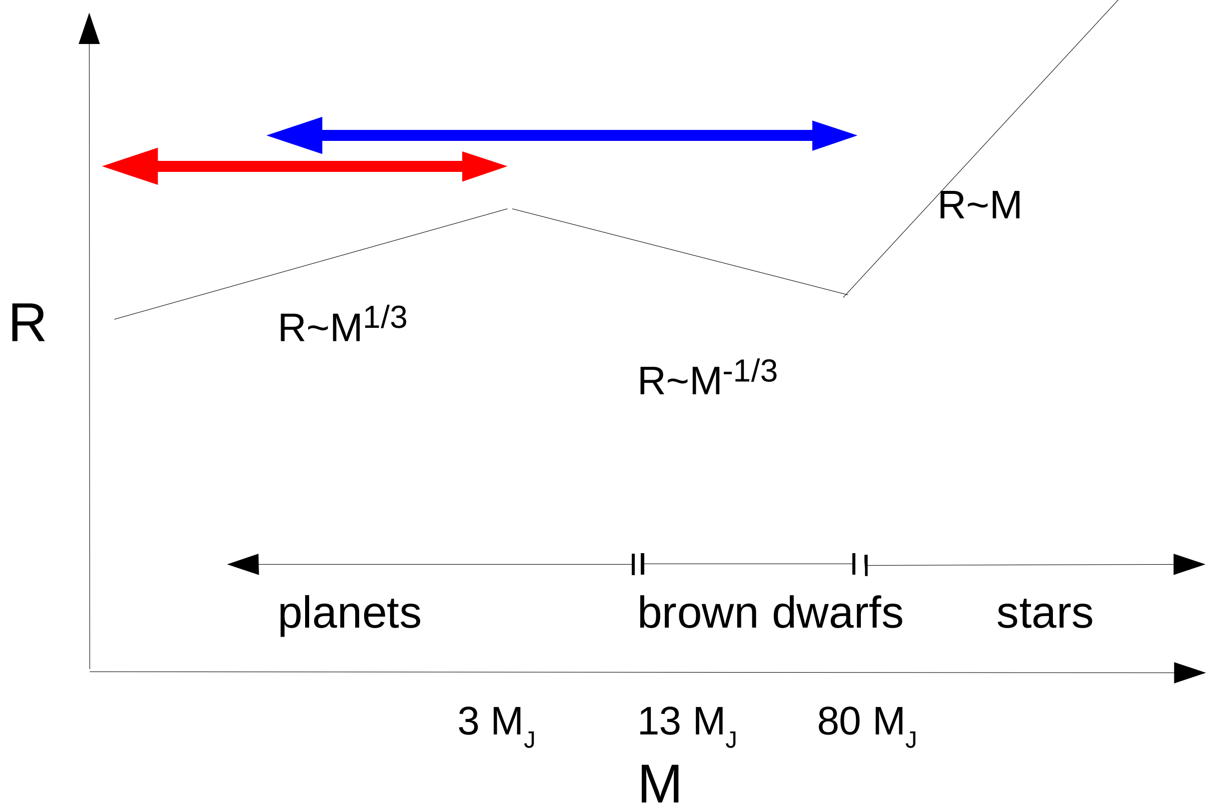


What are planets?

IAU (for solar system):
Orbits Sun, massive enough to be round and to have cleared its neighbourhood.

More general:
1) no nuclear fusion (not even deuterium): $T_c < 10^6$ K
2) pressure provided by electron degeneracy (l ~ h/p ~ d) and/or Coulomb force (d ~ atomic radius)

3) can be solid or gaseous (with solid cores) --- *similar density*

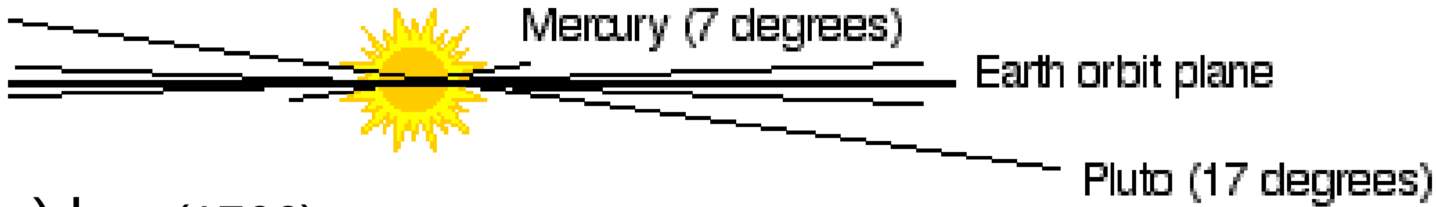


Mass & Mean ρ

	M_J	[g/cm^3]
Jupiter	1.0	1.33
Saturn	0.3	0.77
Neptune	0.05	1.67
Uranus	0.04	1.24
Earth	0.003	5.52
Venus	0.002	5.25
Mars	0.0003	3.93
Mercury	0.0002	5.43

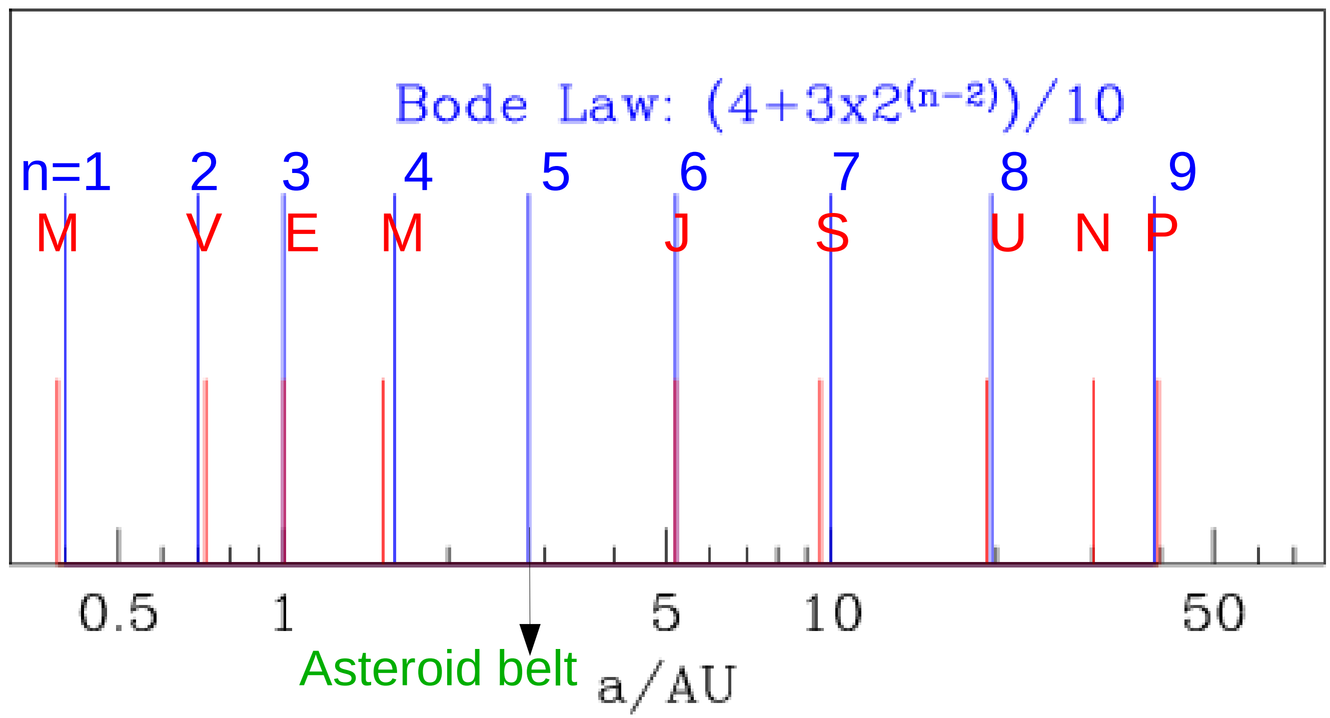
Orbits

inclination: largely coplanar (history)
direction: all the same
eccentricity: a few percent (except for Mercury)



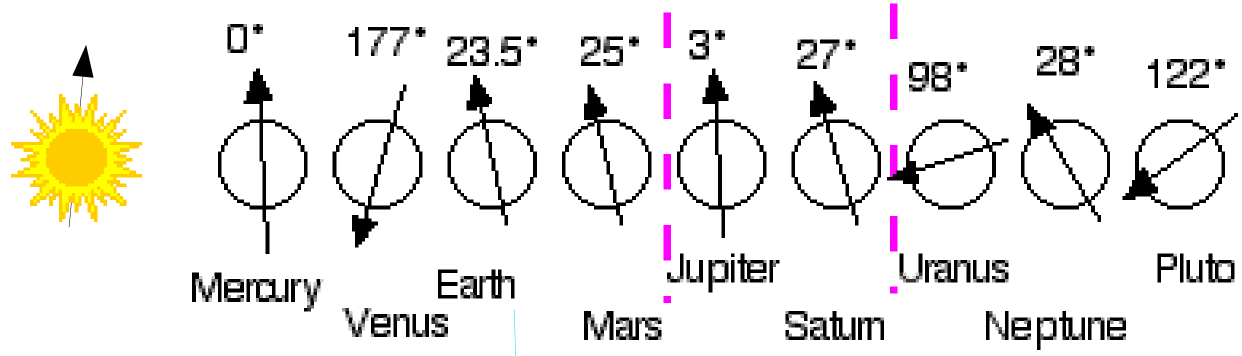
Titus-Bode (fitting) law (1766)

- planetary orbits appear to (almost) satisfy a single relation
- 'Predict' the existence of the asteroid belt (1801: Ceres discovered)
- coincidence or something deeper?
- other systems?



computer simulations indicate that planets are as maximally packed as allowed by stability

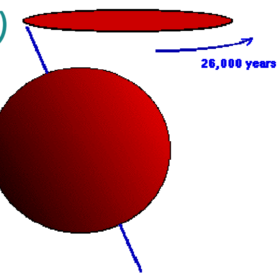
Spin (obliquity)



smaller planets:
almost random, affected by impacts and giant planets

Real giant planets (J&S):
~aligned with orbit, stable

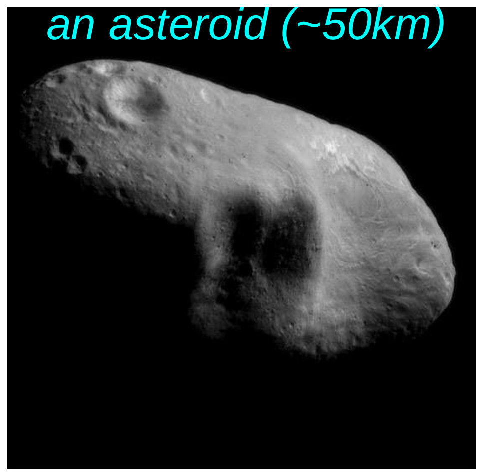
Earth's spin-axis precesses (mildly) while Mars sweeps around wildly



Shape *--- the bigger the rounder*

All gaseous planets are spherical.
Large rocky objects are rather spherical. Smaller ones are less so.

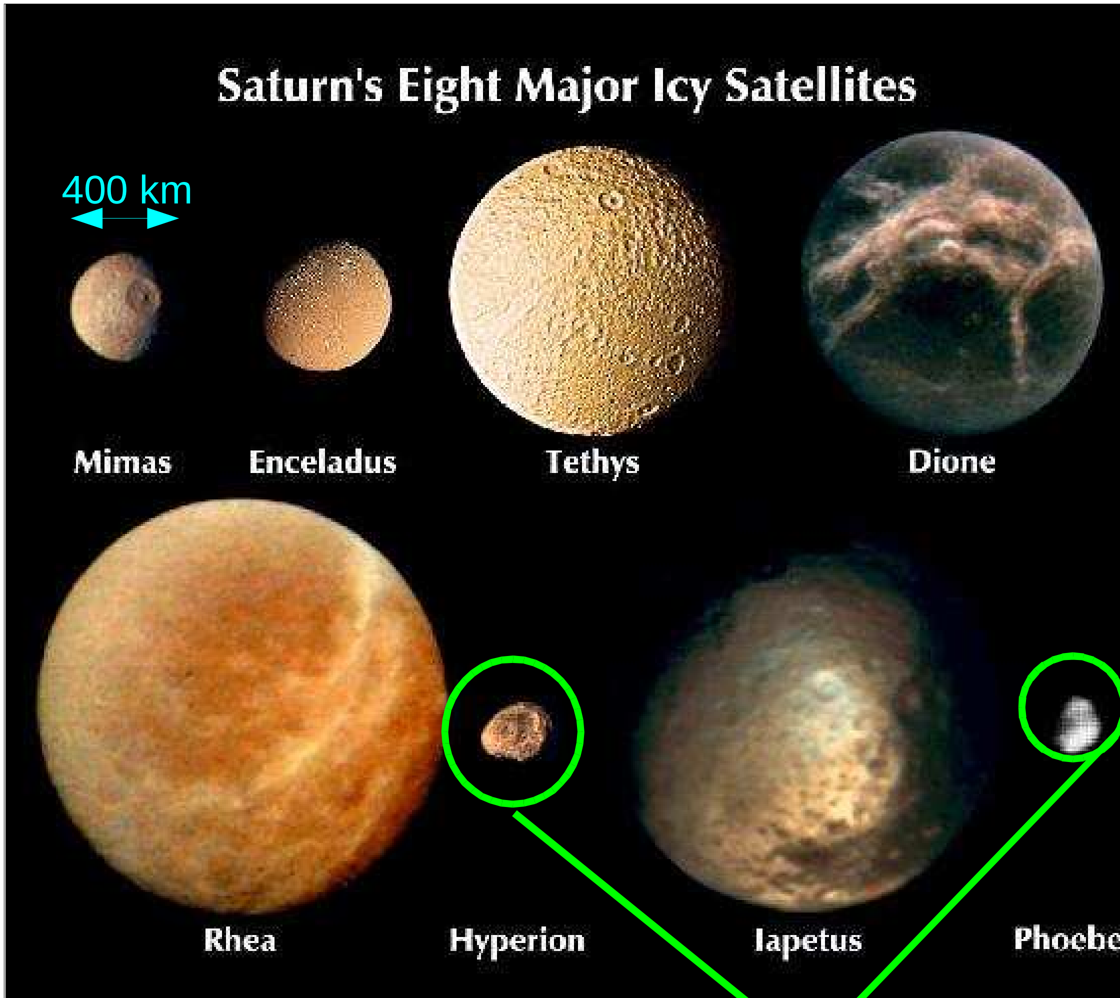
The Moon (~1700km)



an asteroid (~50km)

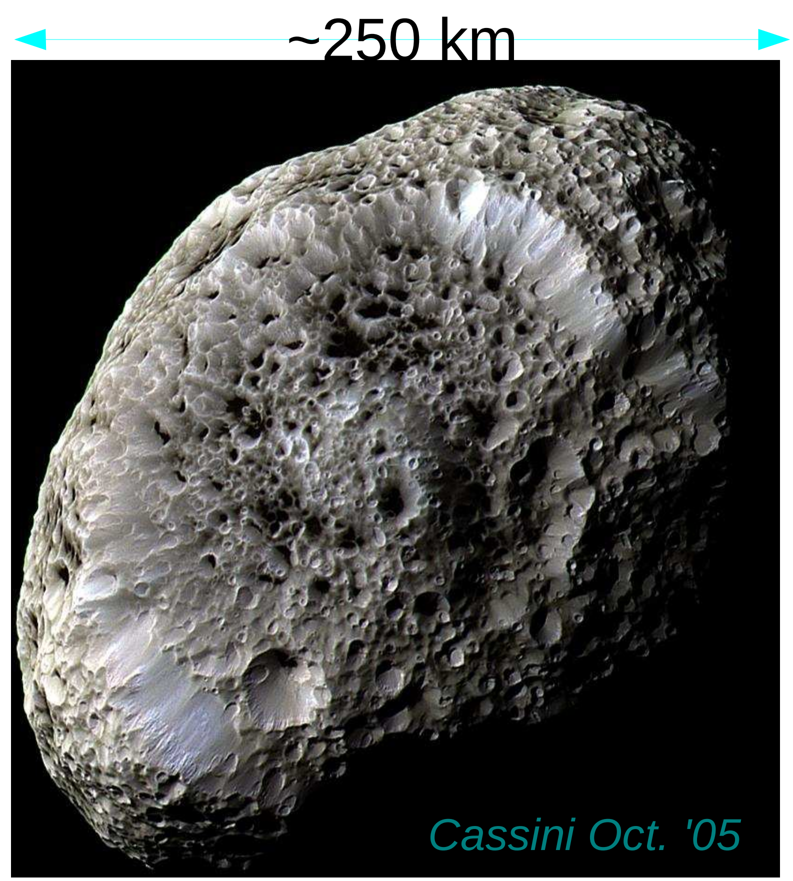
	h (km)	R (km)	$g=GM/R^2$ (m/s^2)
Earth	8	6400	9.8
Mars	24	3400	3.7

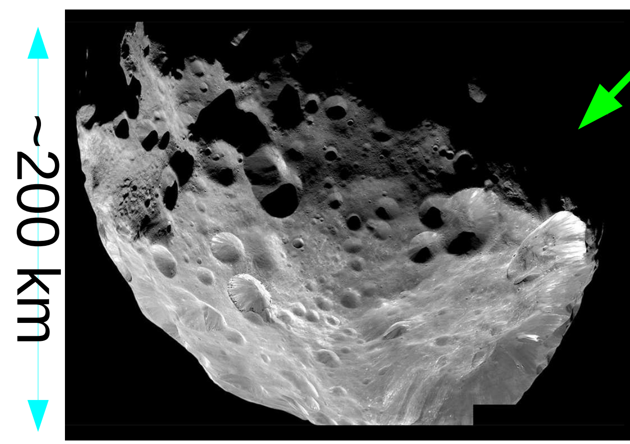
scaling: highest mountain on Earth ~8 km (on Mars ~ 24 km) **h * g ~ constant**
rough estimate: irregular body has mountain h ~ R ==> R ~ 240 km
thus: objects with R > 240 km are approximately spherical



The bigger the rounder

	$\Delta R/R$	$g=GM/R^2$
Earth	8/6400	9.8 m/s^2
Mars	24/3400	3.7 m/s^2
Hyperion:	150/250	~0.4 m/s^2





Passively Heated by the Sun *--- the further the cooler*

Typically we observe objects in reflected light, however, all objects emit re-processed thermal radiation which is observable at longer wavelengths.

Blackbody temperature for a non-self-luminous spherical body at distance ***a*** away from the Sun (with albedo *A* -- reflectivity)

$$L_{abs} = (1-A)\frac{\pi R_p^2}{4\pi a^2}\; 4\pi R_s^2 \sigma T_s^4; \qquad L_{em} = 4\pi R_p^2 \sigma T_p^4$$

If $L_{abs} = L_{em}$, then

$$T_p = \left(\frac{R_o}{2a}\right)^{1/2} T_s (1-A)^{1/4}$$

	a (AU)	A	T_{pred}(K)	T_{act}(K)	
Mercury	0.4	0.06	422 K	100-725	(?)
Venus	0.7	0.77	230K	733	(?)
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Jupiter	5	0.51	113K	125	(?)
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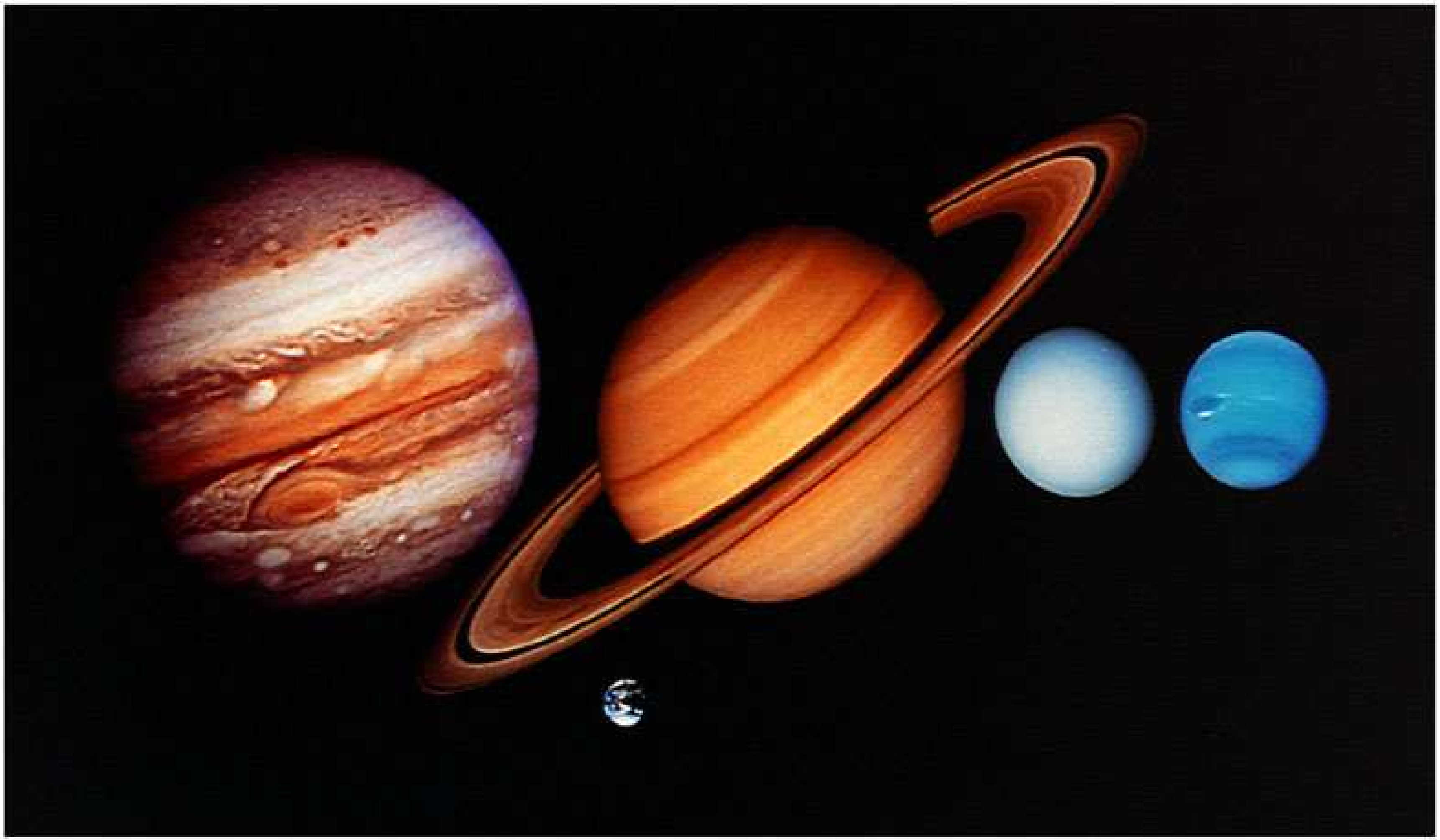
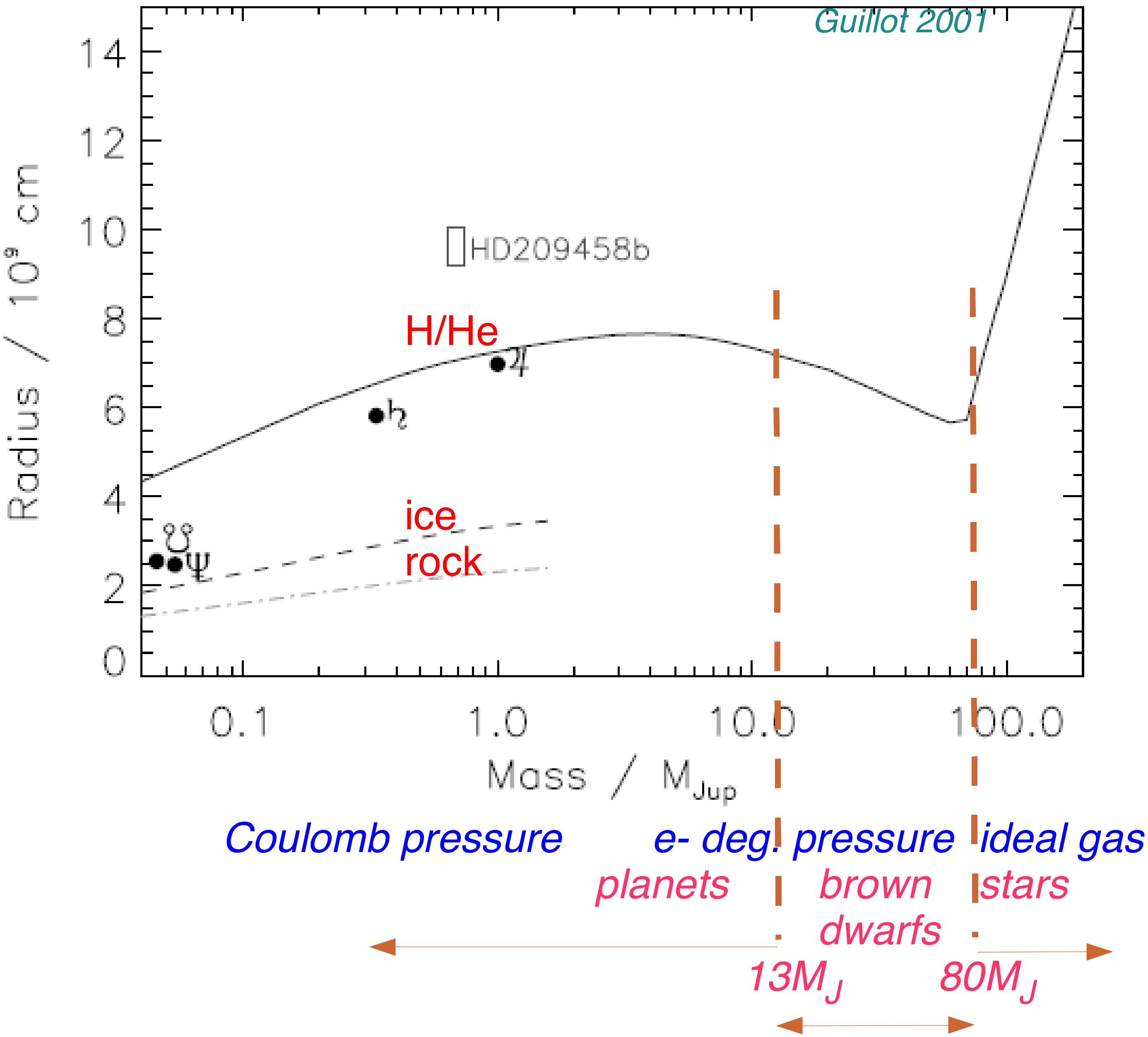
Comet at	5000	0.51	3.4K		

Giant Planets



made mostly of H, He and H-compounds, no solid surface
99.5% planet mass, 99.8% solar system angular momentum

Giant planets border stars



Equation of state determines mass-radius relation

Ideal gas: $P \propto \rho T$

+Fusion: $T_{core} \sim$ Const

$\rightarrow \quad R \propto M$

el. degeneracy: $P \propto \rho^{5/3}$

$\rightarrow \quad R \propto M^{-1/3}$

Coulomb: $\rho \sim$ Const

$\rightarrow \quad R \propto M^{1/3}$

Working definition:
Brown-dwarfs are 'failed' stars that cannot ignite hydrogen (but can burn deuterium); hence $M < 80\ M_J$ $(0.08\ M_\odot)$

Planets are formed in disks around stars. Planets cannot burn deuterium (10^6 K); hence $M < 13\ M_J$

Are planets just gas balls like stars? Probably not.

Jupiter & Saturn: largely degenerate H & He, mean ρ = 1.3 & 0.7 g/cm^3

-- hydrogen metallic (conductive) below certain depth (?)

-- core: solid, heavy metal + ices

Jupiter's core: < 10 M_E (or 0?); Saturn's core: ~ 13 M_E (15% of mass)

Uranus & Neptune: largely ices (H_2O, CH_4, NH_3), mean ρ = 1.2 & 1.7 g/cm^3

-- relatively thin gaseous H & He envelope

-- mostly icy + rocky core

Why do we care about the solid cores?

Formation of giant planets likely starts with a solid core – unlike stars

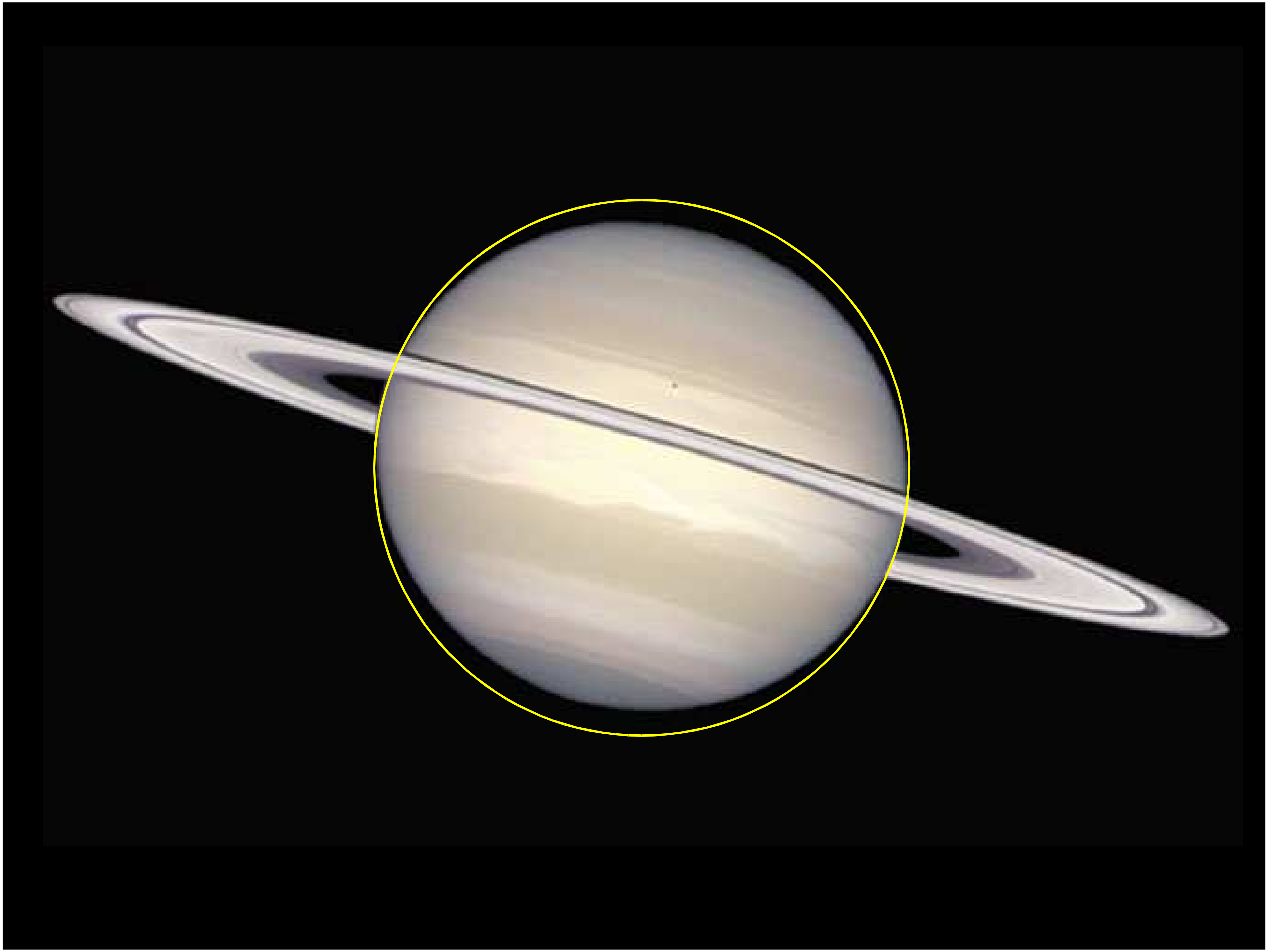
How do we figure out about the cores? Spin it!

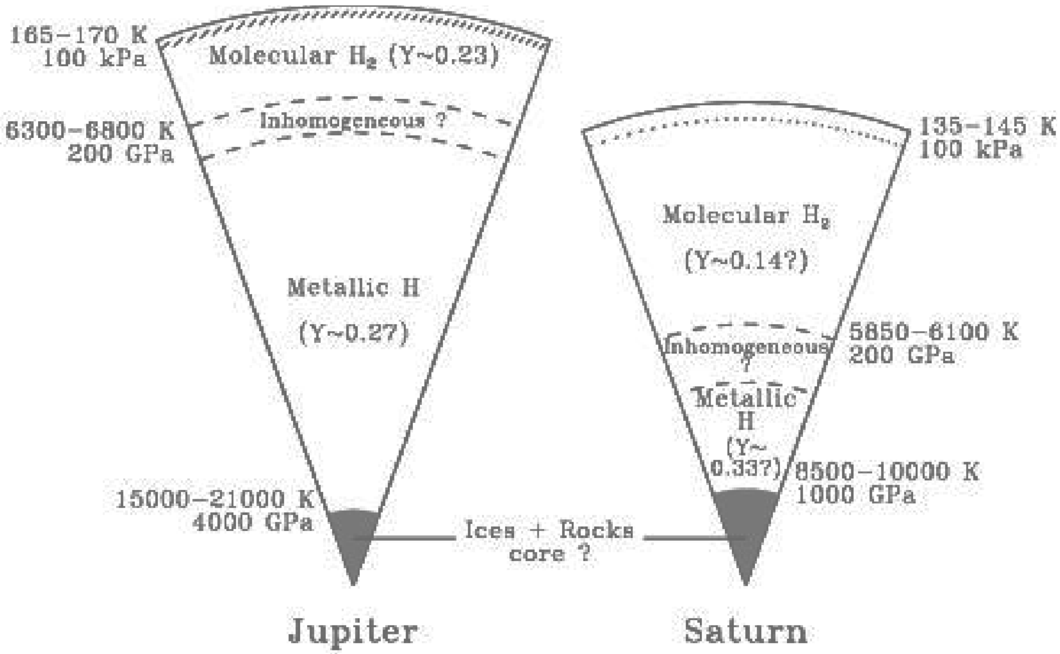
core: a high density central region

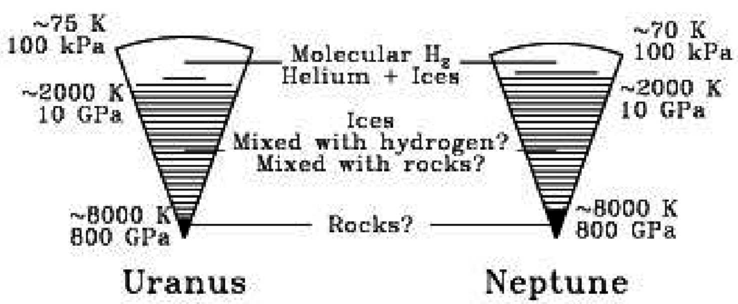
spherical body: gravitational potential is independent of density profile

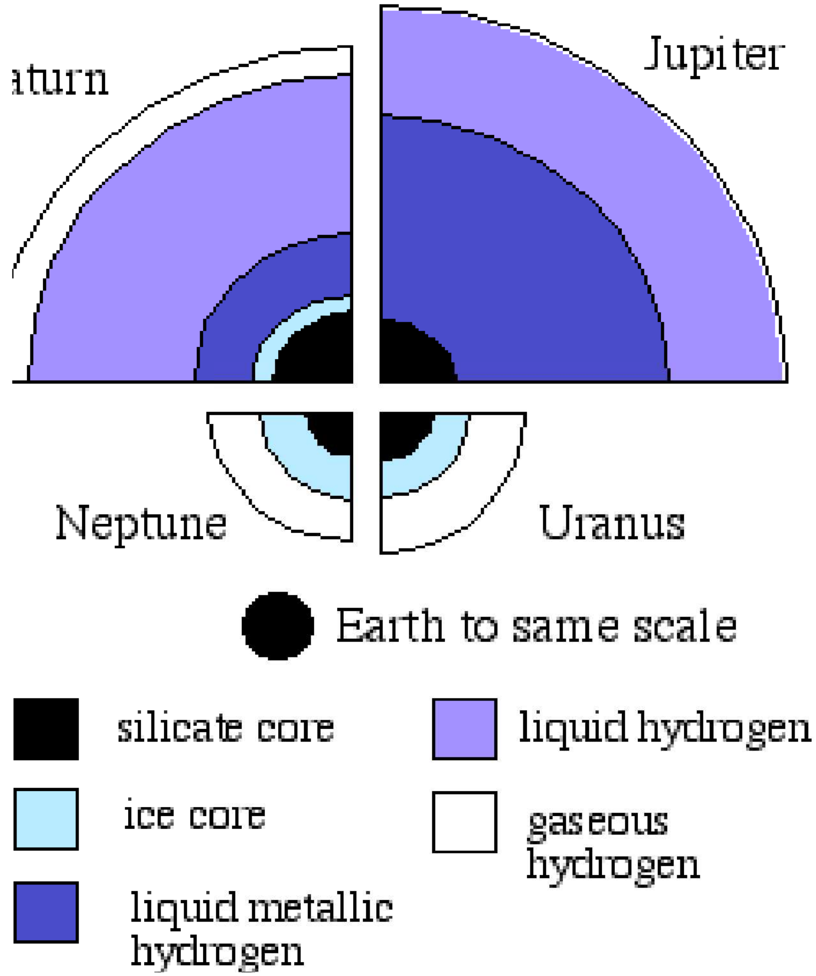
but when the planet rotates, it oblateness depends on $\rho=\rho(r)$

$$\Phi(\theta) = -\frac{GM}{r}\left[1 - \left(\frac{R}{r}\right)^2 J_2 P_2(\cos\theta) - \left(\frac{R}{r}\right)^4 J_4 P_4(\cos\theta) - \ldots\right]$$









Cores of giant planet are likely
primordial and do not form
by gravitational settling.
Did Jupiter melt part of its core?

Energy budget for giant planets

Absorb solar flux: $(1-A)\,4\pi R_o^2 \sigma T_o^4 \times \frac{\pi R_p^2}{4\pi a^2}$

Emit blackbody flux: $4\pi R_p^2 \sigma T_p^4$

$$T_p = (1-A)^{1/4} \left(\frac{R_o}{2a}\right)^{1/2} T_o$$

	Jupiter	Saturn	Uranus	Neptune
passive T_p	113K	83K	60K	48K
actual T_p	130K	95K	59K	59K
$L_{total}/L_{received}$	1.7	1.8	1.0	2.6

3 sources of planetary intrinsic luminosity: primordial + settling + radio-active

Jupiter: **primordial heat** + He settling relative to H
(very long thermal time-scale: ~ 10^9 yrs)

Saturn: primordial heat + He settling relative to H

Uranus: no additional source required

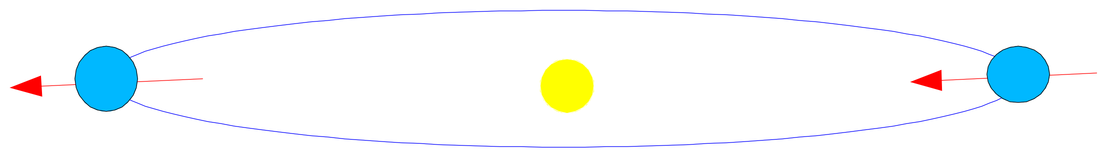
Neptune: Do require add'l source; but so similar to Uranus, so why?

--- what about gravitational contraction? No, already shrunk
--- terrestrial planets: radio-active elements
--- how much energy can you gain by separating H & He?

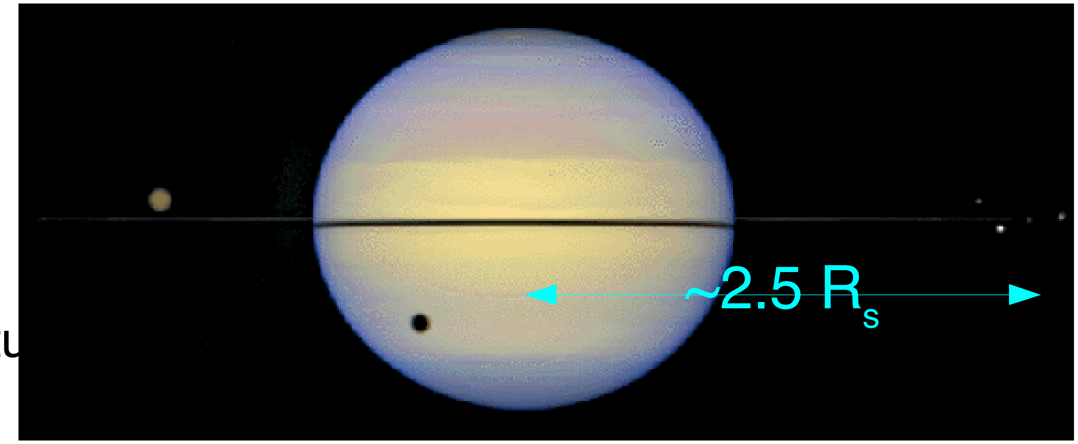
Other cool points?

1) magnetic fields: all 4 have appreciable B fields, Jovian aurorae,
Jupiter's magnetic influence extends past Saturn orbit
generation of these fields -- primordial or dynamo?

2) seasons:
Uranus: 97.92° inclined relative to orbit, very weird seasons!

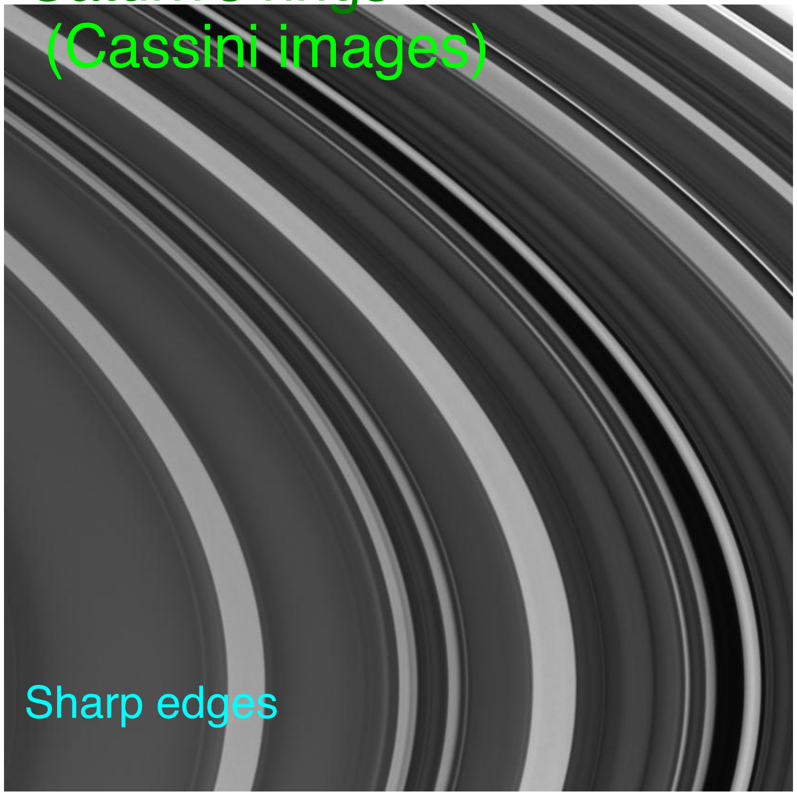


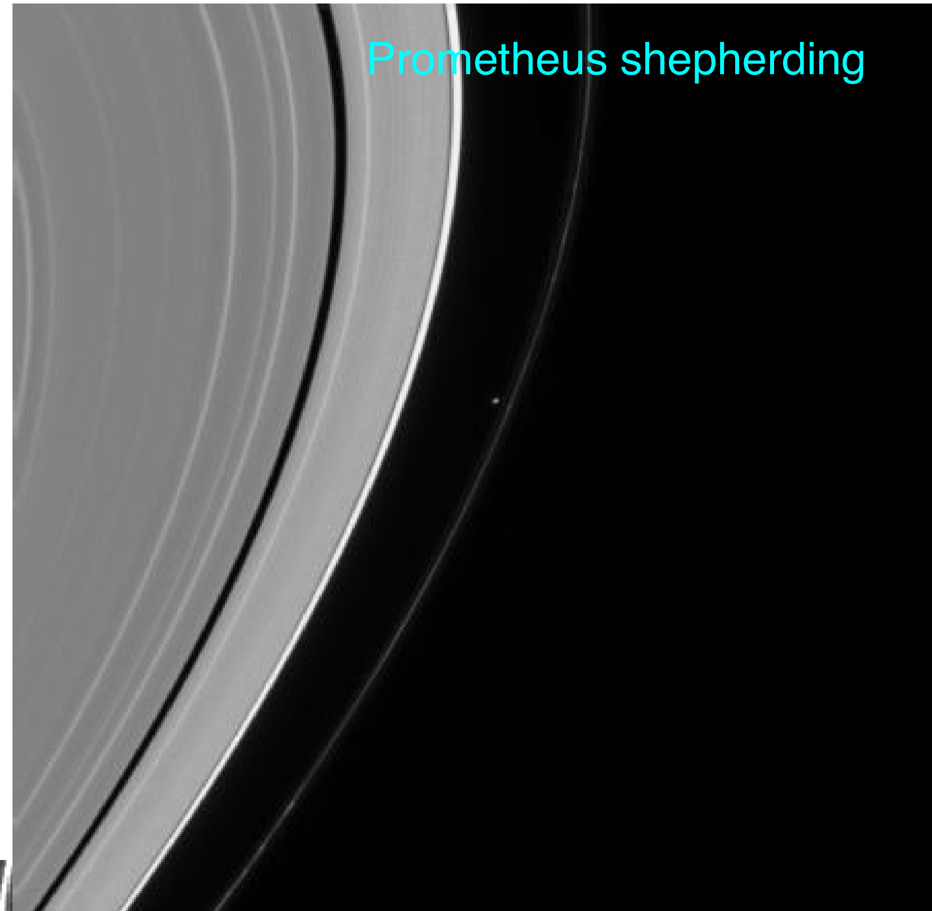
3) rings & satellites: all 4 have rings and many satellites
rings: sandy or icy dust and some boulders, 2.5 planet radii (~Roche radius)
-- $H/R \sim 10^{-6}$ *(a razor blade?)*
--- gaps: shepherding moons
-- origin: tidally disrupted satellites
or primoridal?

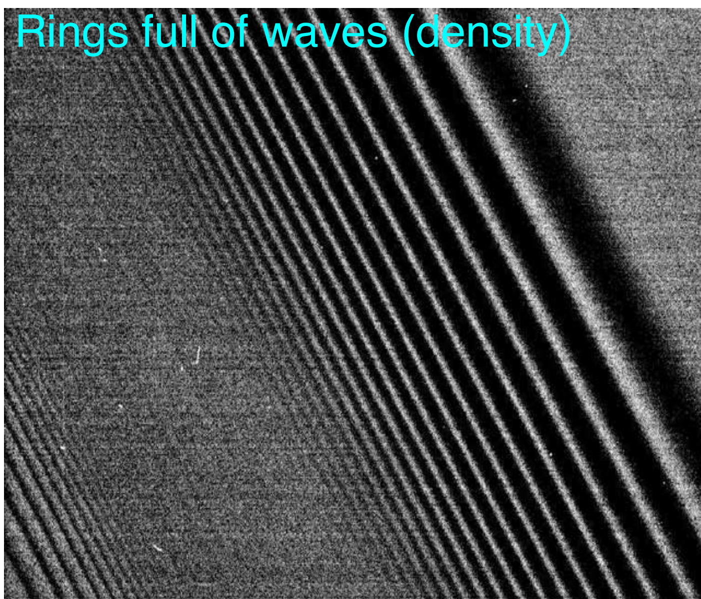


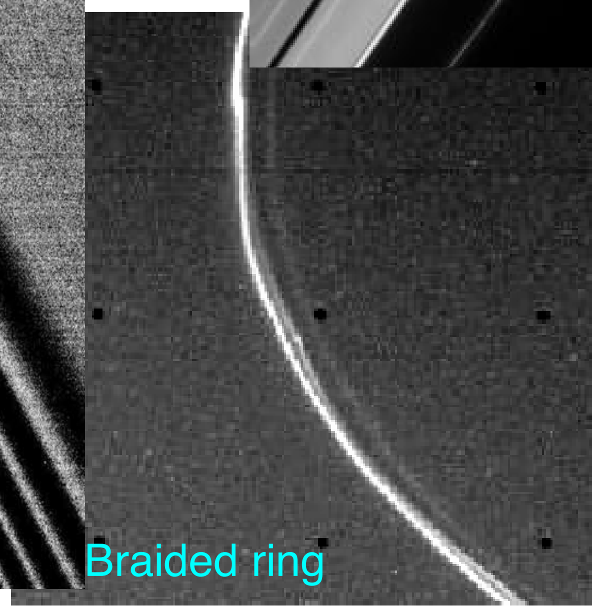
Satellites: worlds of their own
captured (Phoebe) or formed in-situ
Europa (@J): cracky surface
underground H_2O ocean
Titan (@S): smoggy atmosphere
surface H-compound ocean?

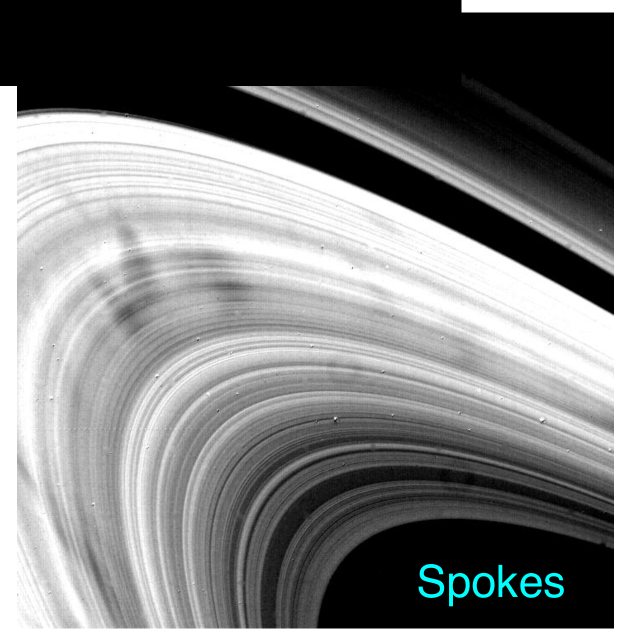
Saturn's rings (Cassini images)

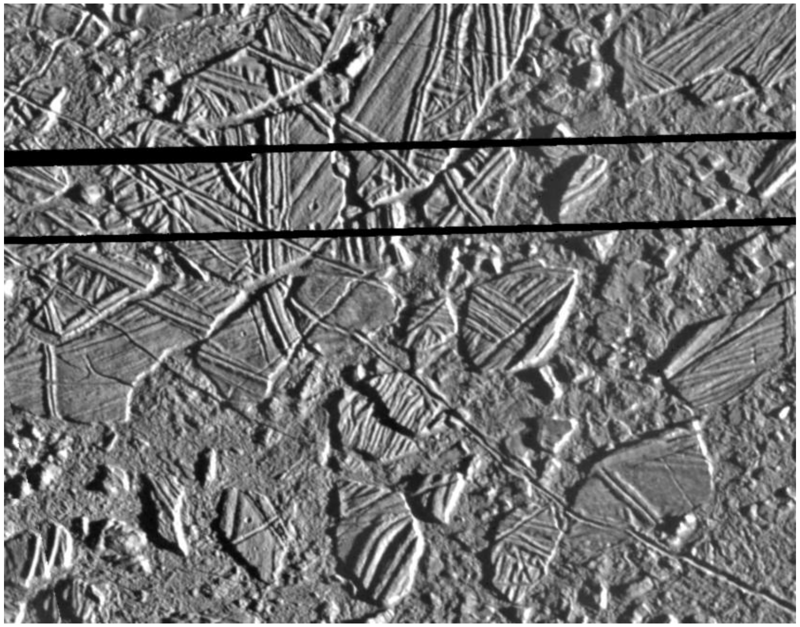


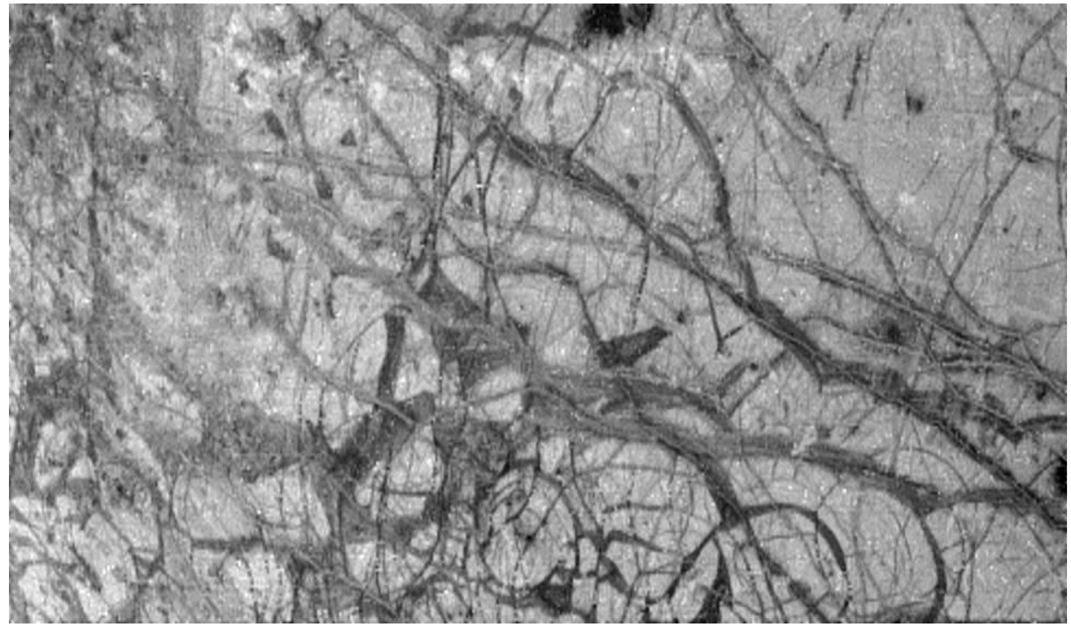


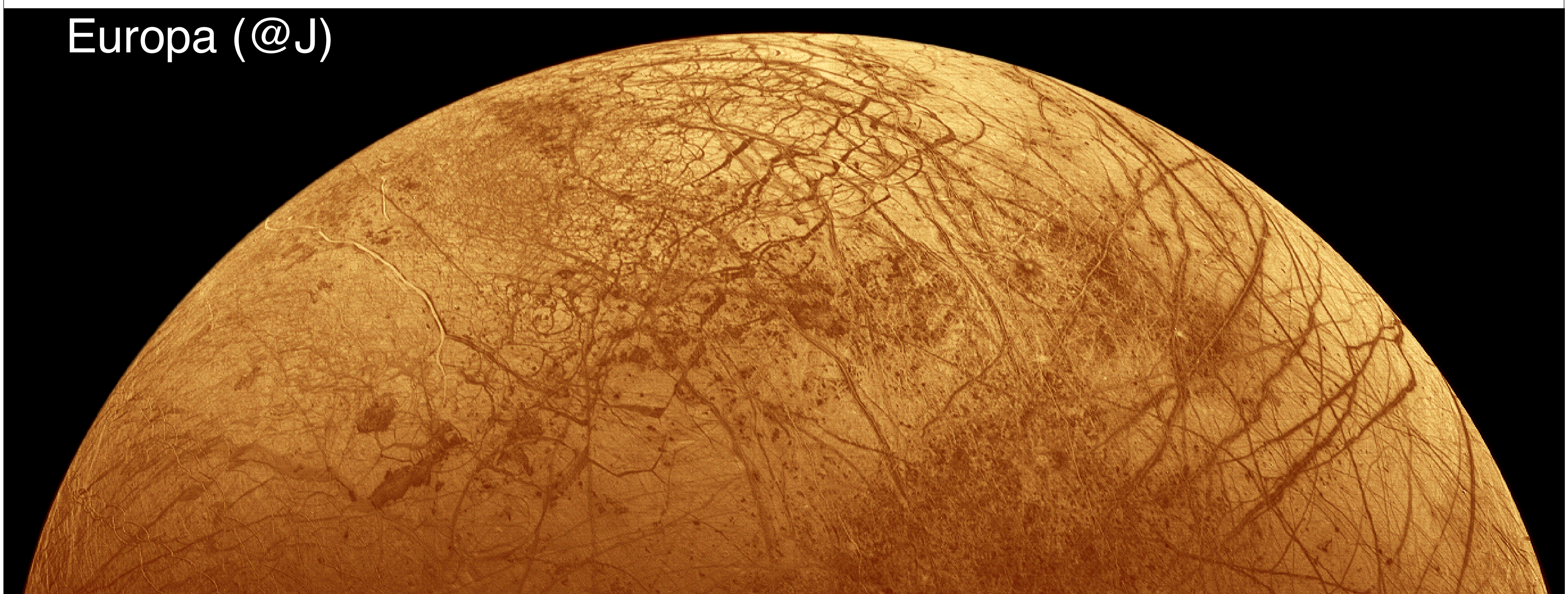






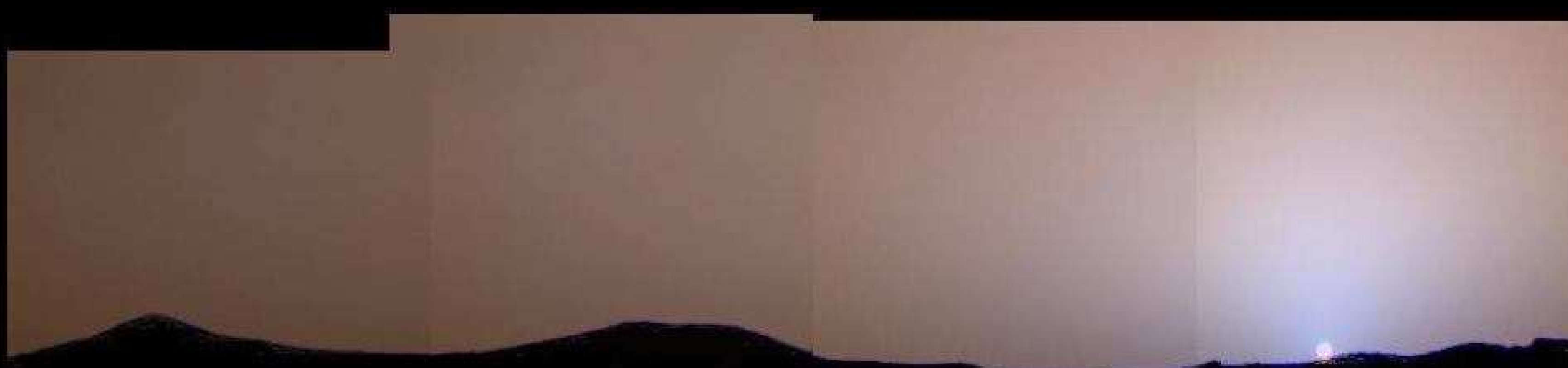





Europa (@J)

Planetary Atmospheres

1) Densities, temperatures
2) Origin of terrestrial planet atmospheres
3) Optics: colour, clouds
4) What happened to Venus?



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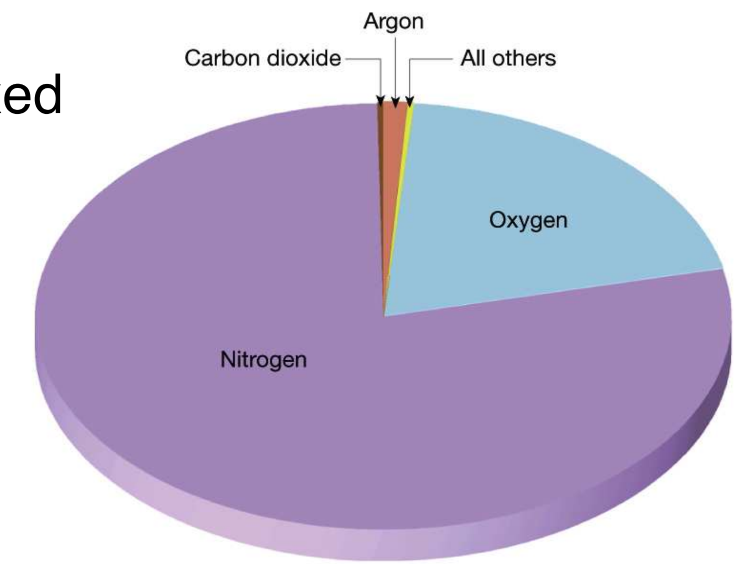
Atmospheres: Terrestrial Planets

	Atm. Composition	surface pressure/T	
Mercury	--	$< 10^{-12}$ bar	100-725 K
Venus	97% CO_2, 3% N_2	92 bar	733 K (460°C)
Earth	78% N_2, 21% O_2,1% Ar	1 bar	288 K (15°C)
Mars	95% CO_2,3% N_2,1.6% Ar	0.006 bar	223 K (-50°C)
Titan (@S)	95% N_2, few% CH_4,Ar	1.5 bar	93 K (-180°C)

Most atmospheres are reasonably well-mixed (no molecular weight separation)



Earth's atmospheric composition
From http://www.ux1.eiu.edu/~cfjps/1400/atmos_origin.html

Density & Temperature of our atmosphere

1) Temperature largely **isothermal;**
density decreases exponentially, H ~ 8 km

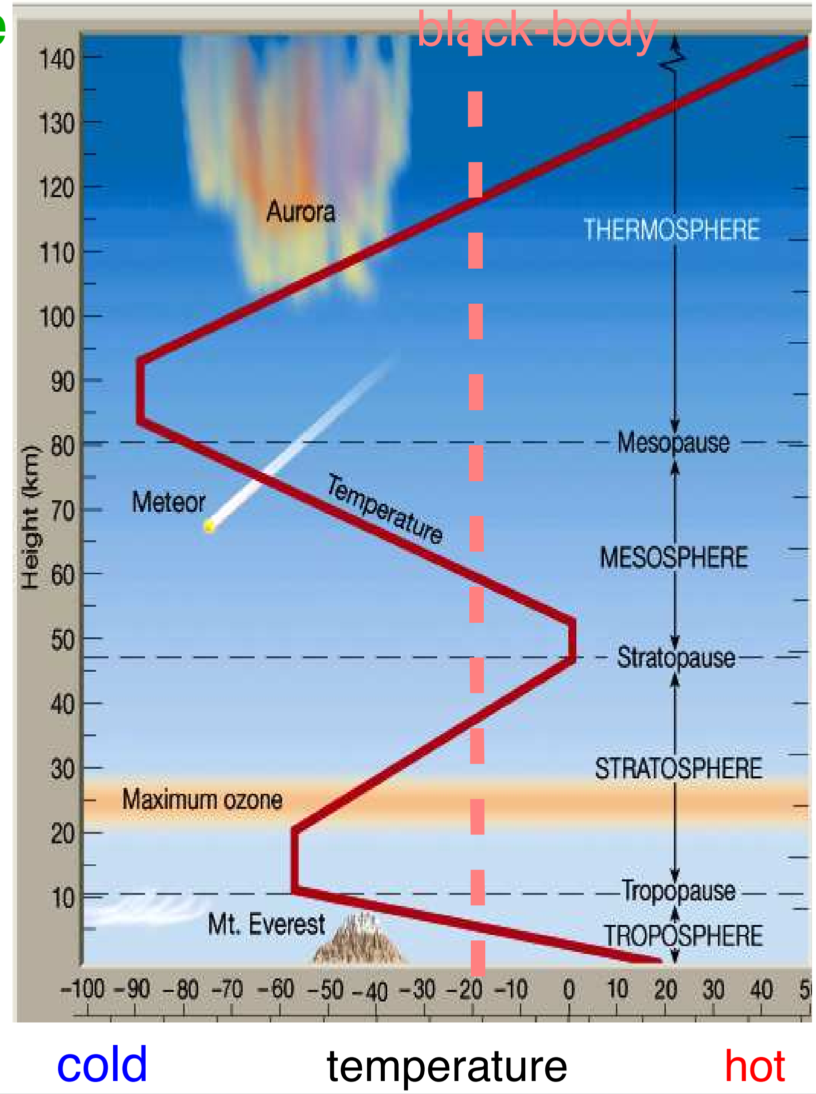
Three local departures (T maxima)

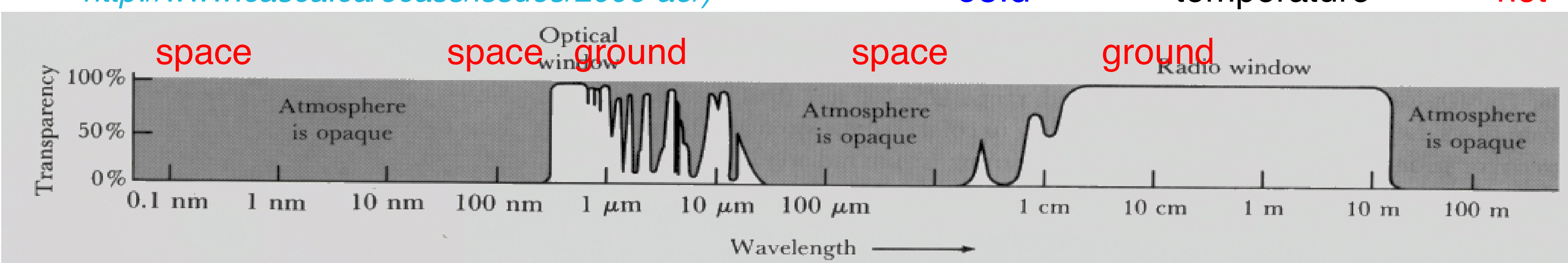
- Thermosphere absorbs X rays (~2000 K)
- Stratosphere absorbs UV (O_3)
- Ground absorbs whatever passes

2) Atmosphere largely transparent in optical,
but opaque in infrared --> green-house effect

- Troposphere heated by ground--> turbulent --> twinkling stars, planes fly @ ~ 10km
- Astronomical observations:
overcome turbulence & avoid absorption

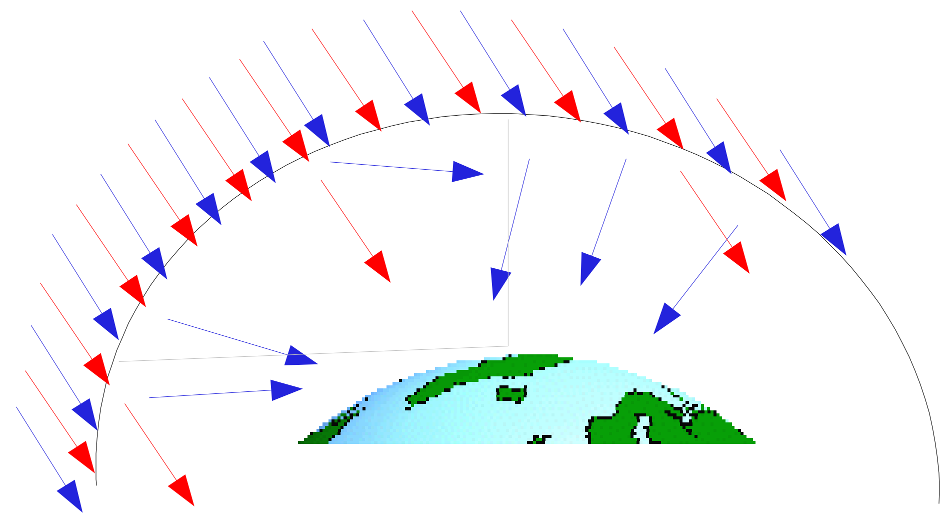
(for Canadian Arctic site-testing, see http://www.hia-iha.nrc-cnrc.gc.ca/atrgv/inuksuit_e.html, http://www.casca.ca/ecass/issues/2006-ae/)





Atmospheric optics: I) Why is the sky blue on Earth? Rayleigh scattering

air molecules & other constituents (N_2, O_2, H_2O droplets, dust...) all have sizes smaller than optical λ, and they preferentially scatter short-λ photons: $\sigma \sim 1/\lambda^4$



Earth: *sky is blue (--> ocean blue)*
sunset is red (reddened)
horizon whiter than zenith
Fall/Winter sky dark blue
UV is diffuse

	x	y	sRGB pixel color
Sun above atmosphere	0.3259	0.3379	#fff3ea
5770 K blackbody *(a Sun approximation)*	0.3287	0.3397	#fff1e6
Illuminant B *("direct sunlight")*	0.3840	0.3516	#ffbfaa

Moon: *sky is black*

Mars: *sky is reddish yellow*

fine-dust (1-10μm) Mie scattering --> white
iron oxide mineral absorption in the blue --> reddish

Atmospheric optics: II) Clouds

What are clouds?

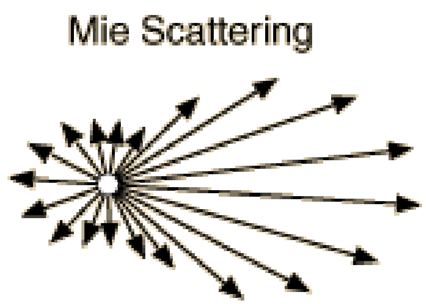
Aggregates of water or ice droplets suspended in air
In troposphere: low clouds-- water; high clouds-- ice

How do they form?

100% hum. + condensation nuclei (dust, cosmic-rays)
e.g., rising air that cools (--> humidity increases)

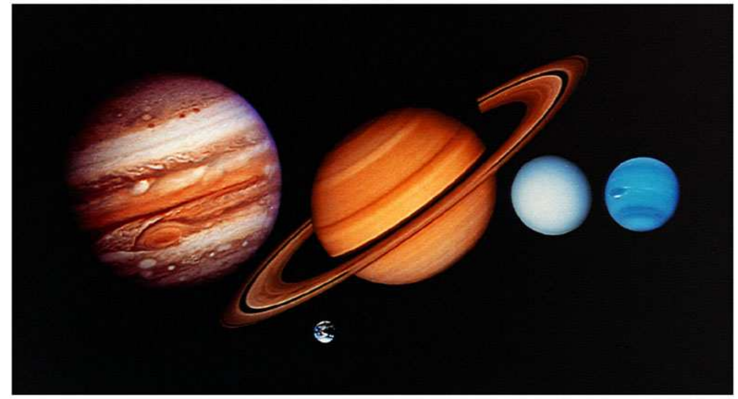
Why are clouds white?

Water droplet colorless, solar light white
Mie scattering (droplets size r ~ 10μm > λ),
nearly geometric optics, no λ dependence
(at sunset, cloud is red)
soap foam: geometric scattering, also no λ dep.



Why don't clouds fall from the sky?
Tiny droplets, fall slowly; updraft mixing?
Fall and evaporate and form new ones?
Electrically charged clouds?

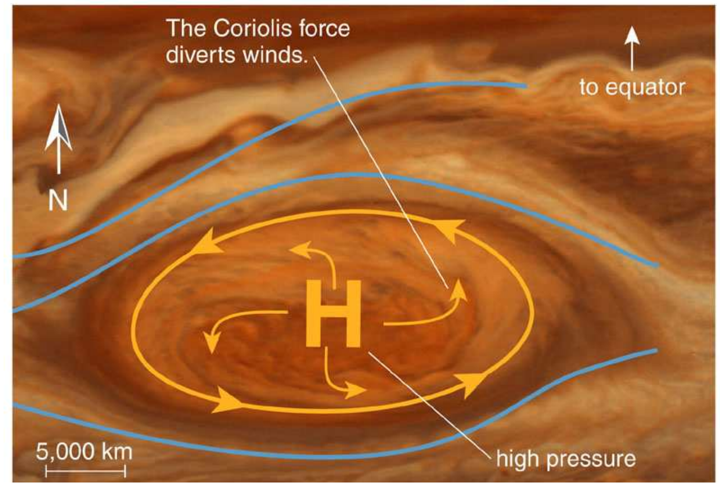
Intermezzo: Gas giant atmospheres



All 4 have deep atmospheres with mostly H_2 & He

(fractions in % by volume, not by mass)

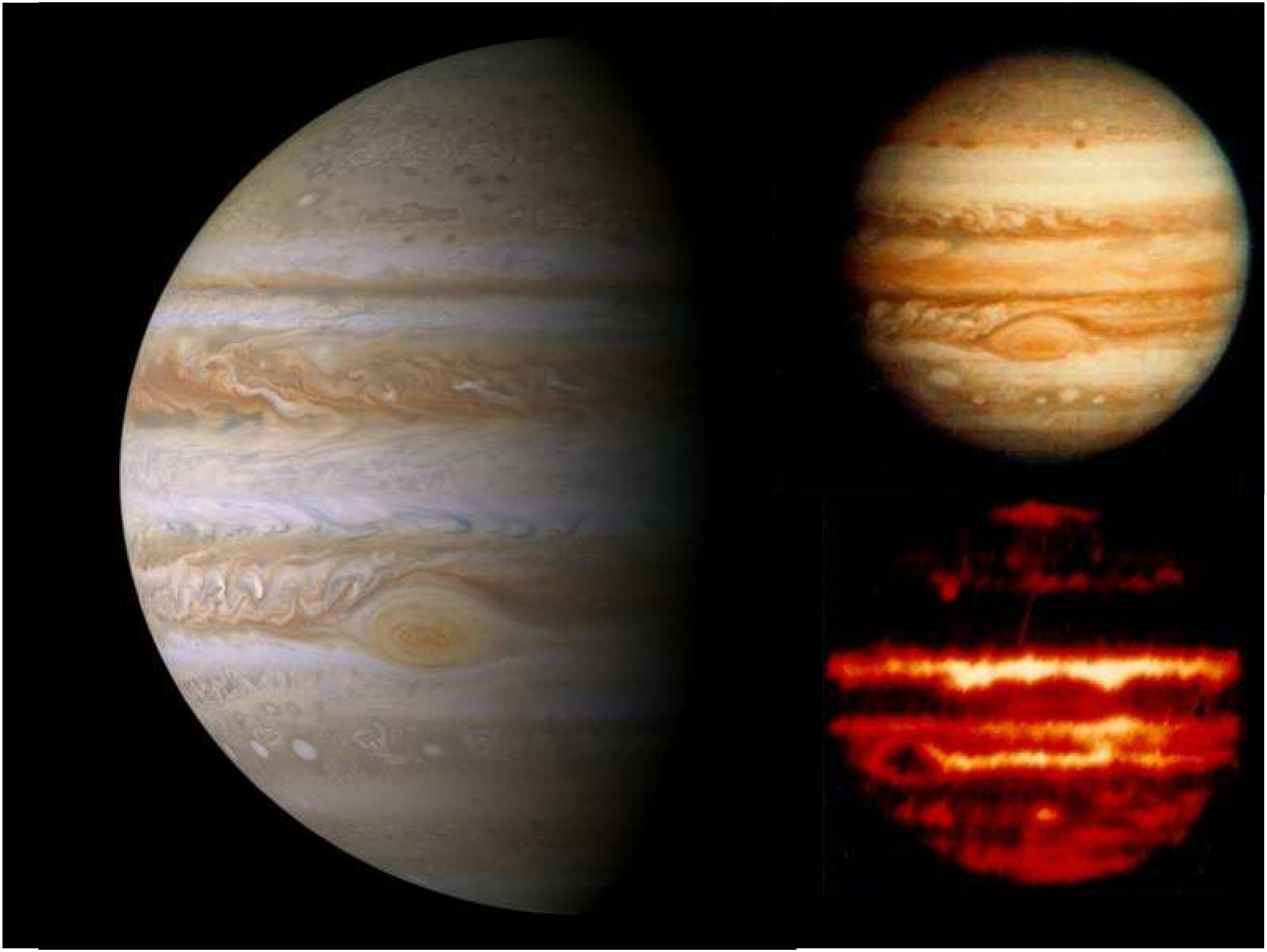
	J	S	U	N	Sun
H	88	97	83	74	86
He	11	3	15	25	14
CH_4	0.2		2	1	
	0.02 NH_3				
	0.0001 H_2O	helium settling	no helium settling		



1) Trace gases condense into **clouds** at diff. temperature
Clouds are also passive tracers of local wind pattern

2) Jupiter, Saturn & Neptune have strong **zonal winds**
(up to 500 m/s)
zonal winds driven by solar irradiation,
a combination of cold pole-- hot equator pressure gradient & Coriolis force:
great red-spot of Jupiter: a giant anti-cyclonic vortex, surprisingly long-lived
cyclone: $2 \mathbf{V} \times \Omega = -\text{grad } P/\rho$; tornado: $V^2/r = -\text{grad } P/\rho$

3) Uranus: uniquely bland & sedate (no internal heat flux, obliquity 97 deg)



Origin of Earth's atmosphere

Our (& Venusian) atmosphere cannot be primordial

1) N_2, CO_2, H_2O are not condensed at 1AU from Sun, O_2 does not naturally occur

2) Earth too low in mass to accrete gas directly

3) Gas is unlikely to have been trapped in solids and dragged to Earth, since noble gases (Ne, Kr, Xe) are heavily depleted relative to solar abundance.

4) New-born Earth molten and hot (10^3K)
--> most gases can escape thermally.

Some relief only in that in the early bombardment period (~ 700 Myr) water can be brought in by comets & asteroids.
(Note: D/H ratio in comets ~2 higher than ocean, so these cannot do it alone)

Origin of Earth's atmosphere (cont'd)

Our atmosphere is obtained gradually: volcanic outgassing & invaders

	1st atmosphere	2nd atmosphere	3rd atmosphere
	thermal escape	**outgassing/accretion**	**absorbing CO_2**
	H & He(?)	CO_2/NH_3 outgassed	most H_2O liquid
		H_2O accreted/outgassed	CO_2 got locked in
		(solid crust/ocean, 3.5Gyrs ago)	O_2 produced
P:	?	~ 100 bar (like Venus!)	~ 1 bar
T:	$\sim 10^3$K	$0^oC < T < 100^oC$	~ 15^oC

sinks of CO_2: sedimentary rock via H_2O, life (carbon) via photon-synthesis
sources of CO_2: volcanic outgassing (+human activities)
sinks of H_2O: subducting plates
sources of H_2O: outgassing, comets/asteroids?

Currently sensitive balance reached, mild green-house

run-away green-house: too much CO_2, H_2O can all disappear -->
--> sink disappears as well while outgassing produces yet more CO_2

Venus: divergent evolution from Earth

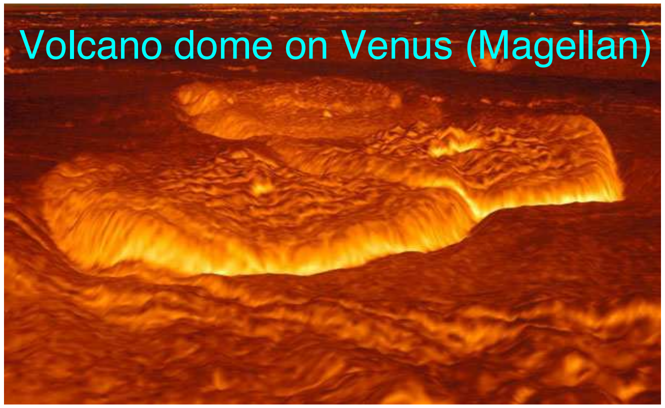
	a(AU)	mass(M_E)	spin	atm. Pressure	T	tectonics	ocean
Earth:	1	1	1 day	1bar	288 K	Yes	Yes
Venus:	0.7	0.8	243 day	92bar	770 K	No	No

1) 97% CO_2 in the atmosphere, ~ 700K, *no CO_2 sink due to dryness*

2) Why so dry? high D/H ratio indicates past large H_2O reserve
   Green-house runaway and H_2O photo-evaporated

3) Cratering no older than ~0.8 Gyr --> tectonics stopped recently

A planet is a nonlinear system.
Strongly divergent evolution can occur.



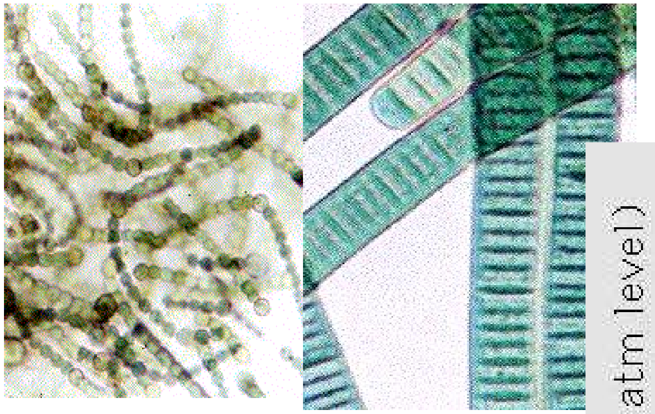
Cause & Effect?

1) Slightly closer to the Sun and got torched?
   Or formation site had naturally less H_2O?

2) Too much CO_2 to start with and H_2O never condensed
   (But: Initial Earth atm. ~100 bar, mostly CO_2 --> would require *fine tuning*?)

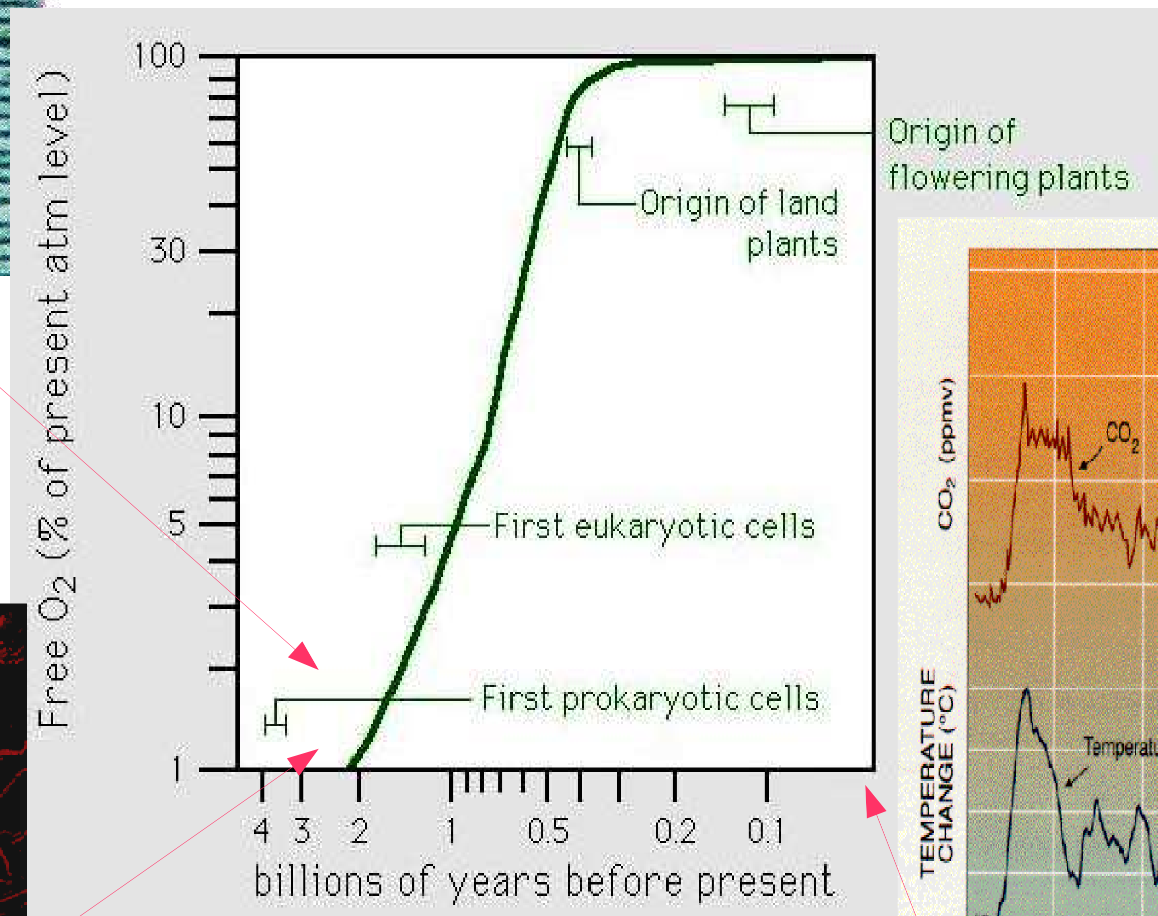
The Story for Mars: 2^{nd} atmosphere gradually lost, no outgassing (tectonics)

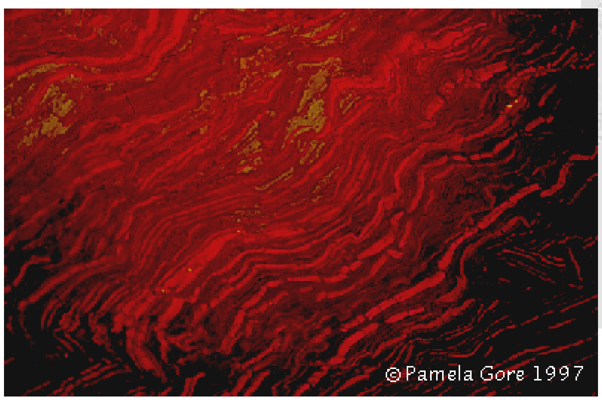
Origin of O_2 on Earth: photosynthesis; $CO_2 + H_2O + h\nu \text{ ---> } O_2$ + carbo-hydrate



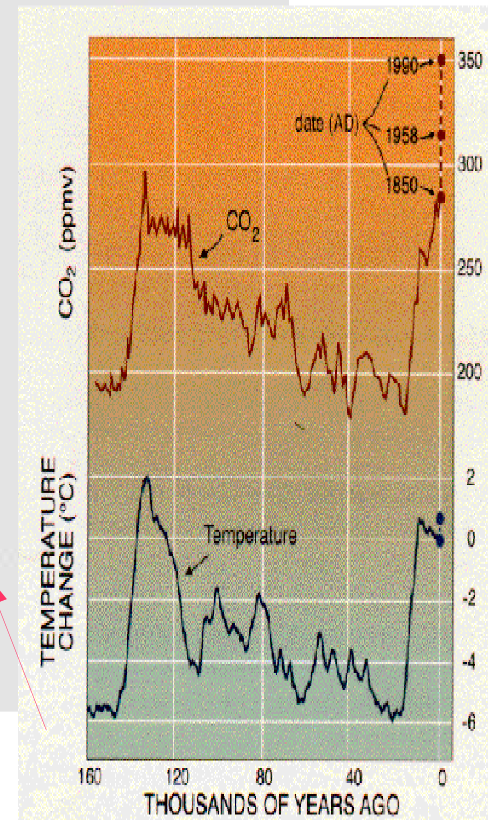
Archean Life: blue-green 'algae' or cyanobacteria (3.5-2.2 BYA) anerobic

From http://www.clas.ufl.edu/users/mrosenme/Oceanography





Red-banded un-oxidized iron-rich rocks, pre-cambrian, ~2.5BYA
http://www.dc.peachnet.edu/~pgore/geology/geo102/precamb.htm



CO_2 and atm. T correlation
(April 1989, Scientific. American)