The Solar System and Extrasolar Planets

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AIP

DFG

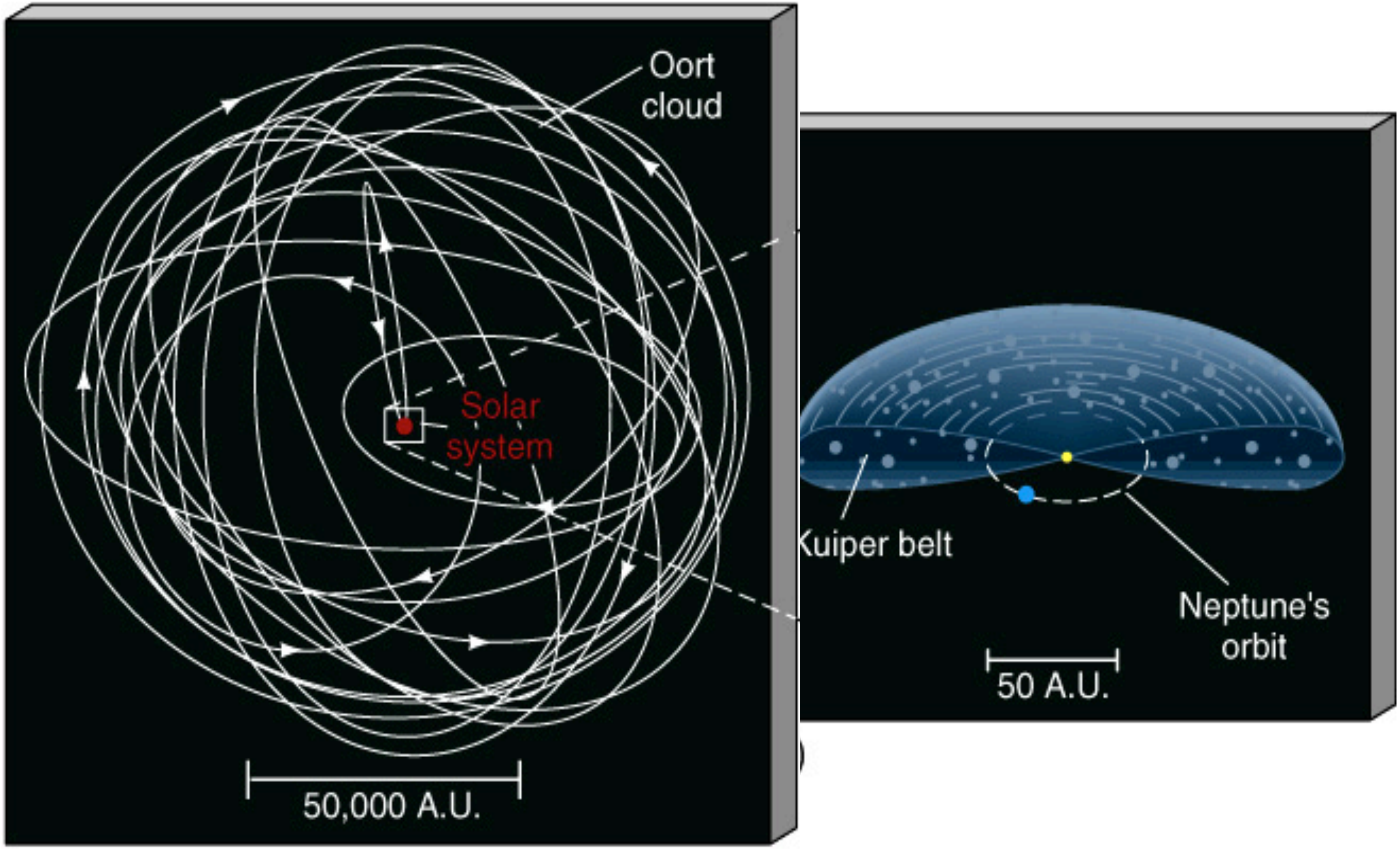
Some web pages on exo-planets

- www.solarviews.com/ss.html
- www.seds.org/billa/tnp (the nine planets)
- exoplanets.org
- www.astronautica.com
- www.public.asu.edu/~sciref/exoplnt.htm
- www.astrobiology.com/extrasolar.html
- www.obspm.fr/encycl.htm

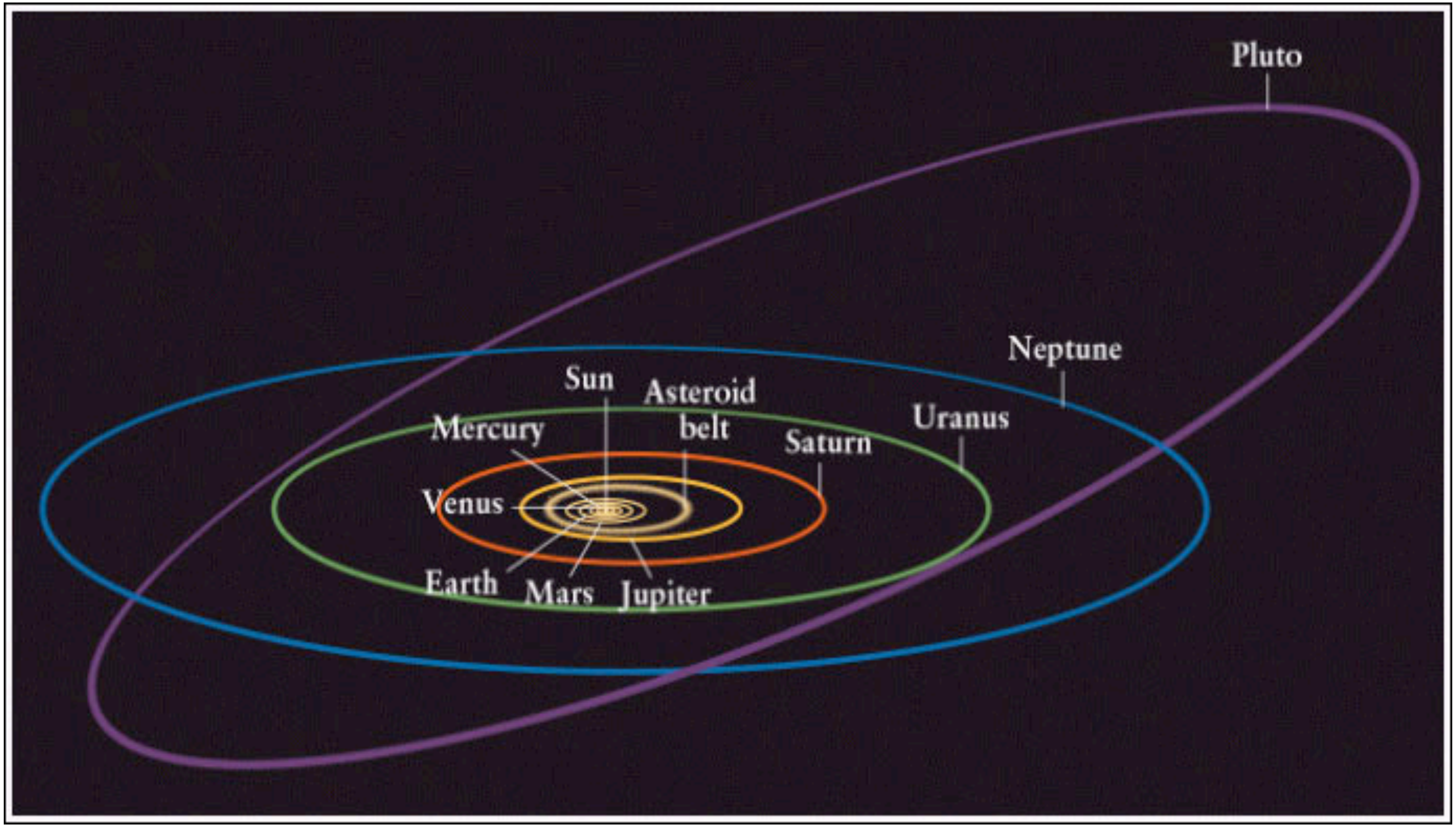
Overview

- Properties of the solar system
- Properties of extrasolar planets
- Methods to detect extrasolar planets

The planetary system I

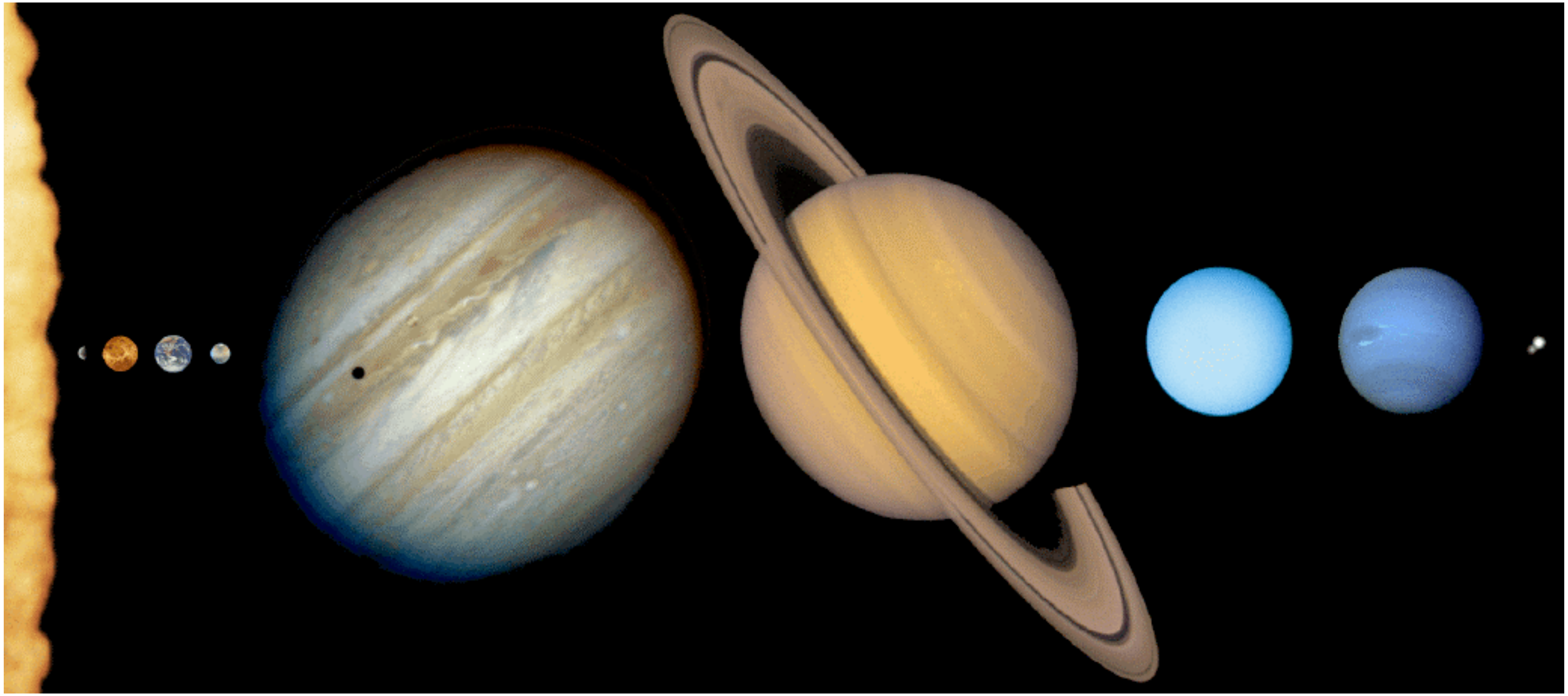


The planetary system II



~80 AU

Comparison of sizes

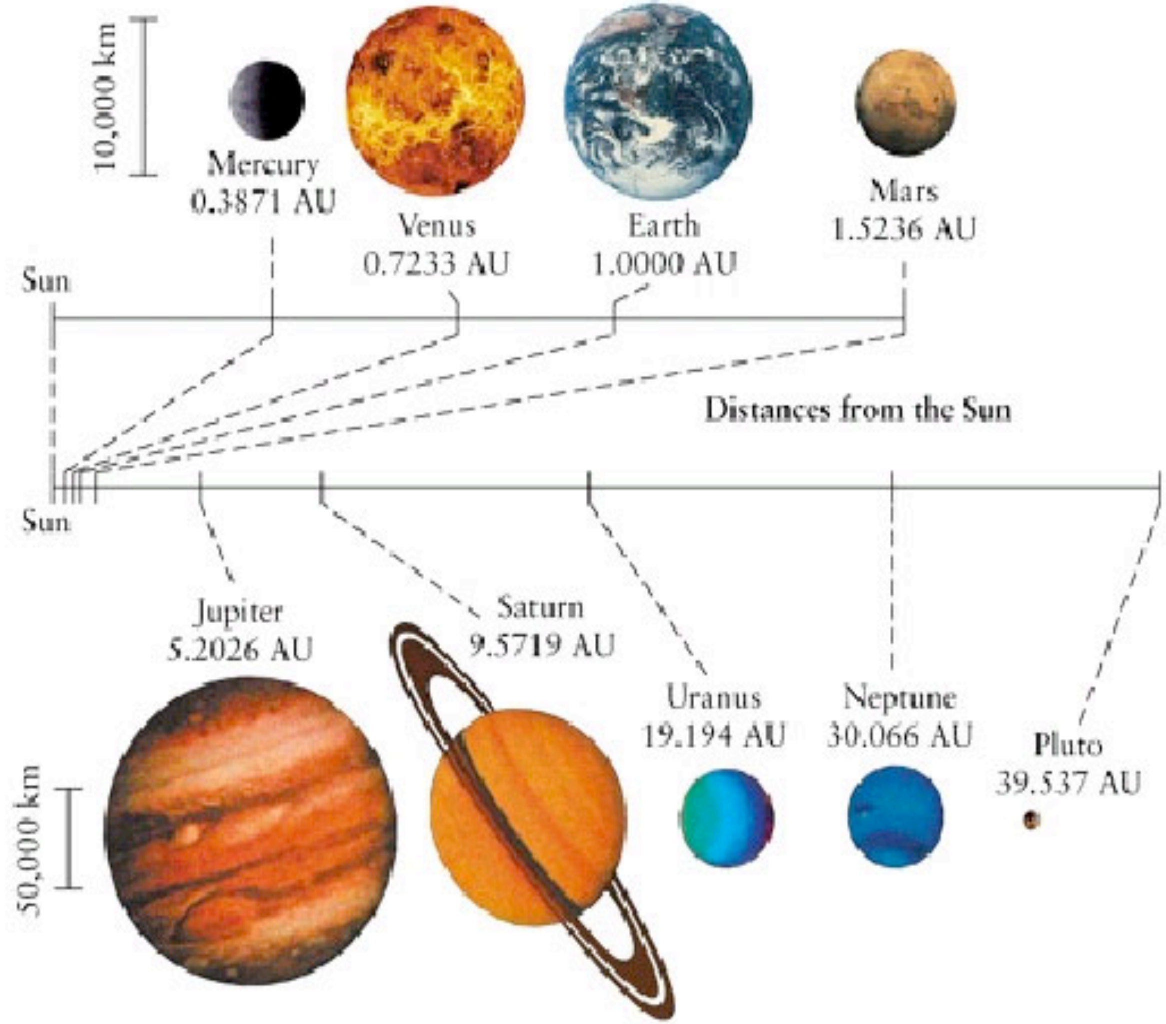


Some basic facts

- The Solar System is composed of:
  - 1 Star – the Sun
  - 9 Planets – Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto (which is actually a Kuyper belt object)
  - Over 60 Moons (and counting)
  - Asteroids, Comets, Meteoroids, and other objects!
- The planets all orbit around the Sun in the same direction (and most moons orbit around their planet the same way).
- Relative to Earth's orbital plane, most other planets orbit in roughly the same plane.
  - Most inclined: Mercury at 7º and Pluto at 17°
- Most planets have near circular orbits.
  - Most eccentric: Mercury (e = 0.21) and Pluto (e=0.25)

Terrestrial vs. Jovian Planets

Terrestrial Planets	**Jovian Planets**
Small size, low mass	Large and massive
Dense, rocky solid surfaces	Low density, huge gaseous atmospheres
Close to the Sun (within 1.5 AU)	Farther away (from 5.2 to 30 AU)
Heavy gas atmospheres (N_2, O_2, CO_2)	Lighter elements, H and He
Slow rotators	Faster rotators, differential rotation
Few satellites (3)	Many moons (over 60)
Weak magnetic fields	Strong magnetic fields
No ring system	Planetary rings



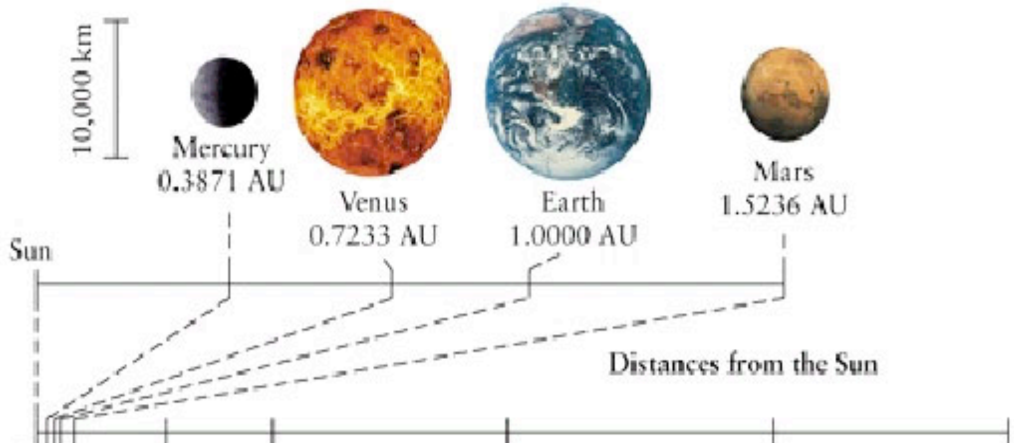
(NASA)

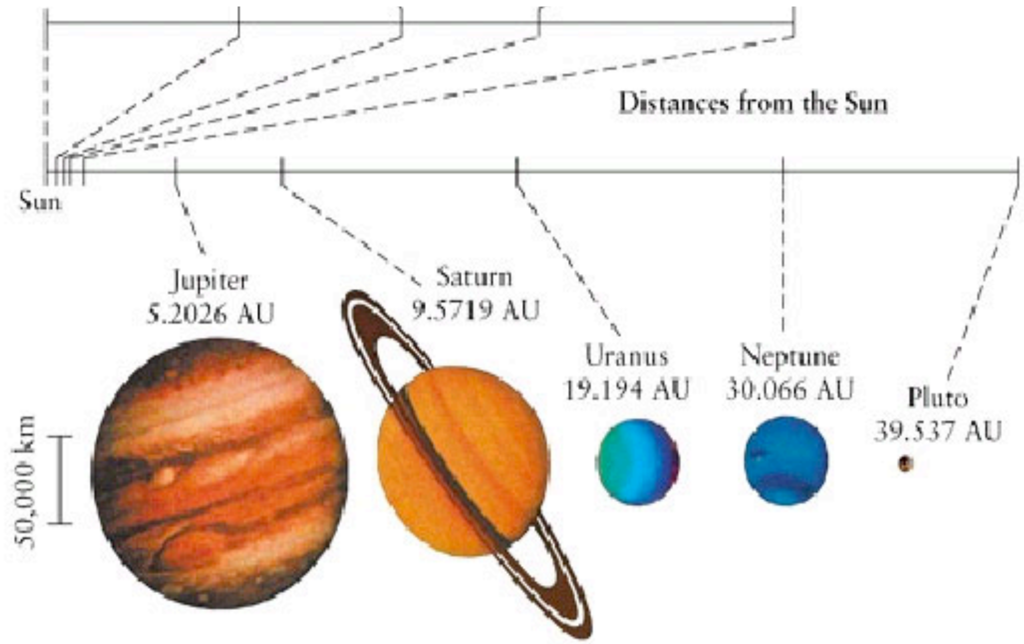
Inner,
terrestrial
Planets

Outer,
Jovian
Planets

Table 7-1 Characteristics of the Planets

	The Inner Planets			
	Mercury	Venus	Earth	Mars
Average distance from Sun (10^6 km)	57.91	108.2	149.60	227.93
Average distance from Sun (AU)	0.3871	0.7233	1.0000	1.5236
Orbital period (years)	0.2408	0.6152	1.0000	1.8808
Orbital eccentricity	0.206	0.007	0.017	0.093
Inclination of orbit to the ecliptic	7.00°	3.39°	0.00°	1.85°
Equatorial diameter (km)	4880	12,104	12,756	6794
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (kg)	3.302×10^{23}	4.868×10^{24}	5.974×10^{24}	6.418×10^{23}
Mass (Earth = 1)	0.0553	0.8150	1.0000	0.1074
Average density (kg/m^3)	5430	5243	5515	3934





(NASA)

The Outer Planets

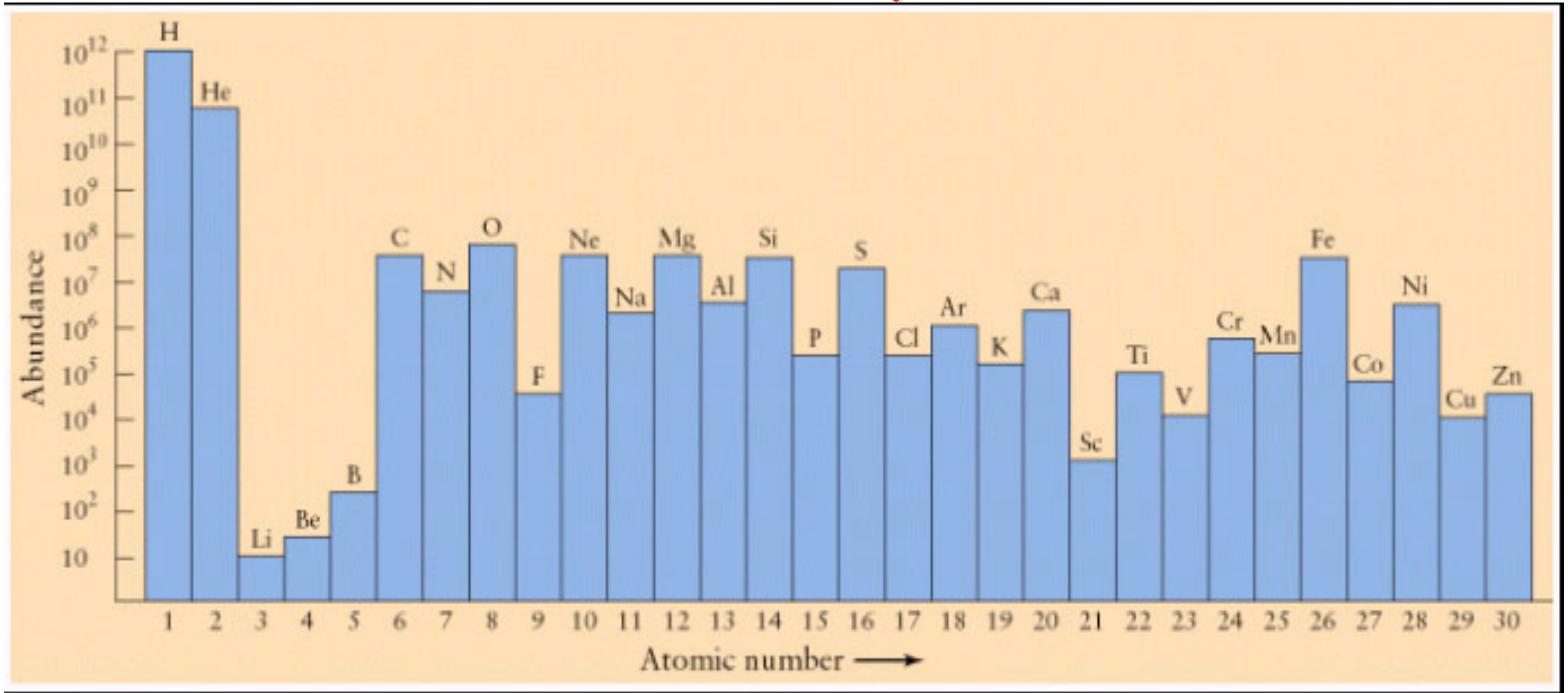
	Jupiter	Saturn	Uranus	Neptune	Pluto
Average distance from Sun (10^6 km)	778.30	1431.9	2877.4	4497.8	5914.7
Average distance from Sun (AU)	5.2026	9.5719	19.194	30.066	39.537
Orbital period (years)	11.856	29.369	84.099	164.86	248.60
Orbital eccentricity	0.048	0.053	0.043	0.010	0.250
Inclination of orbit to the ecliptic	1.30°	2.48°	0.77°	1.77°	17.12°
Equatorial diameter (km)	142,984	120,536	51,118	49,528	2300
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883	0.180
Mass (kg)	1.899×10^{27}	5.685×10^{26}	8.682×10^{25}	1.024×10^{26}	1.31×10^{22}
Mass (Earth = 1)	317.8	95.16	14.53	17.15	0.002
Average density (kg/m^3)	1326	687	1318	1638	2000

Table 7-2 The Seven Giant Satellites

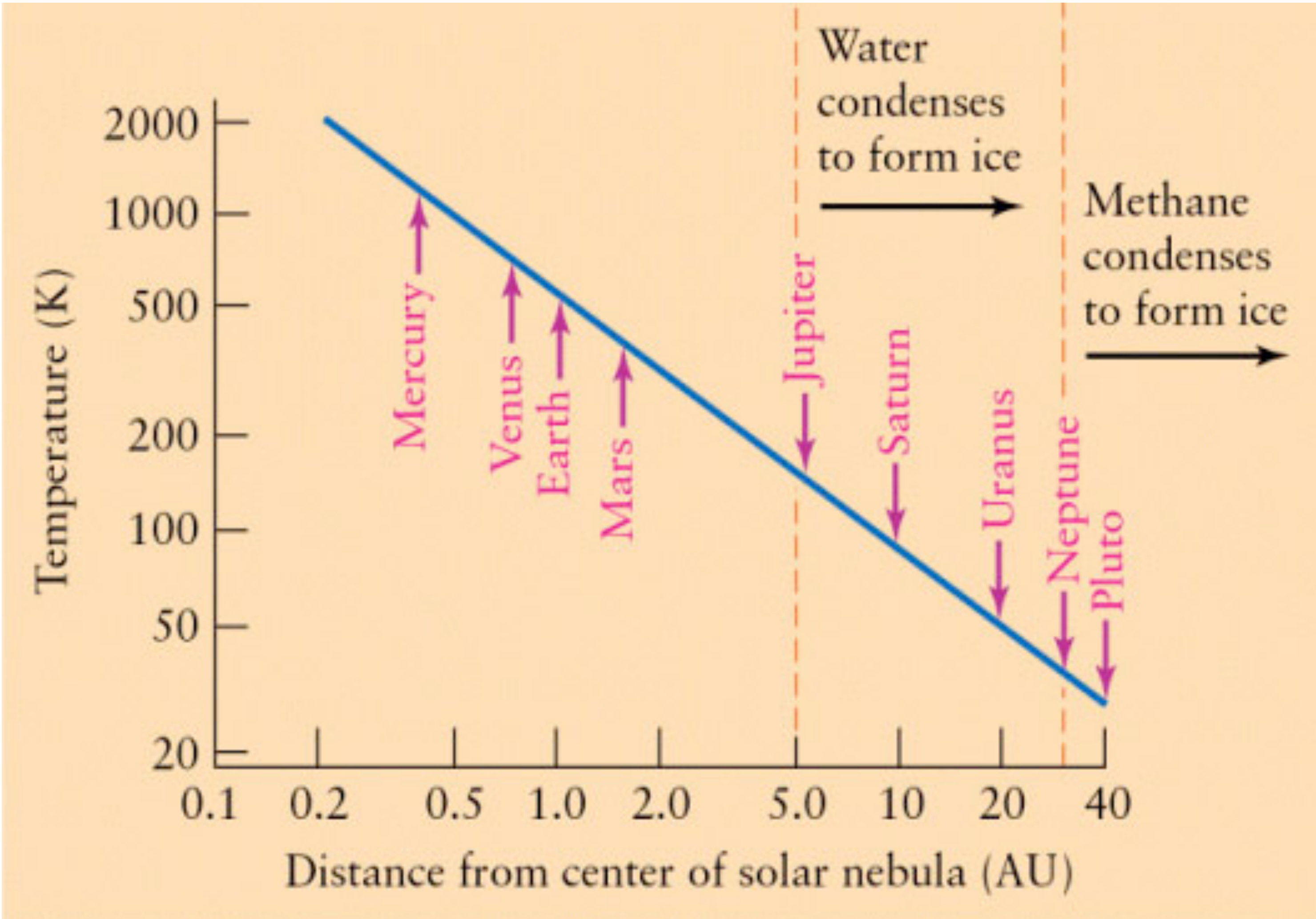
	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	7.35×10^{22}	8.93×10^{22}	4.80×10^{22}	1.48×10^{23}	1.08×10^{23}	1.34×10^{23}	2.15×10^{22}
Average density (kg/m^3)	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No

(JPL/NASA)

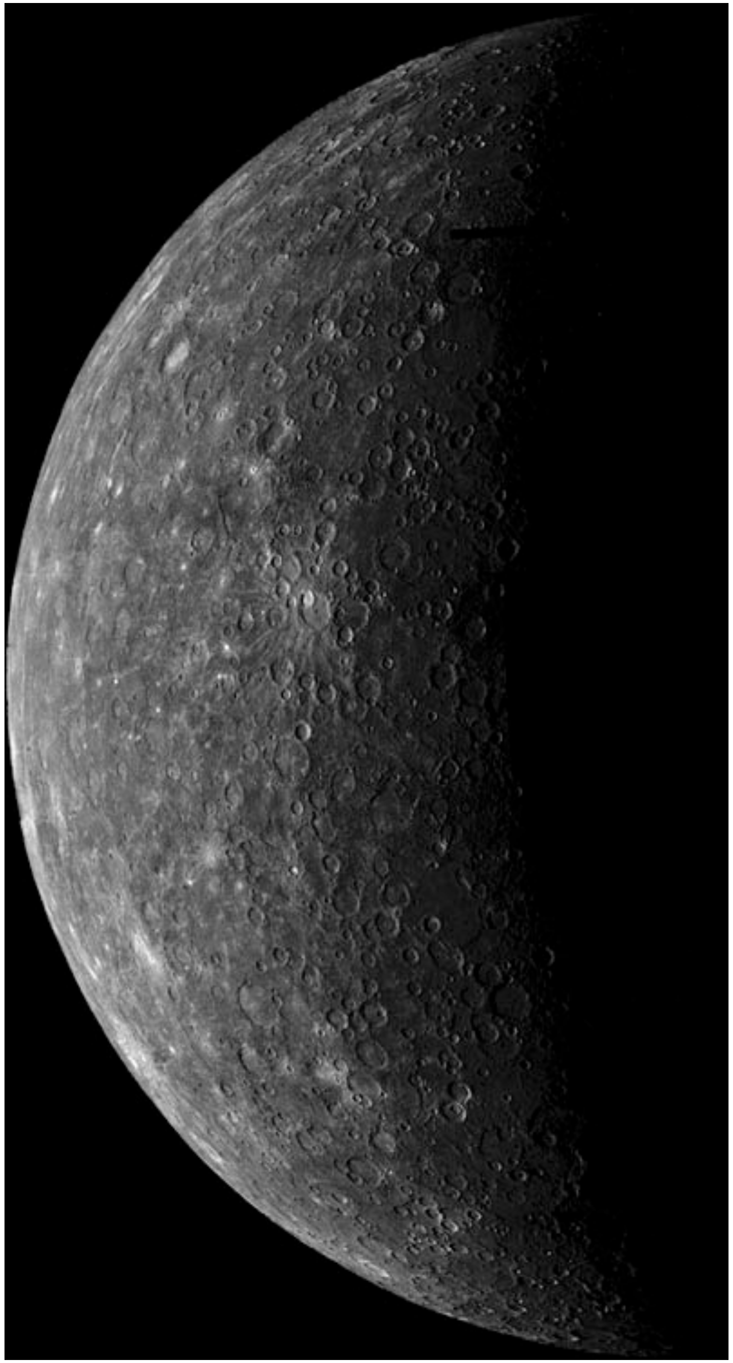
The relative abundances of the elements are the result of cosmic processes.



For every 10^{12} atoms of hydrogen, there are only 6 atoms of gold.

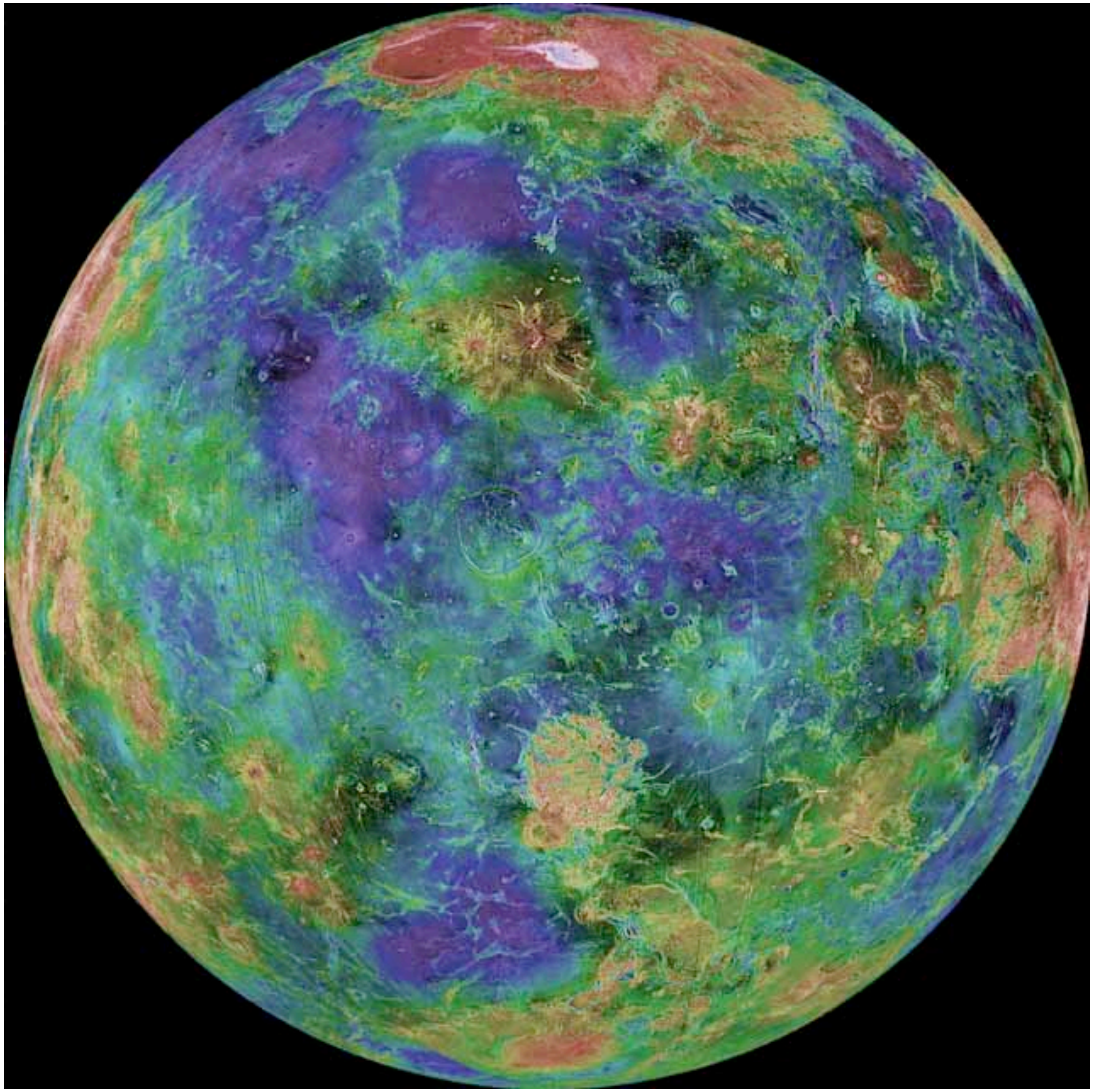


Water condenses to form ice
Methane condenses to form ice
Temperature (K)
2000
1000
500
200
100
50
20
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
0.1
0.2
0.5
1.0
2.0
5.0
10
20
40
Distance from center of solar nebula (AU)



Mercury

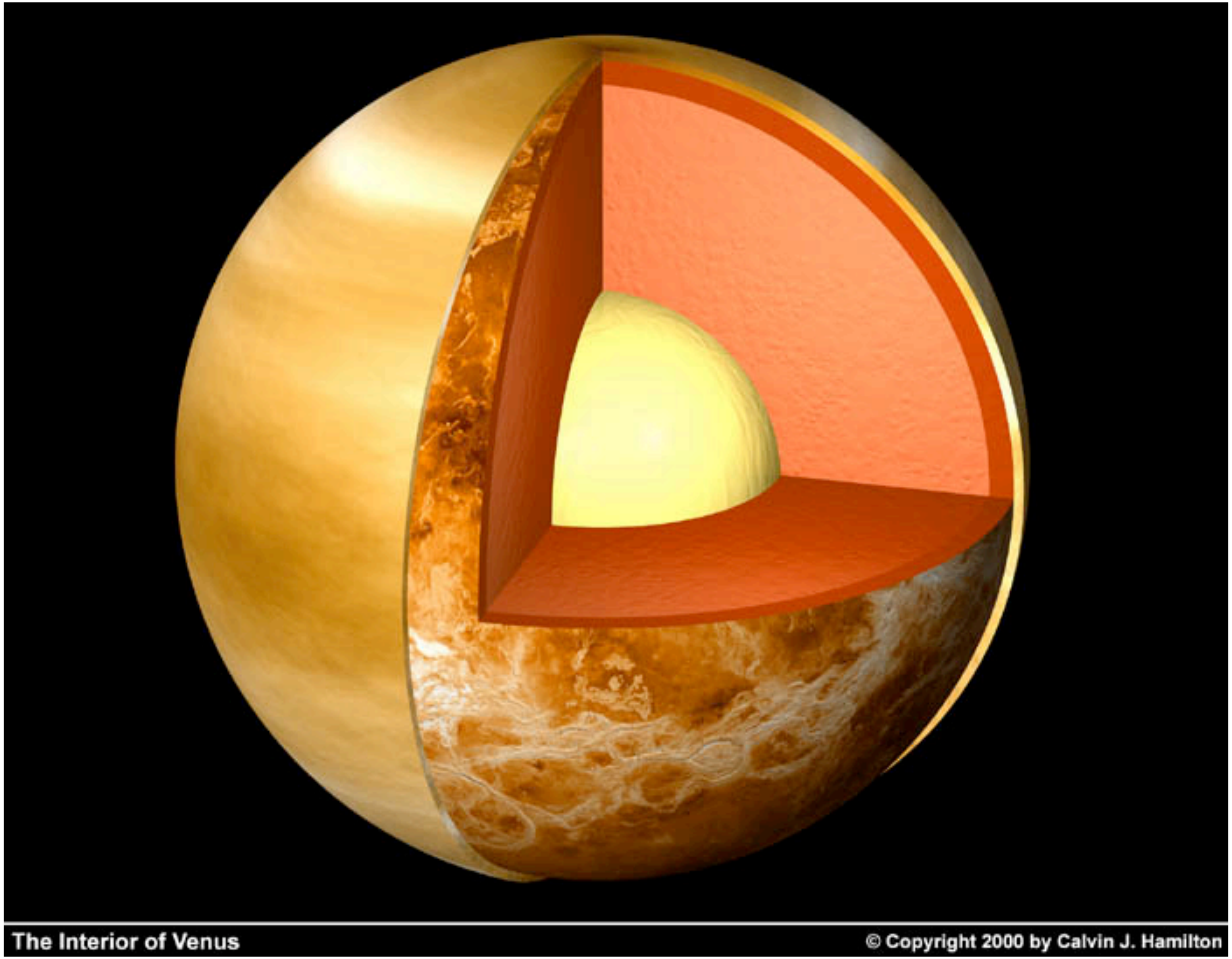
- Orbit: 57,910,000 km = 0.38 AU from Sun
- Period: 88 days in 3:2 resonance
- diameter: 4,880 km
- mass: 3.30e23 kg
- Extreme T variations from 70K to 900K
- No plate tectonics
- Inner Fe core ~1900km, silicate layer ~600km



Venus

- Orbit: 108,200,000 km (0.72 AU) from Sun
- Diameter: 12,103.6 km
- Mass: 4.869e24 kg
- Period: 225 days
- Diameter: 12,104 km
- Mass: 5.9e24 kg
- Strong plate tectonics
- Iron core ~1800km, outer silicate mantle ~600km

Venus



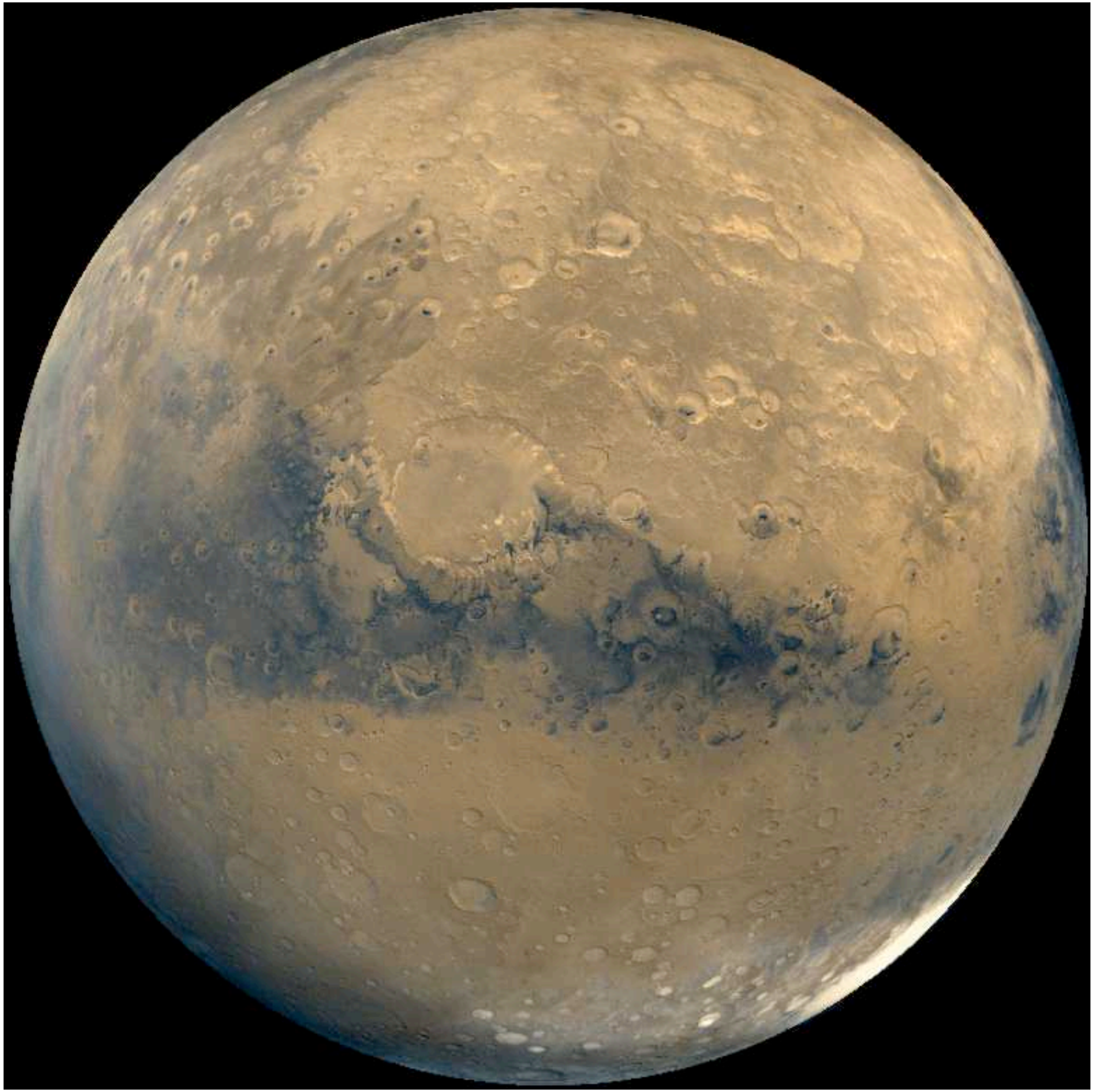
Iron core

Thick mantle

Solid crust

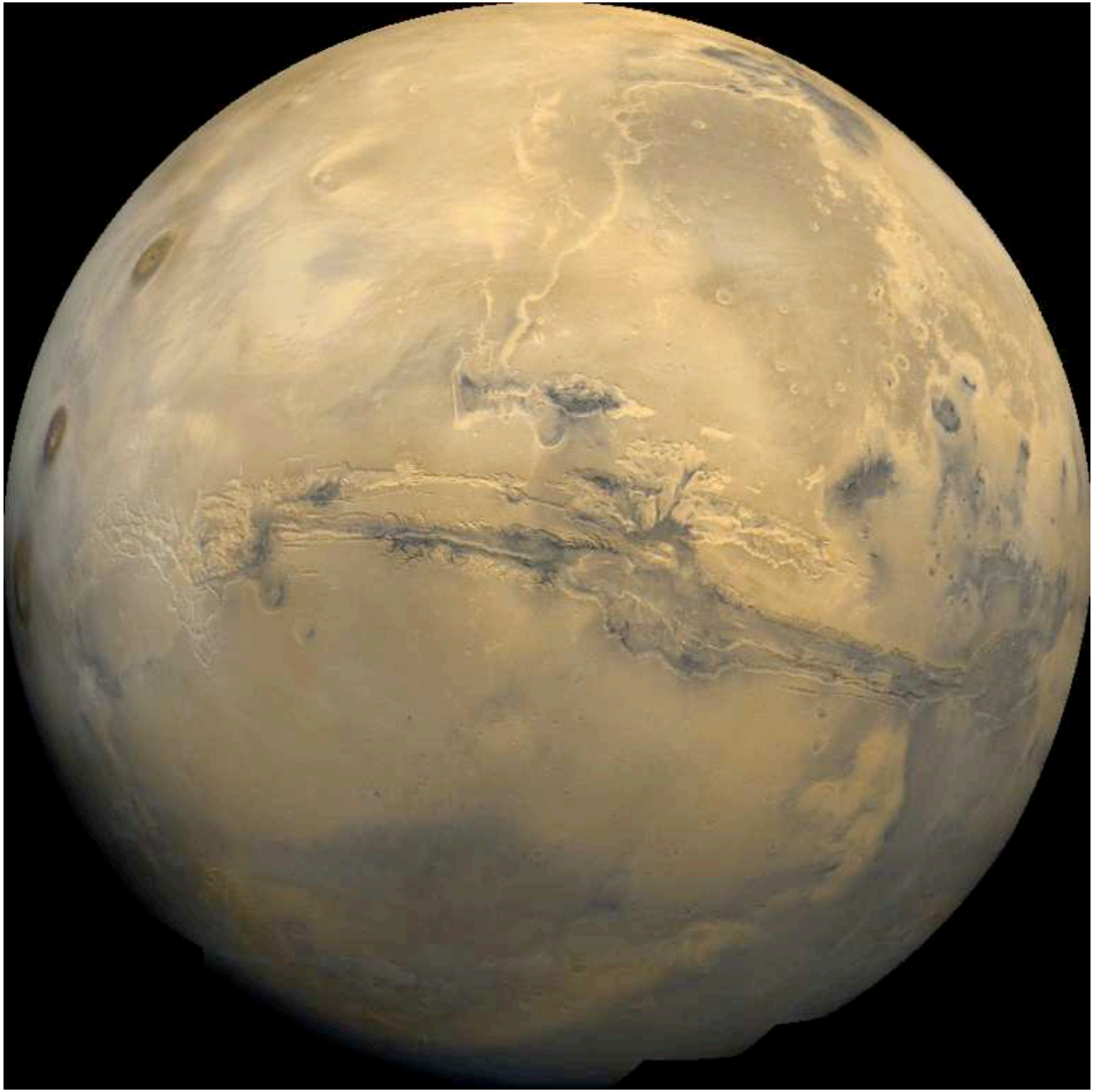
Earth

- Orbit: 149 million km
  1 AU from Sun
- Mass: 4.869e24 kg
- Period: 365 days
- Diameter: 12,756 km
- Mass: 4.9e24 kg
- Strong plate tectonics
- $T_{surface}$ ~ 15C



Mars

- Orbit: 228 million km = 1.5 AU
- Mass: 6.421e23 kg
- Period: 689 days
- Diameter: 7,794 km
- Mass: 6.4e23 kg
- Plate tectonics
- Water ice underneath surface
- $T_{surface}$ ~ -63C



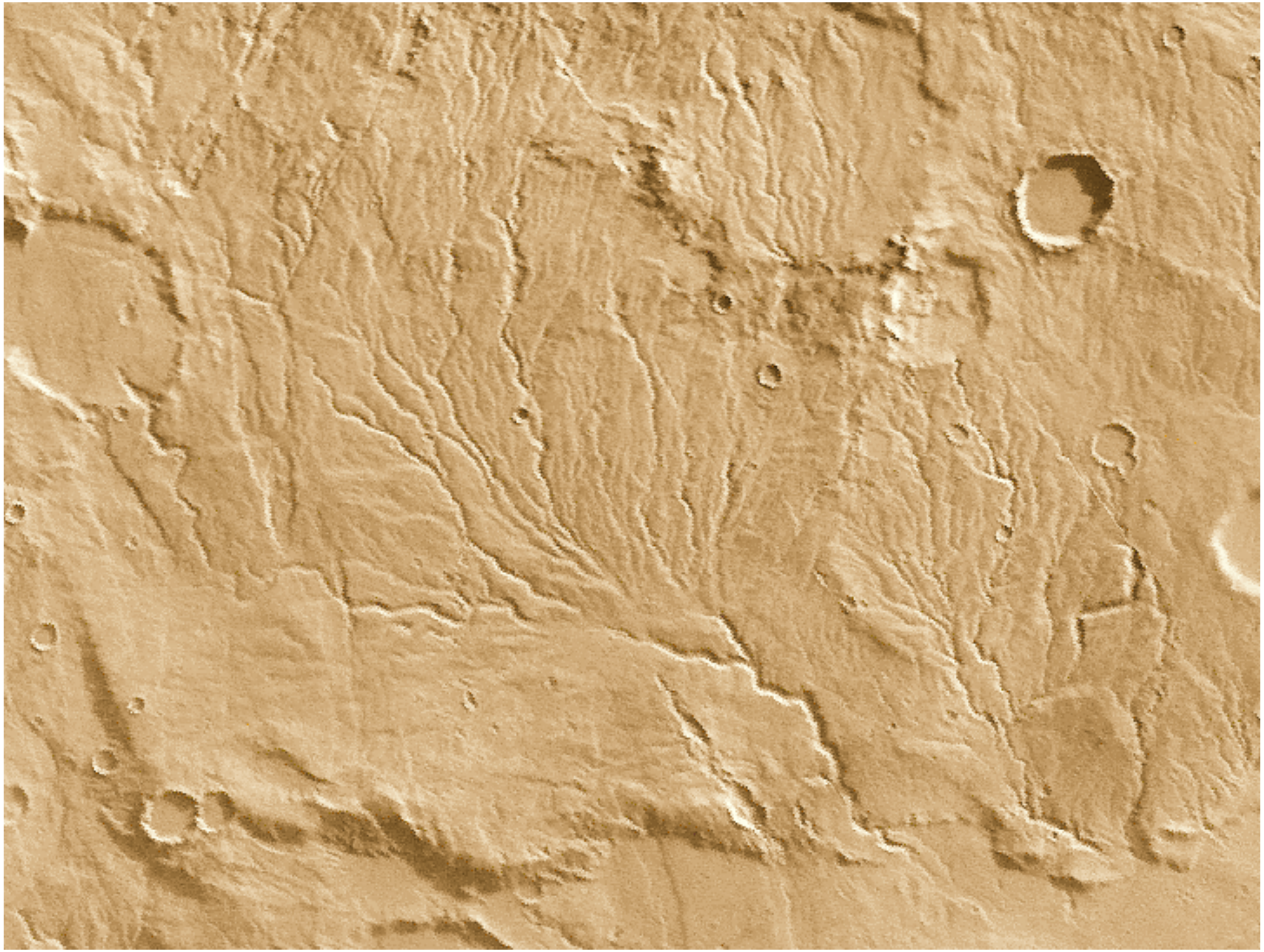
Mars

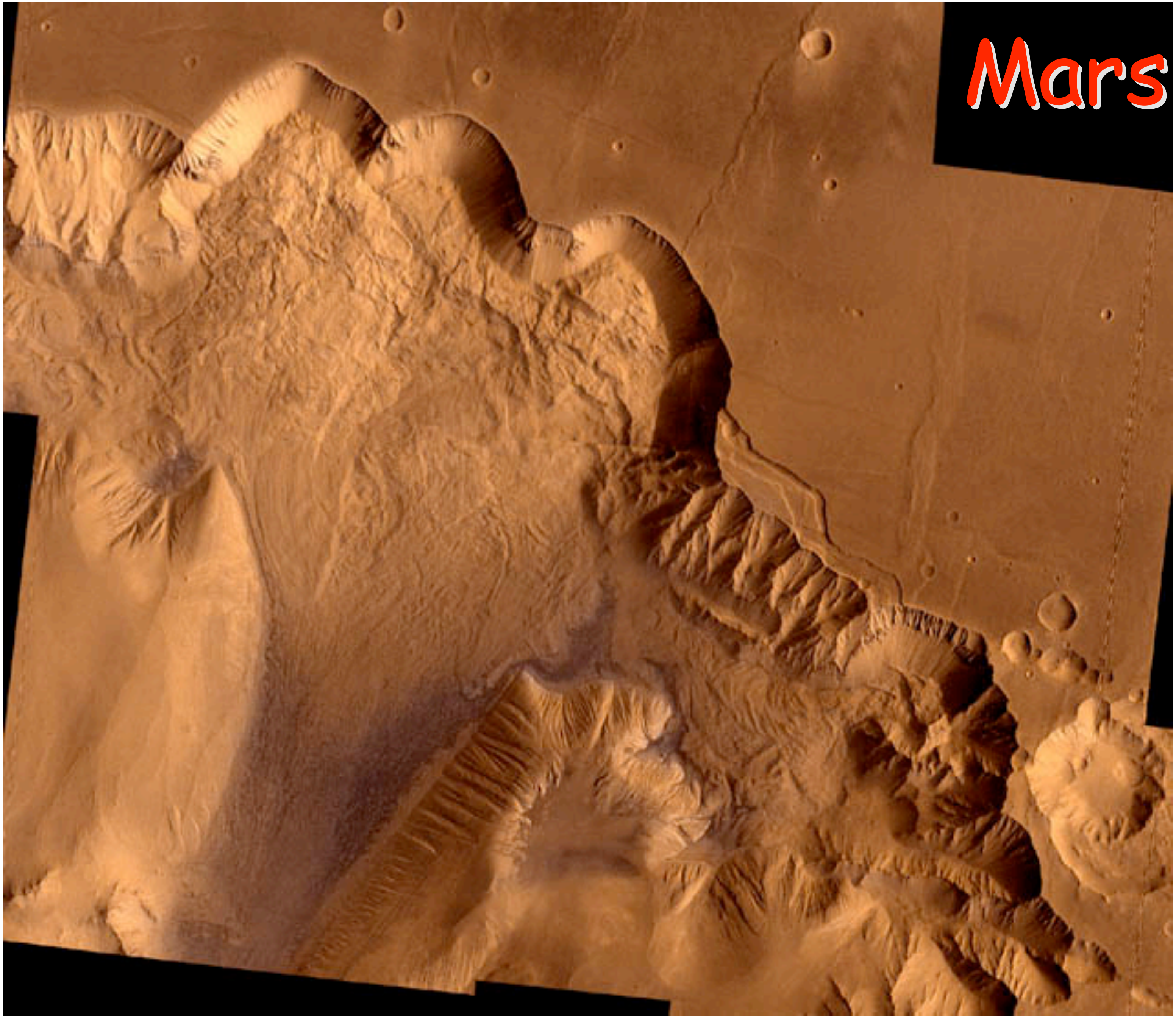
Mars

Streamline-shaped islands Chasm

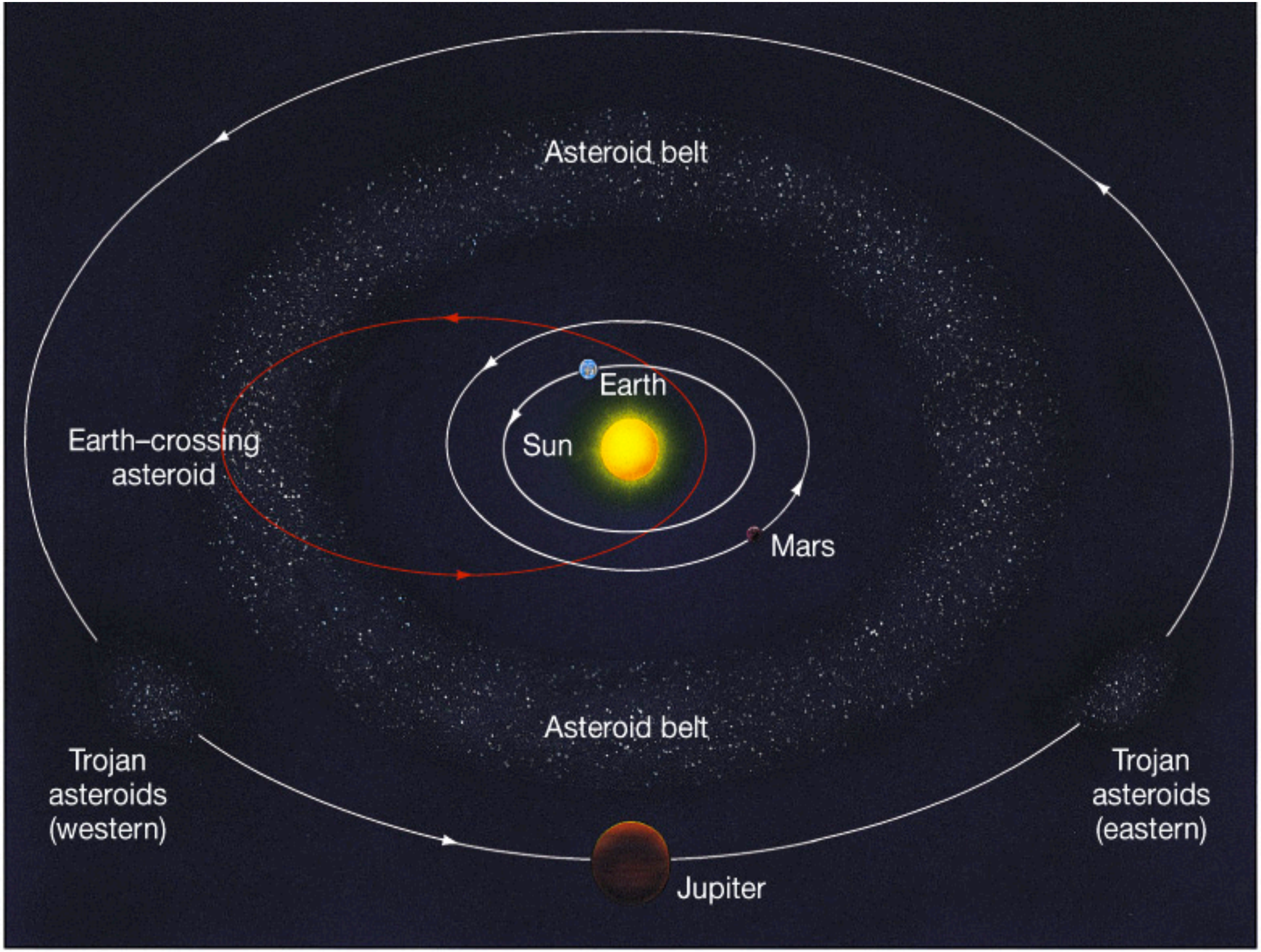
Mars

Network of valleys





Orphis Chasm



Asteroid belt
Earth
Earth–crossing asteroid
Sun
Mars
Asteroid belt
Trojan asteroids (western)
Trojan asteroids (eastern)
Jupiter

Asteroids

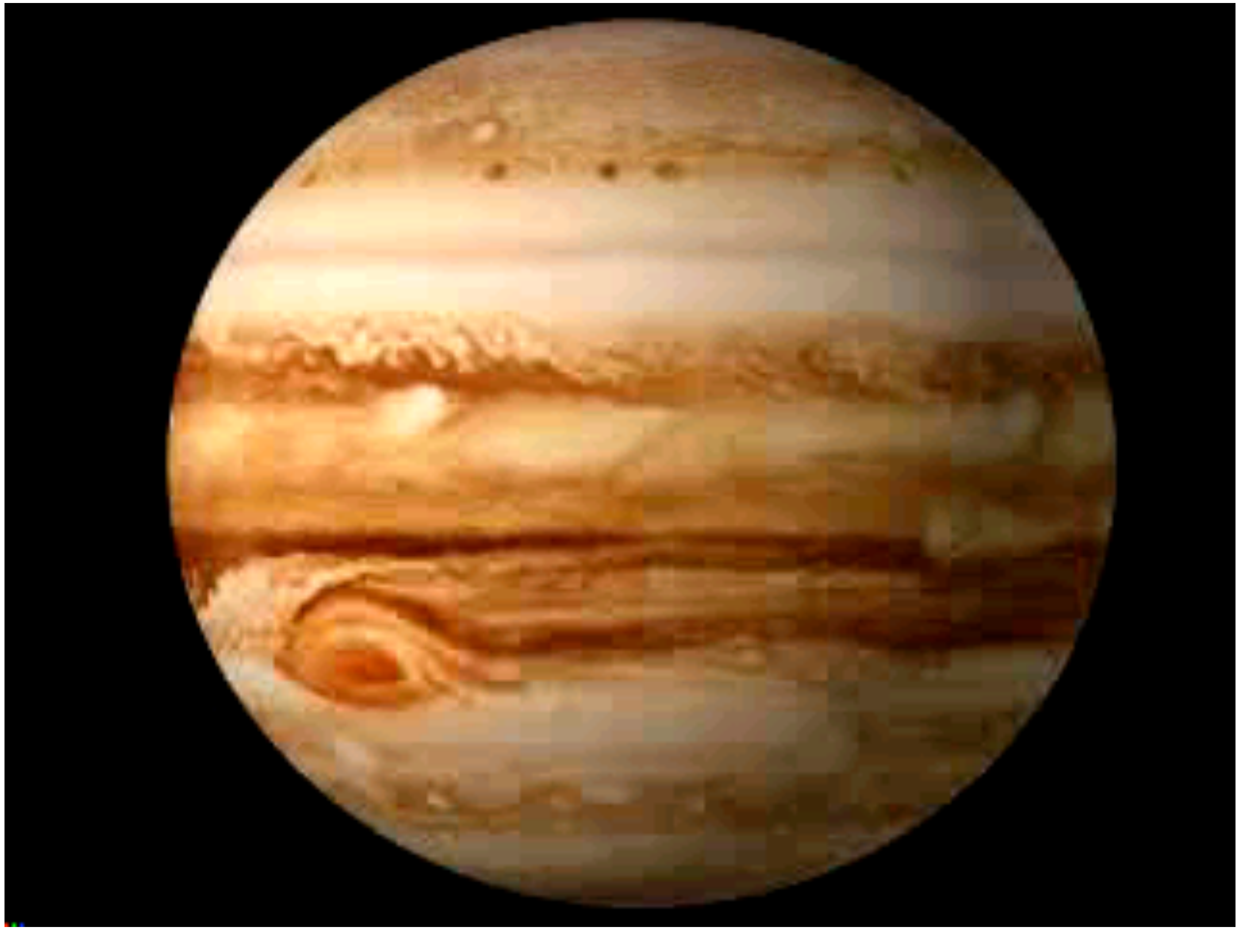
- Mostly located between 2.1 – 3.3 AU from the Sun (between Mars and Jupiter).
    - **Trojans** – share an orbit with Jupiter.
    - Some pass near Earth or cross its orbit (Near-Earth Objects).
- Irregular, cratered objects.
    - Not large enough to gravitationally form into a spherical object.
- Low density (Mathilde ~ 1.3 g/cm^3)
    - Can't be solid rock. Must be collection of fragments.
- Different types depending on composition (similar to meteorites).

The Origin of Asteroids

- Jupiter's gravitational influence prevented a planet from forming around 2.8 AU.
- Collisions over time have broken the planetesimals into smaller pieces, creating what we see today.

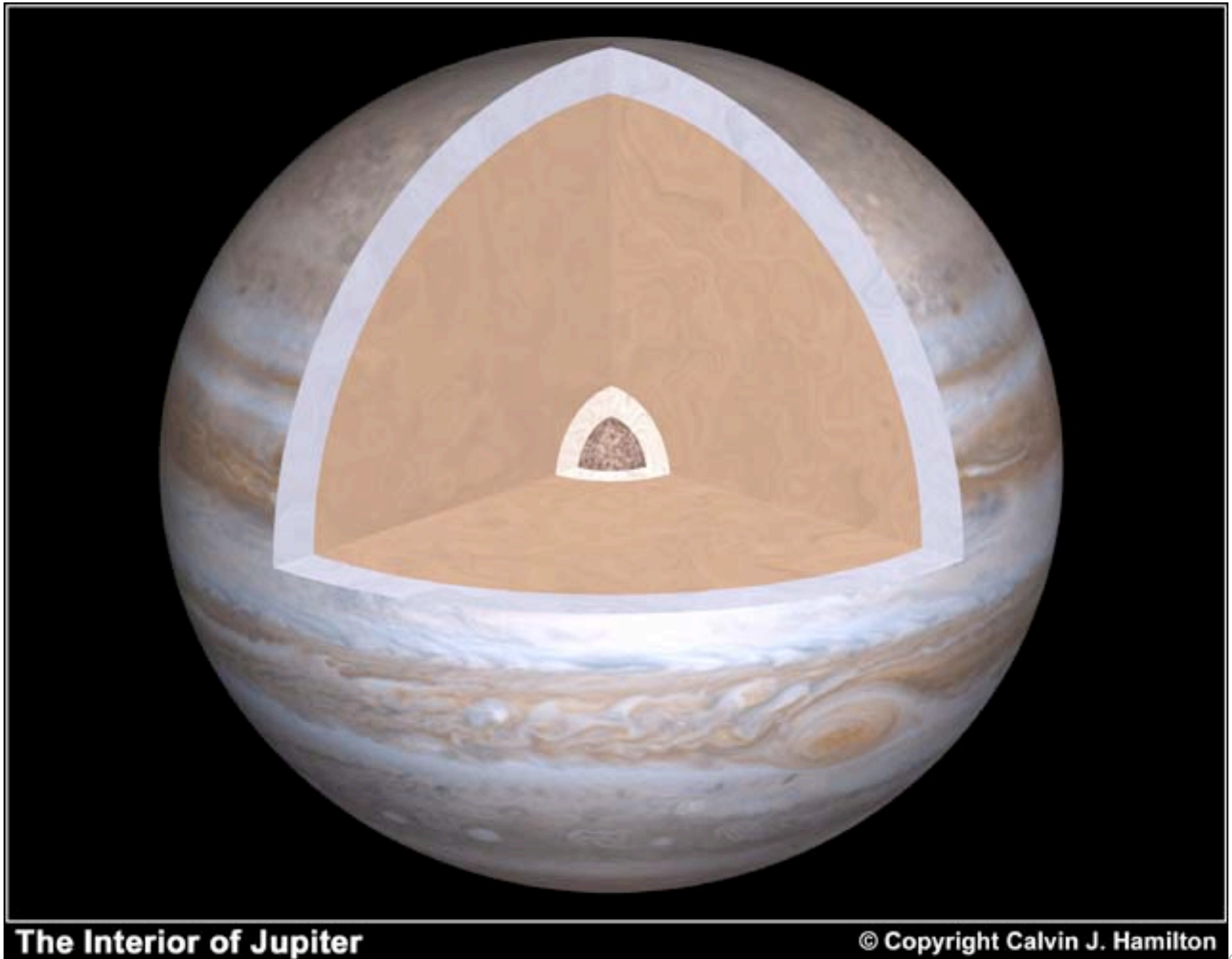
Jupiter

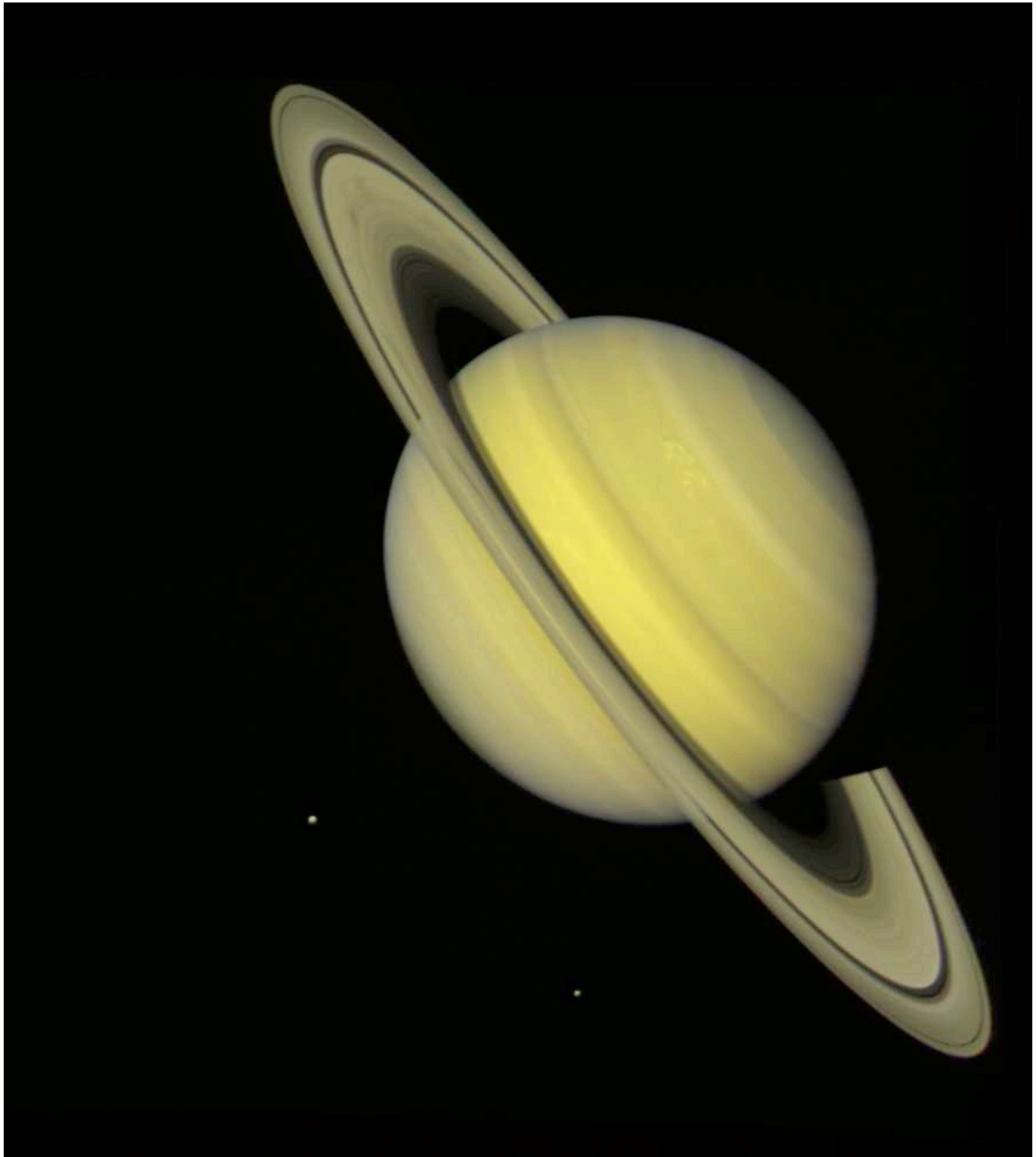


GREAT RED SPOT

- Orbit: 778 million km = 5.2 AU
- Mass: 1.9e27 kg
- Rotation: 0.41 days
- Period: 4332 days
- Diameter: 142,984 km
- Gas planet (inner structure not know, maybe solid core)
- Mean density: 1.33 g/cm^3
- ~ solar chemical composition
- T_{clouds} ~ −121C

Jupiter





Saturn

- Orbit: 1,429 million km = 10.2 AU
- Mass: 5.7e26 kg
- Rotation: 10.2 h
- Period: 29.45 yr
- Diameter: 120,536 km
- Gas planet (with inner solid, core)
- Mean density: 0.69 g/cm^3
- ~ solar chemical composition
- T_{clouds} ~ –125C

Saturn

Solid inner core
(rocks, ice)

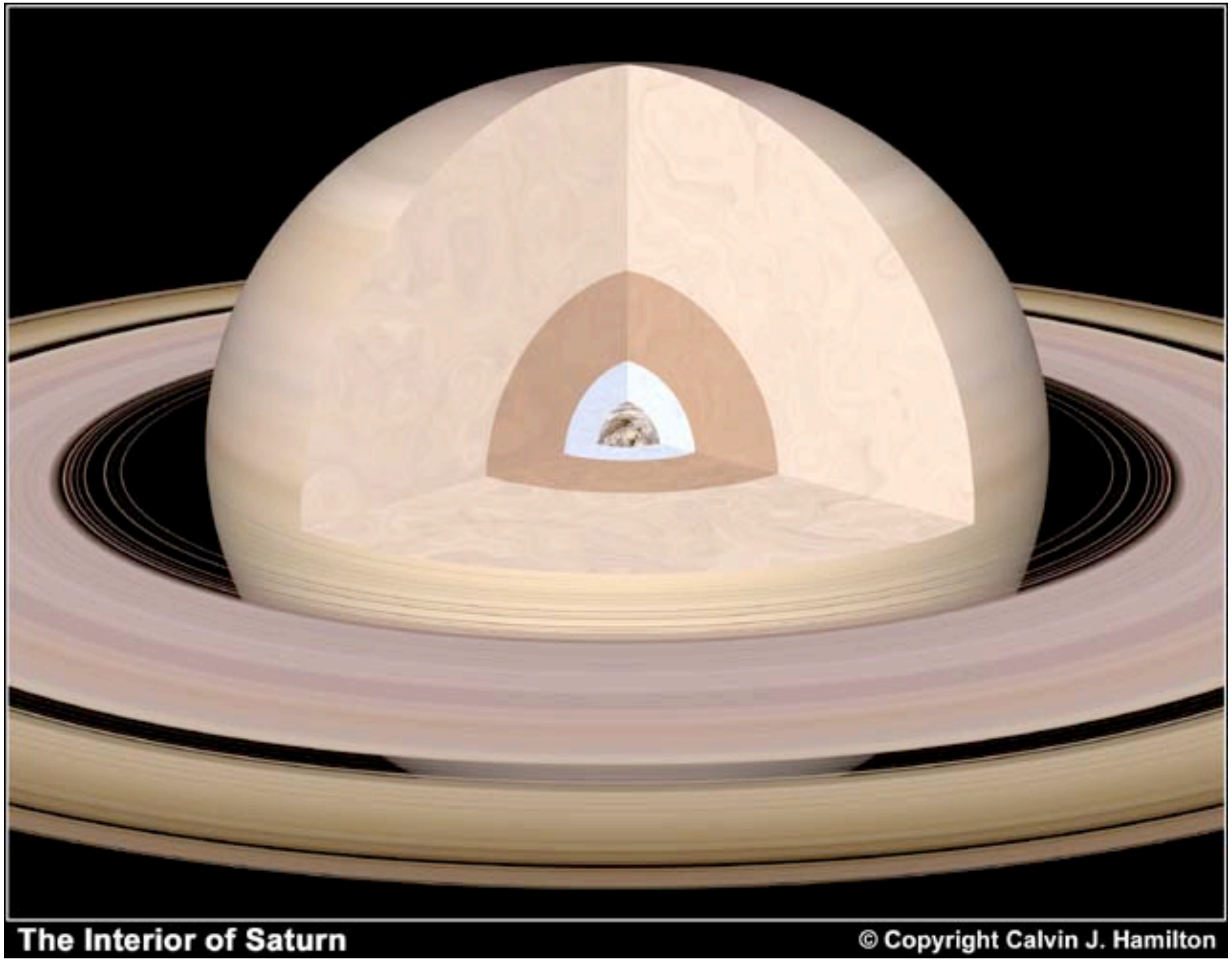
Icy core
(H, CH_4, NH_3)

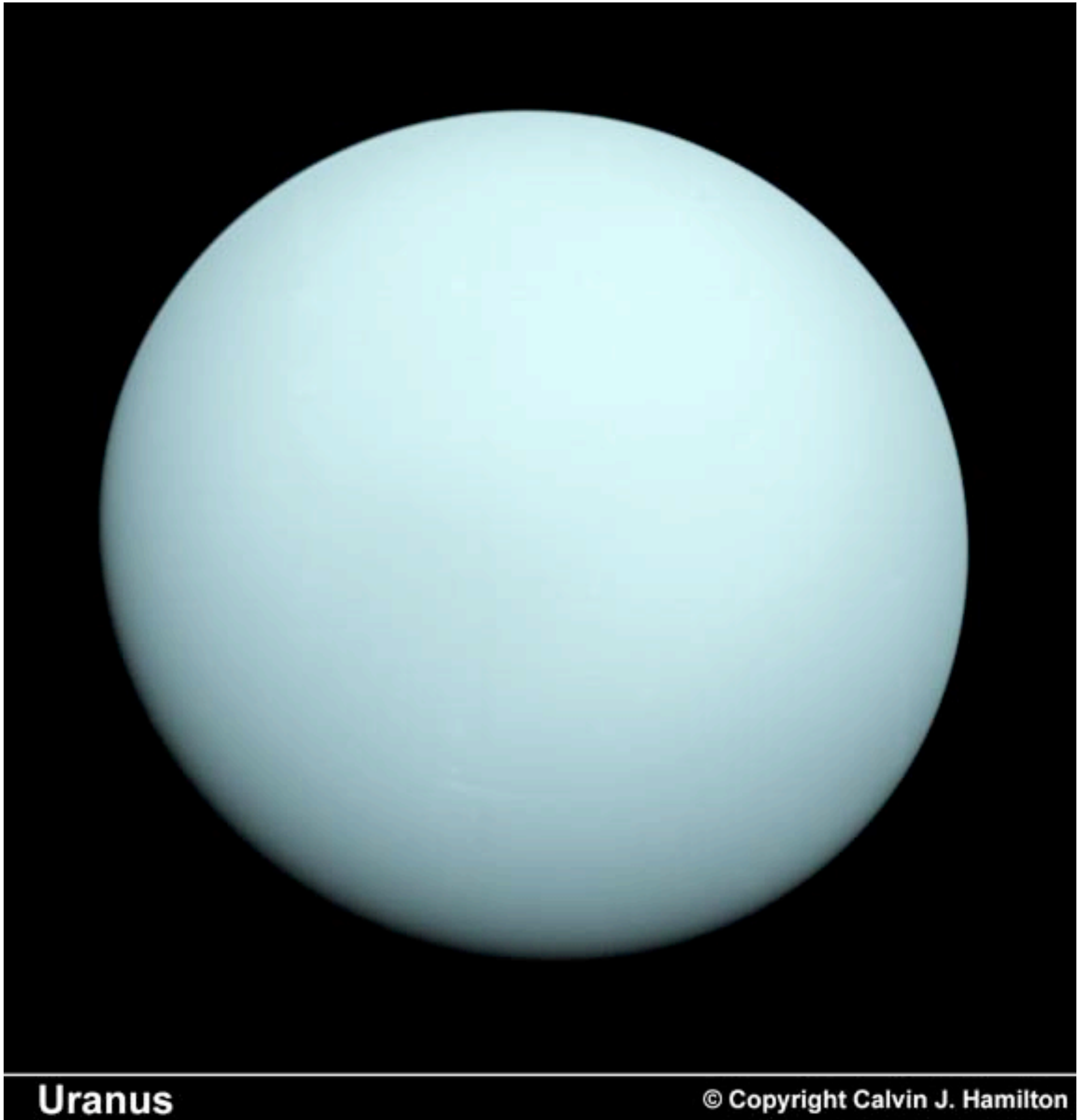
Metallic hydrogen

Liquid hydrogen

Gaseous hydrogen

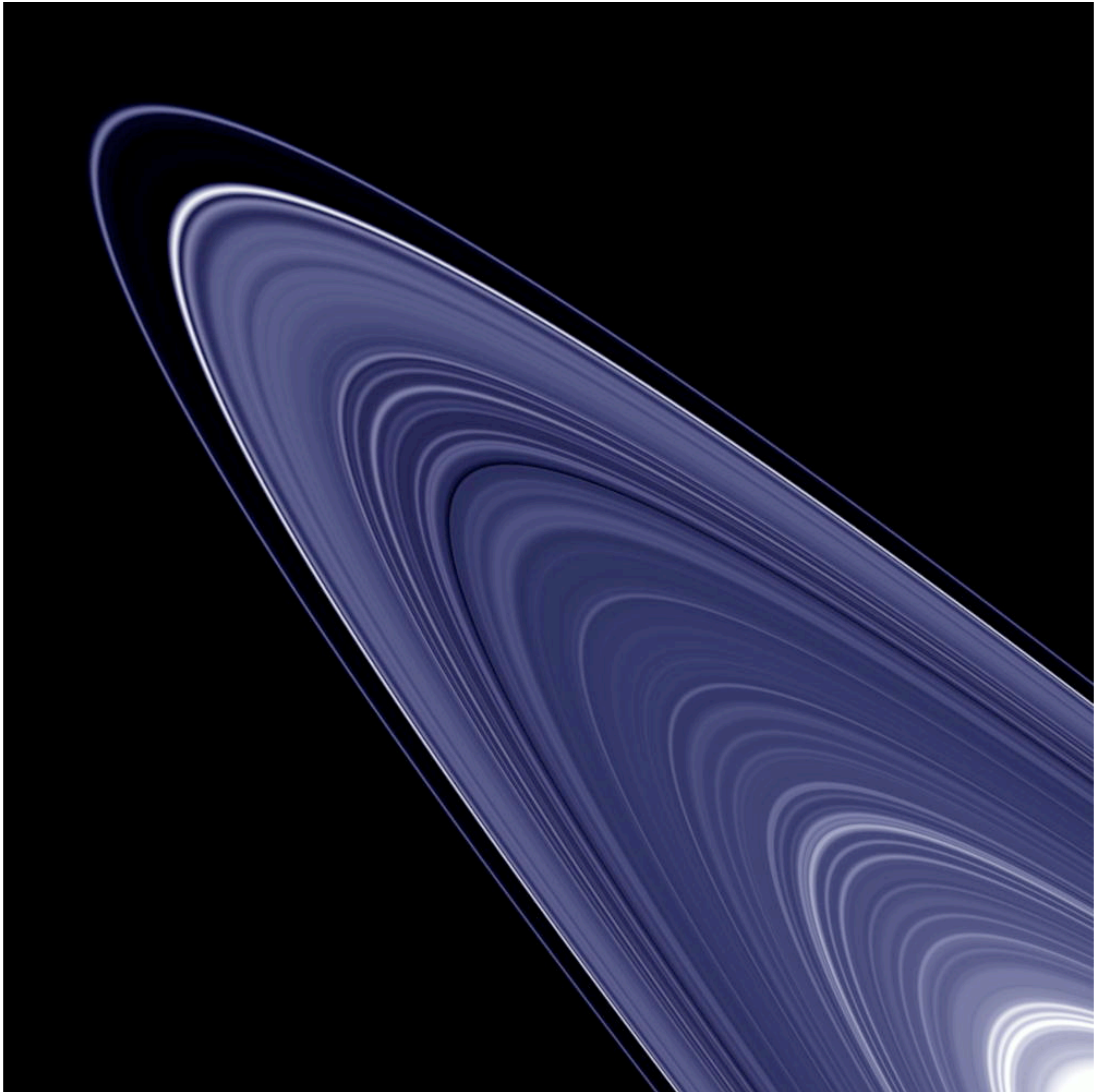
Cloud layer



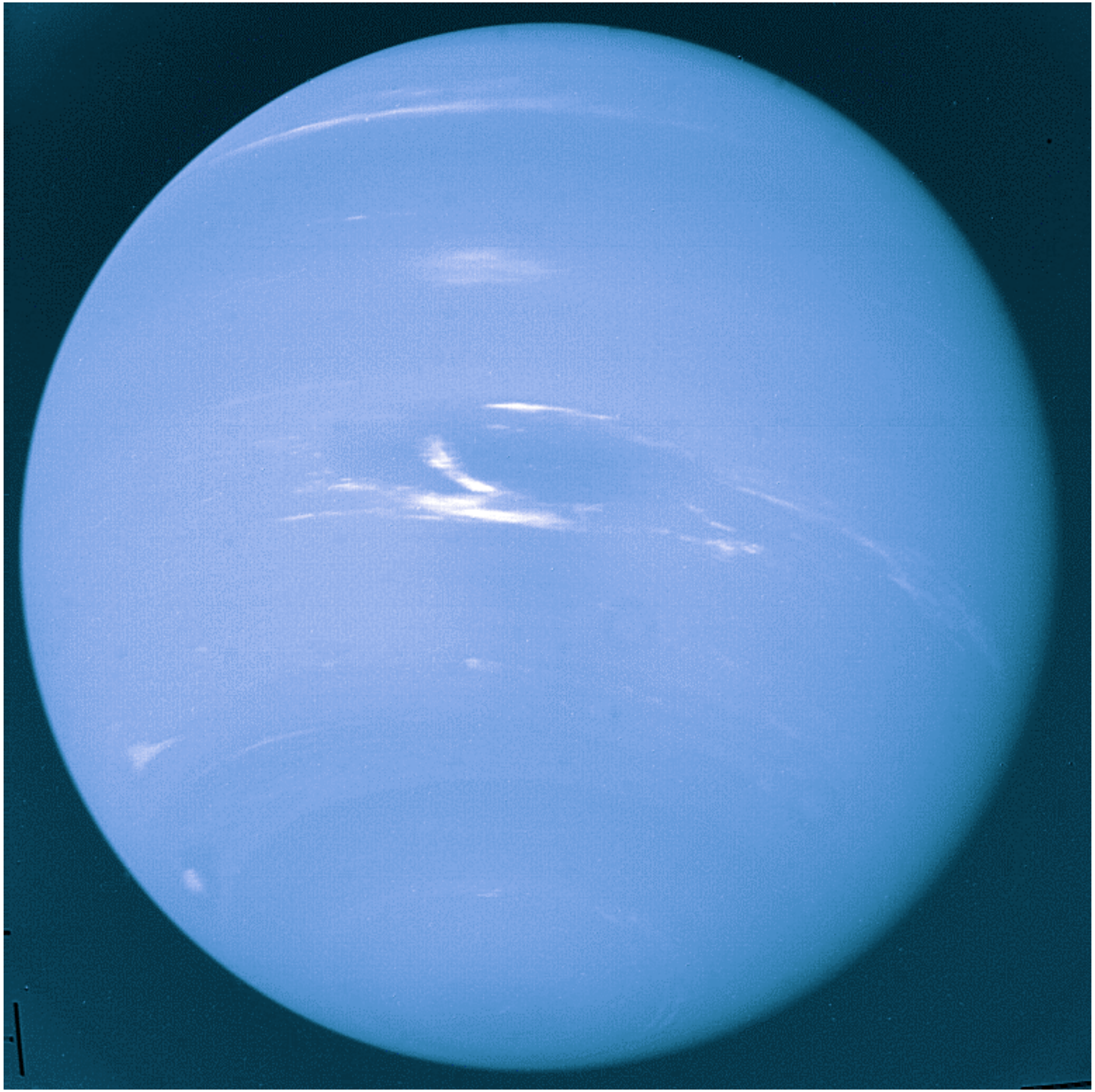


Uranus

- Discovered by William Herschel in 1781
- Orbit: 1,781 million km = 19.2 AU
- Mass: 8.7e25 kg
- Rotation: 17.9 h
- Period: 84 yr
- Diameter: 51,118 km
- Gas planet (with inner solid, core)
- Mean density: 1.29 g/cm^3
- $T_{clouds} \sim -193$ C (green due to Methane)



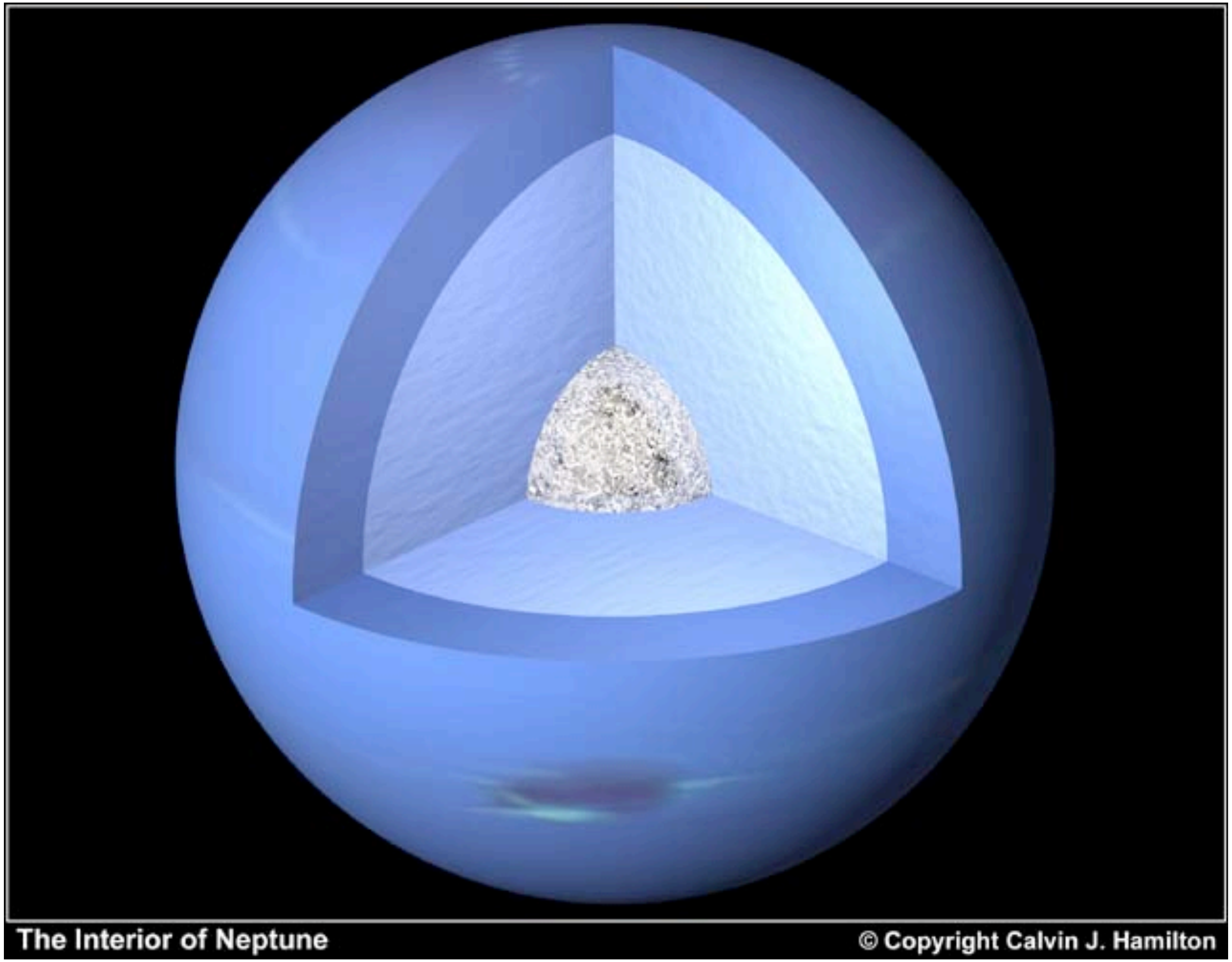
All gas planets
have a ring
system, and
so does
Uranus.



Neptune

- Discovered by Johann Gottfried Galle in 1846
- Orbit: 4,504 million km = 30 AU
- Mass: 1.0e26 kg
- Rotation: 16.1 h
- Period: 165 yr
- Diameter: 49,492 km
- Gas planet (great dark spot)
- Mean density: 1.64 g/cm^3
- T_{clouds} = –193 to –153 C

Neptune



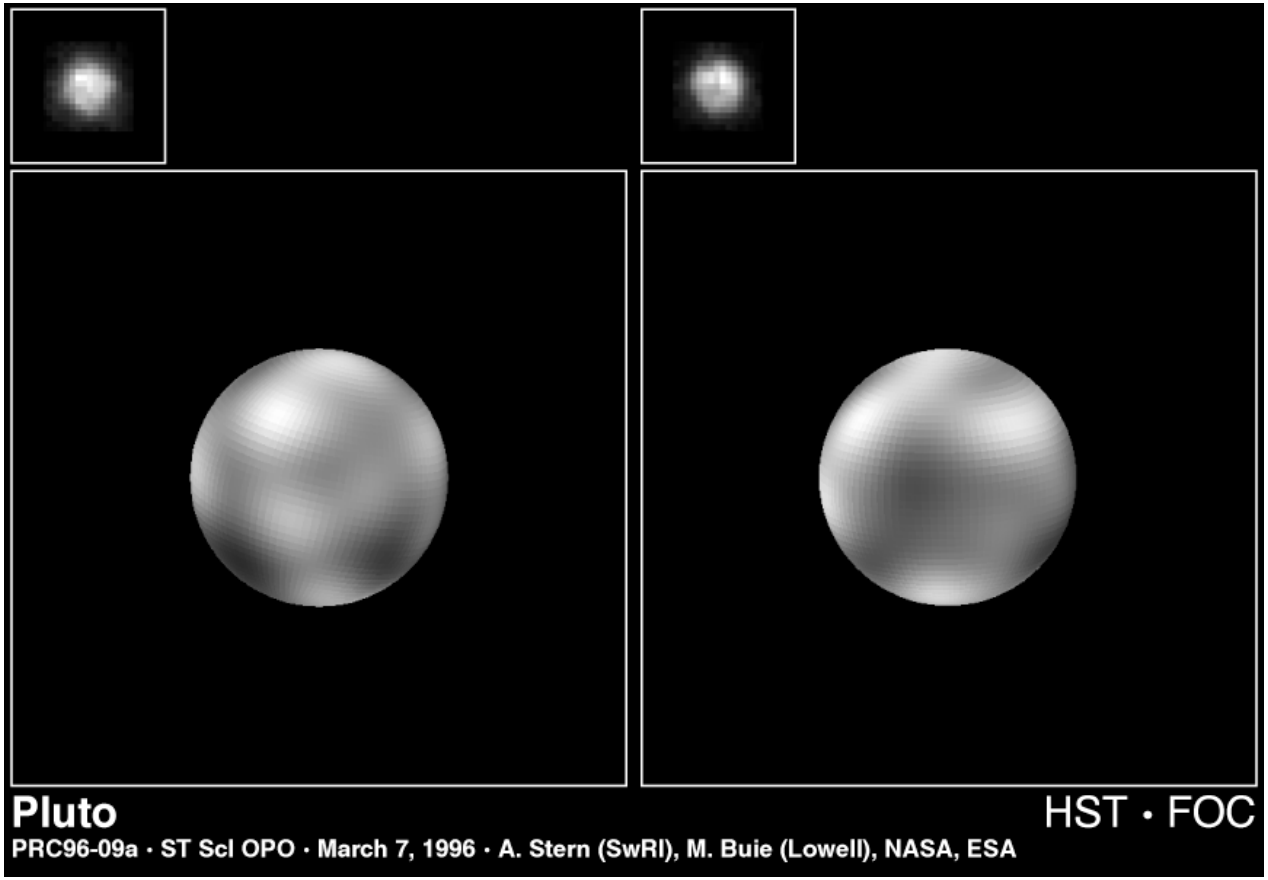
Solid inner core

Thick mantle of water,methane and ammonia

Envelope of H_2, He, methane, ammonia, etc.

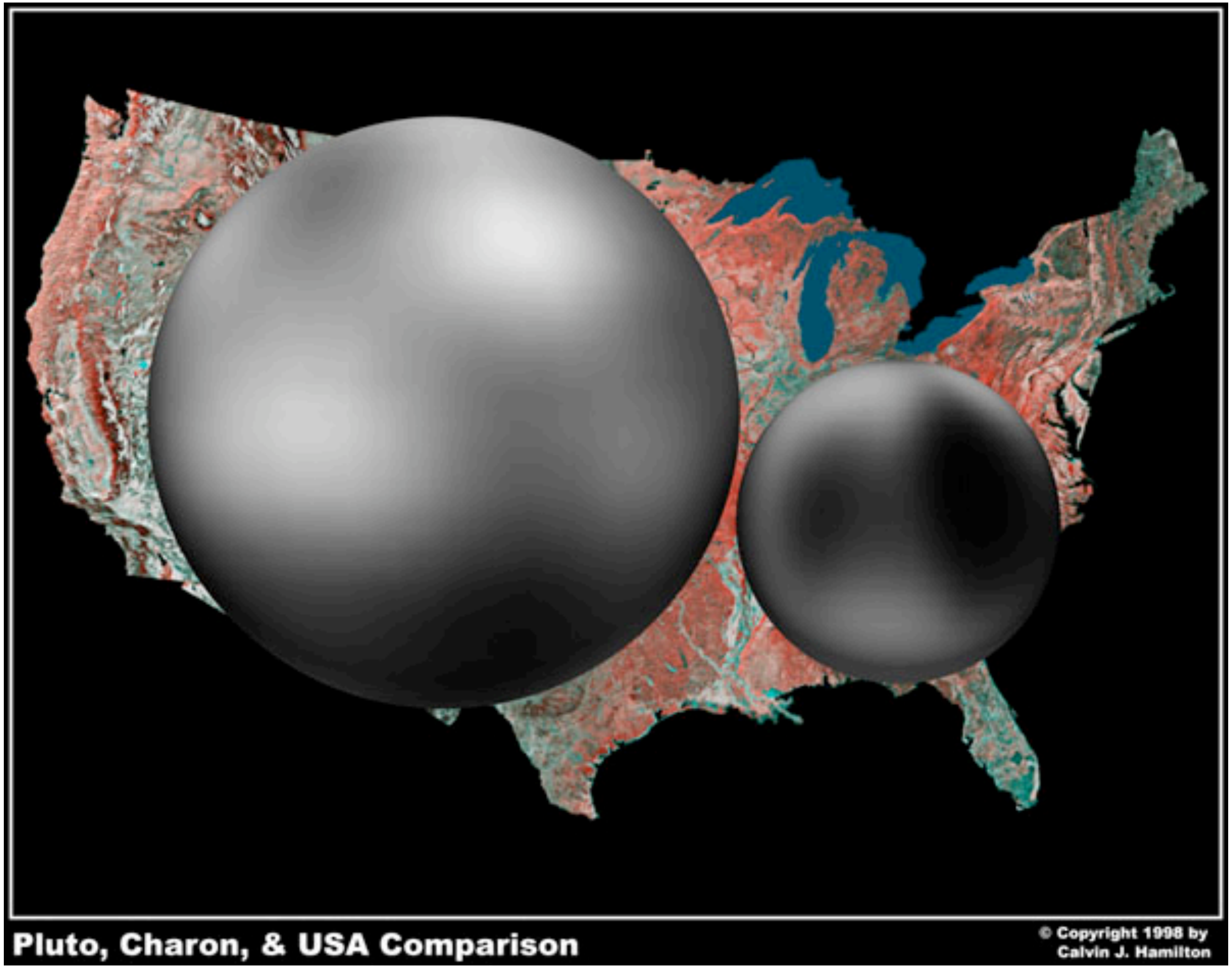
Structure similar to Uranus

Pluto



- Discovered by Clyde Tombaugh in 1930
- Orbit: 5,915 million km = 39.5 AU
- Mass: 1.27e22 kg
- Rotation: 6.4 days
- Period: 165 yr
- Diameter: 2,274 km
- Kuyper belt object
- Binay system with Charon
- Mean density: 2.05 g/cm^3

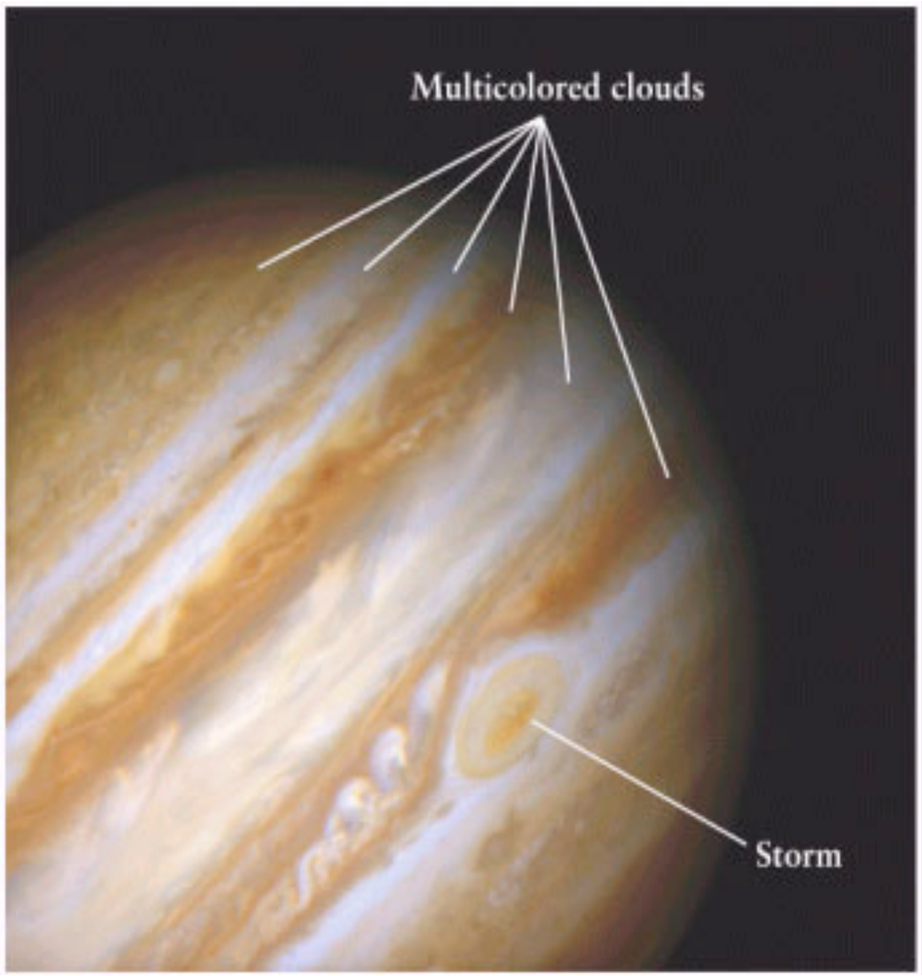
Pluto


Pluto, Charon, & USA Comparison
© Copyright 1998 by
Calvin J. Hamilton

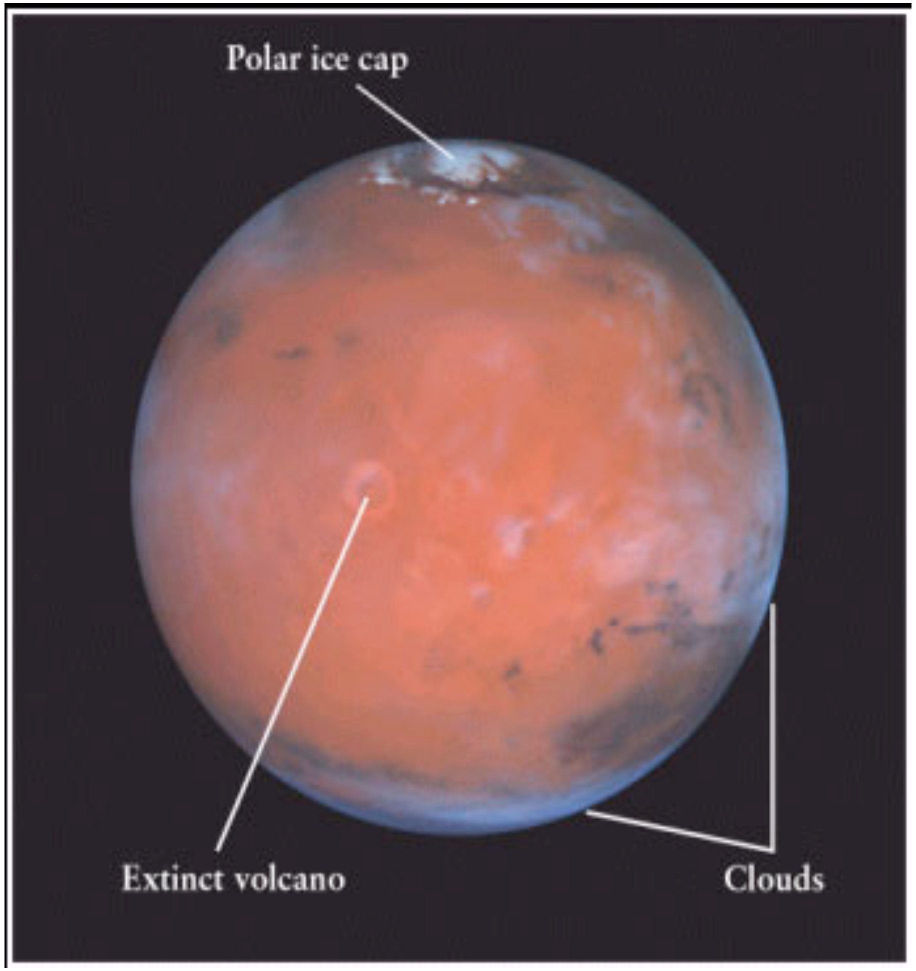
Hydrogen and helium are abundant on the Jovian planets, whereas the terrestrial planets are composed mostly of heavy elements.

Jupiter's cloudtops are composed of mostly the lightest elements, hydrogen and helium.

Hydrogen and helium are colorless; the colors in the atmosphere are caused by trace amounts of other substances.



Hydrogen and helium are abundant on the Jovian planets, whereas the terrestrial planets are composed mostly of heavy elements.



Mars is composed mostly of heavy elements such as iron, silicon, magnesium, and sulfur.

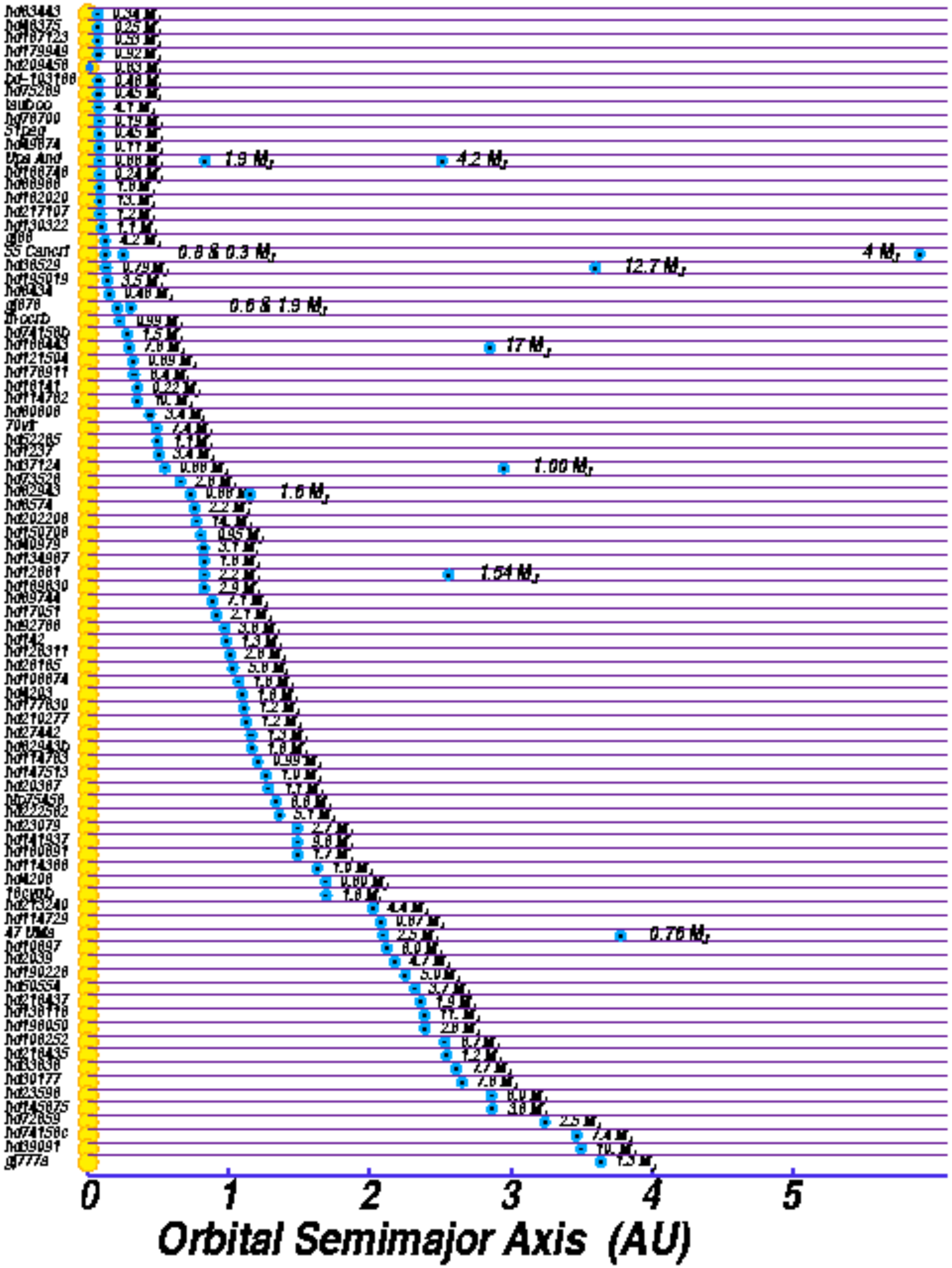
The Martian atmosphere, as seen in this Hubble Space Telescope image is thin and nearly cloudless. The large volcano on the left is Olympus Mons, nearly three times larger than Earth's Mt. Everest.

Properties of Exoplanets

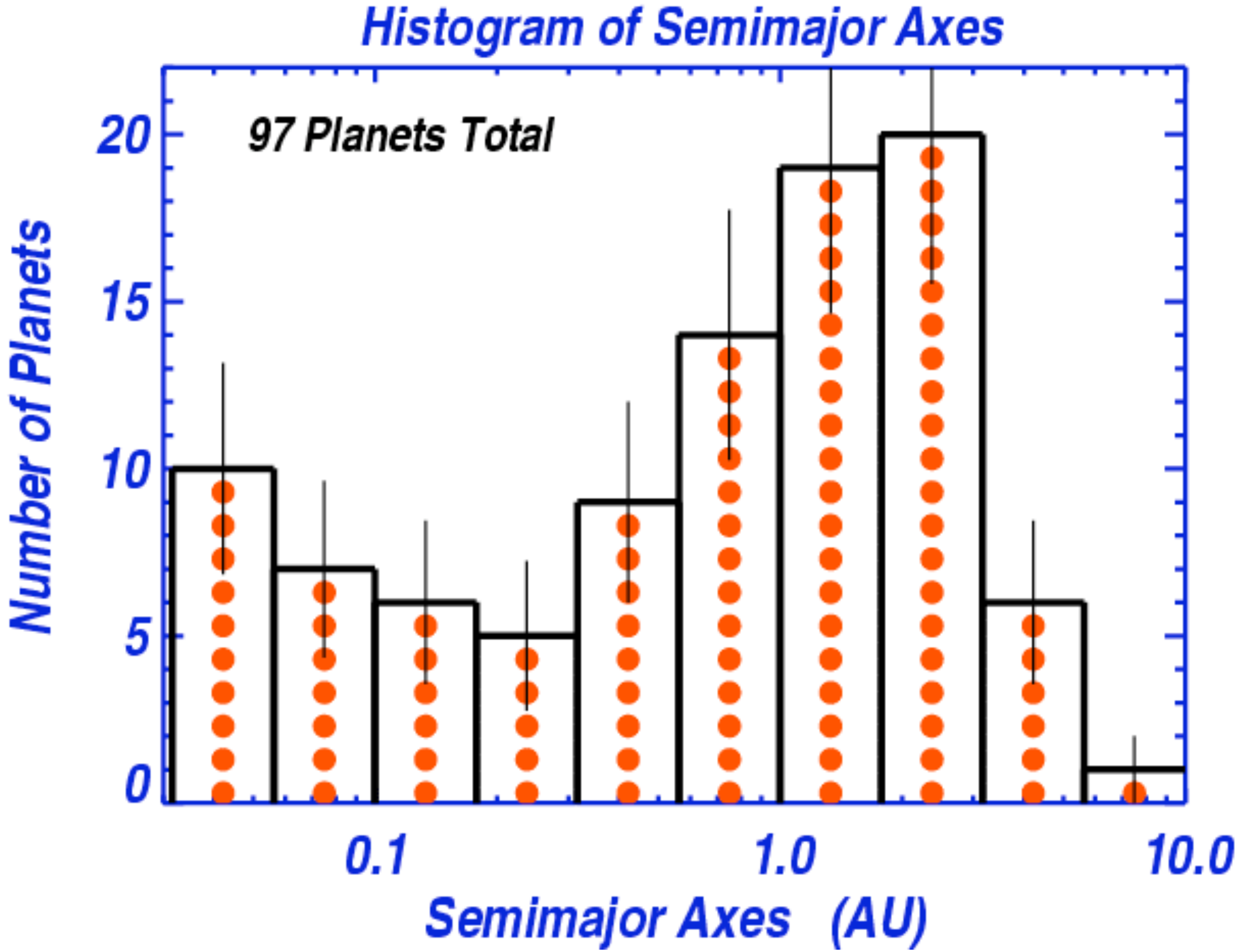
- By now 102 exoplanets known
  (overview www.exoplanets.org)
- Five systems discovered (all in resonances)
- Massive planets (obs. Bias?)
- Short period (obs. Bias?)
- Found around G stars, some around F stars
- None detected in GC's
- Hot Jupiters / hot saturns (i.e. all are massive gas planets)

Properties of Exoplanets

- Hot Jupiters / hot saturns (i.e. all are massive gas planets)
- Can they form there? Migration?
- Is our solar system special? Or do we only see a strong selection effect?



Distribution of semimajor axes


Histogram of Semimajor Axes
97 Planets Total
Number of Planets
0
5
10
15
20
0.1
1.0
10.0
Semimajor Axes (AU)

Properties of Exoplanets

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Planet Search Techniques

Pulsar timing

Radial Velocity Measurements

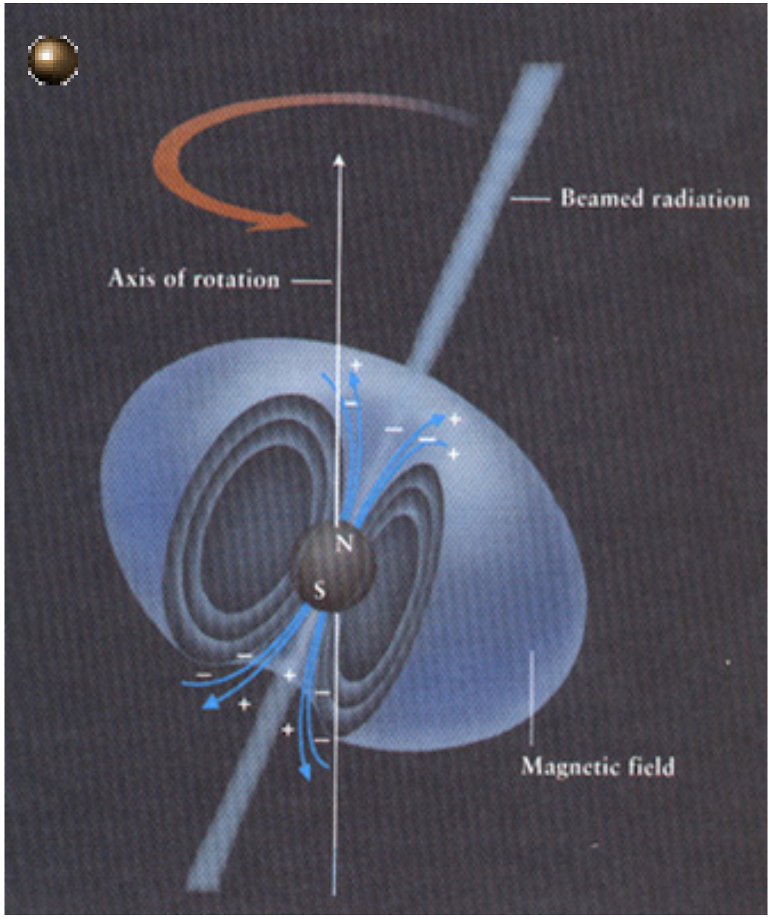
Astrometry

Photometry

Gravitational Microlensing

Eclipsing systems

Pulsar Timing

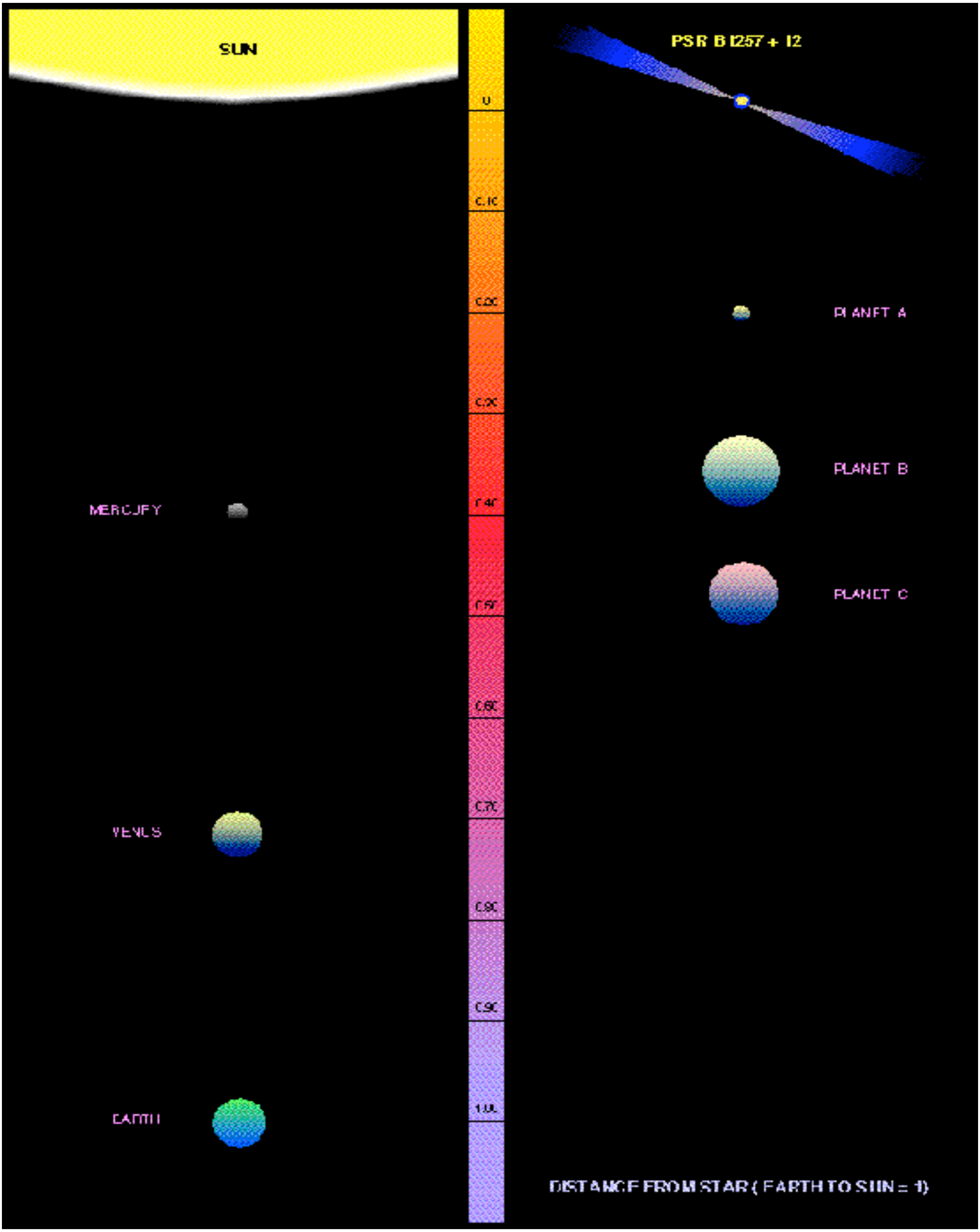


Measure time shifts in the pulse frequency of pulsar signal

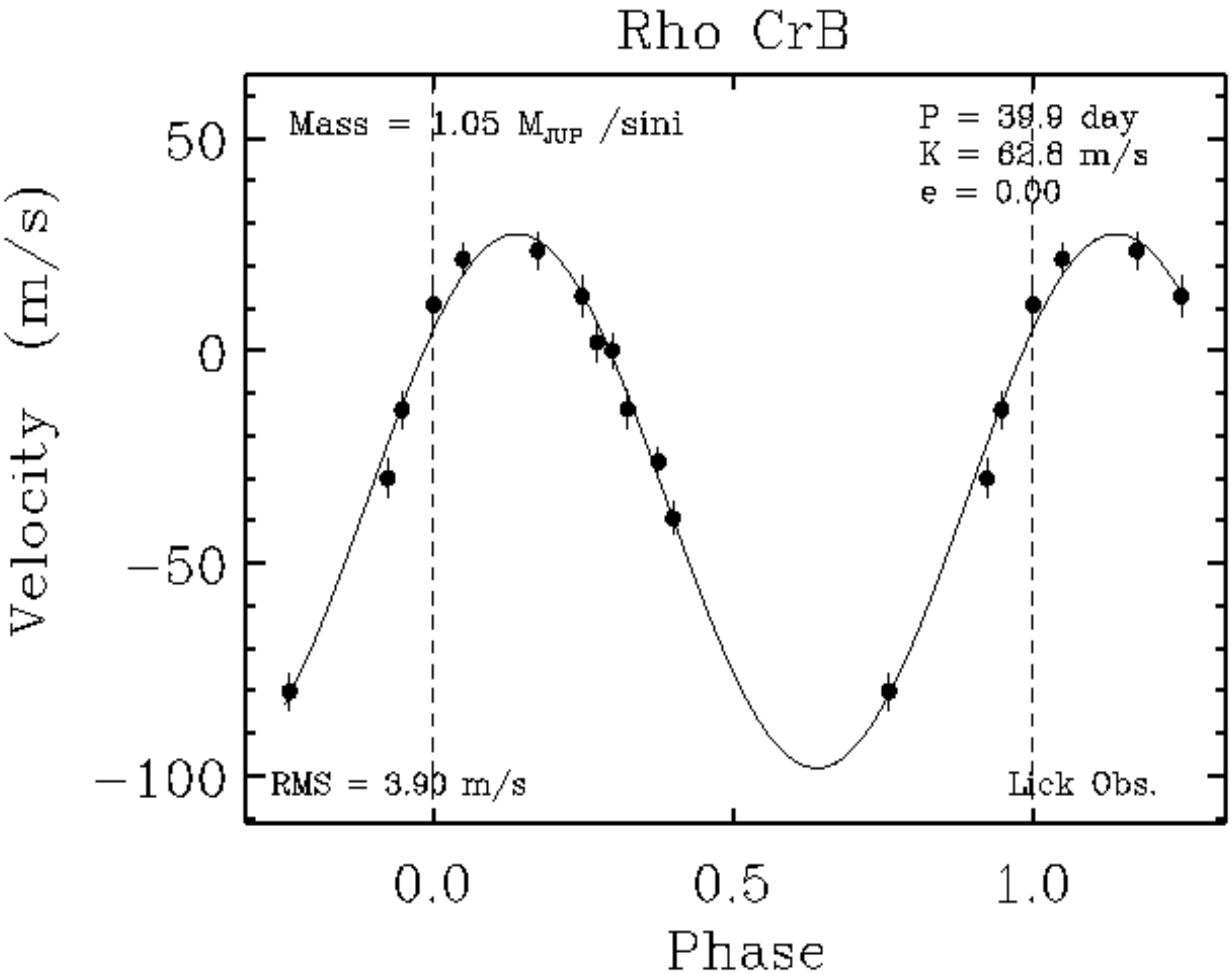
Indicates Doppler motions

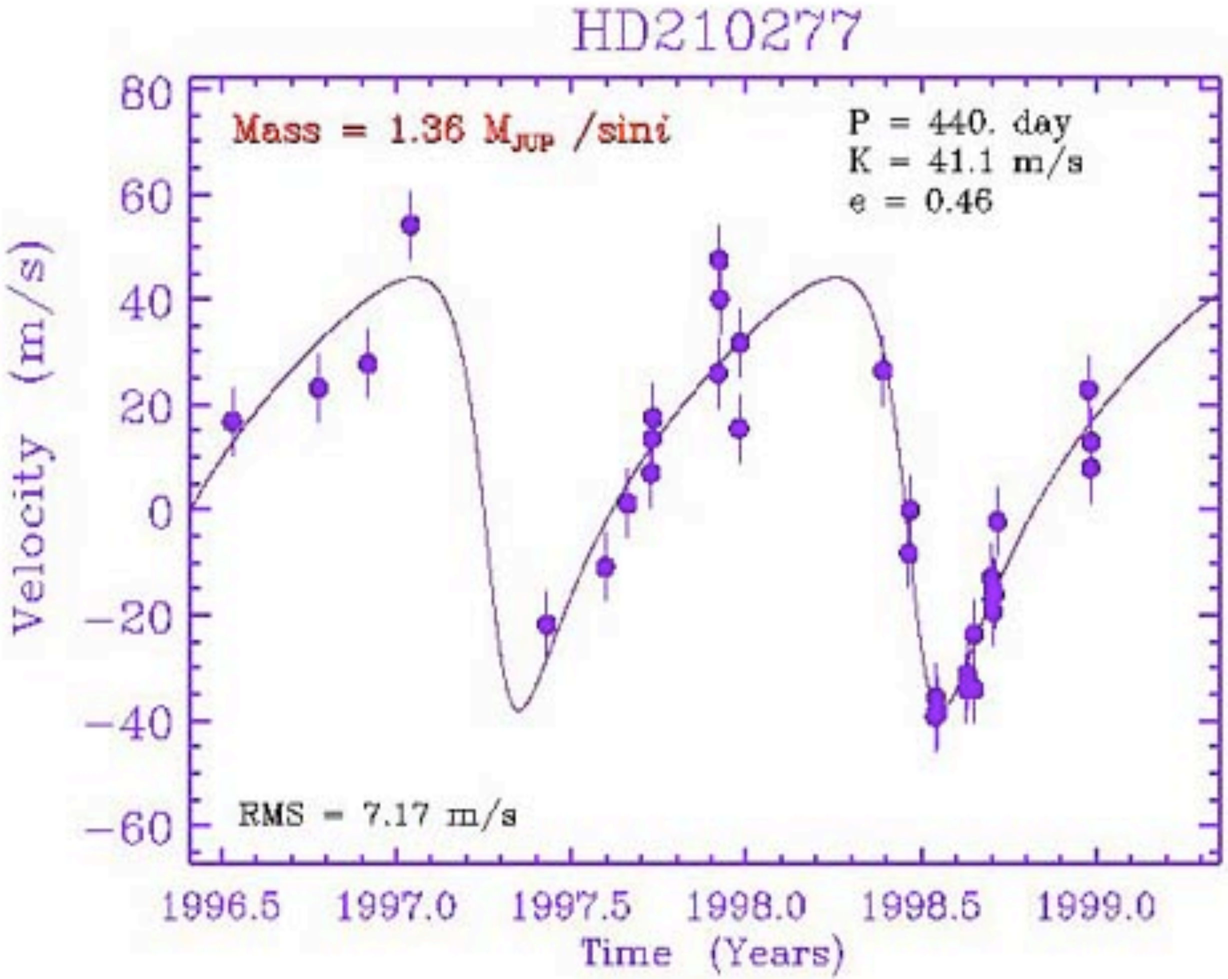
First detection ever of an extrasolar planet: in a pulsar in Virgo in 1991

Actually triple system found


SUN
MERCURY
VENUS
EARTH
PSR B 1257 + 12
PLANET A
PLANET B
PLANET C
0
DISTANCE FROM STAR (EARTH TO SUN = 1)

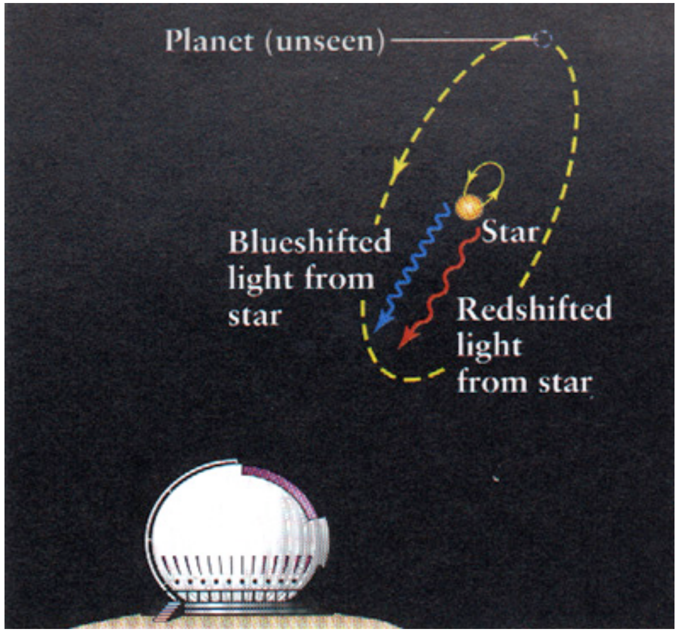
Radial Velocity Measurements

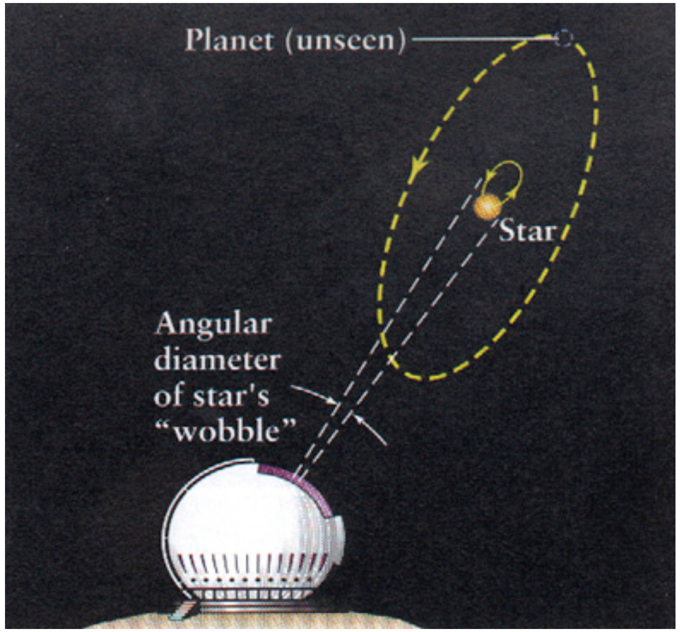


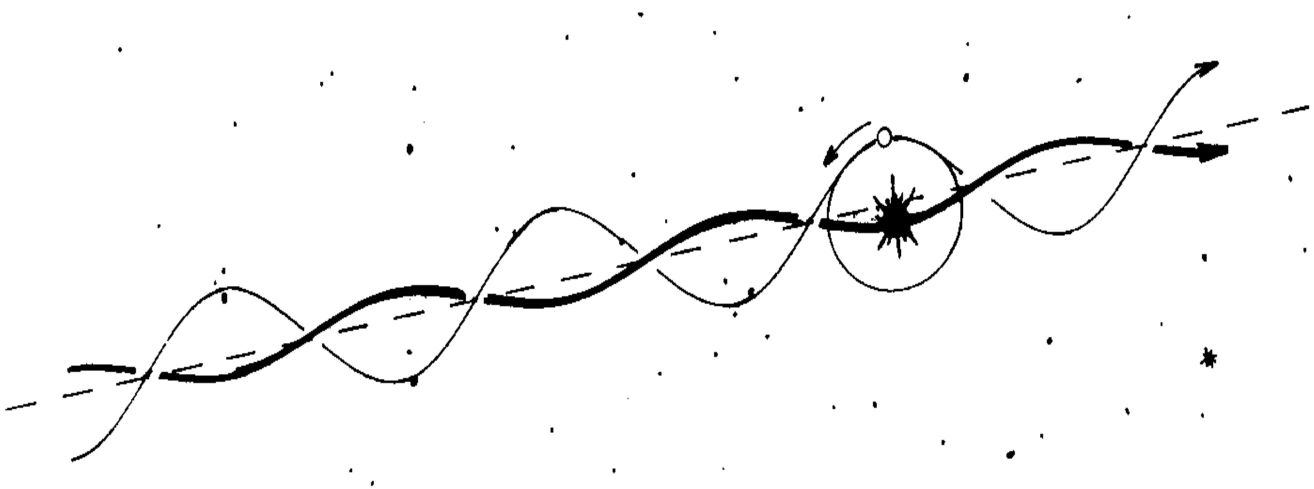

HD210277
Mass = 1.36 M_JUP /sini
P = 440. day
K = 41.1 m/s
e = 0.46
RMS = 7.17 m/s
Velocity (m/s)
Time (Years)
80
60
40
20
0
−20
−40
−60
1996.5
1997.0
1997.5
1998.0
1998.5
1999.0

Astrometry

- Definition : measures the position of a star against the sky (the proper motion)
- Basic Idea : low-mass companions will cause a wiggle in a star's path
- possible to obtain more information than by observing the radial velocity
- requires high-precision observations


Planet (unseen)
Star
Blueshifted light from star
Redshifted light from star


Planet (unseen)
Star
Angular diameter of star's "wobble"



Photometry

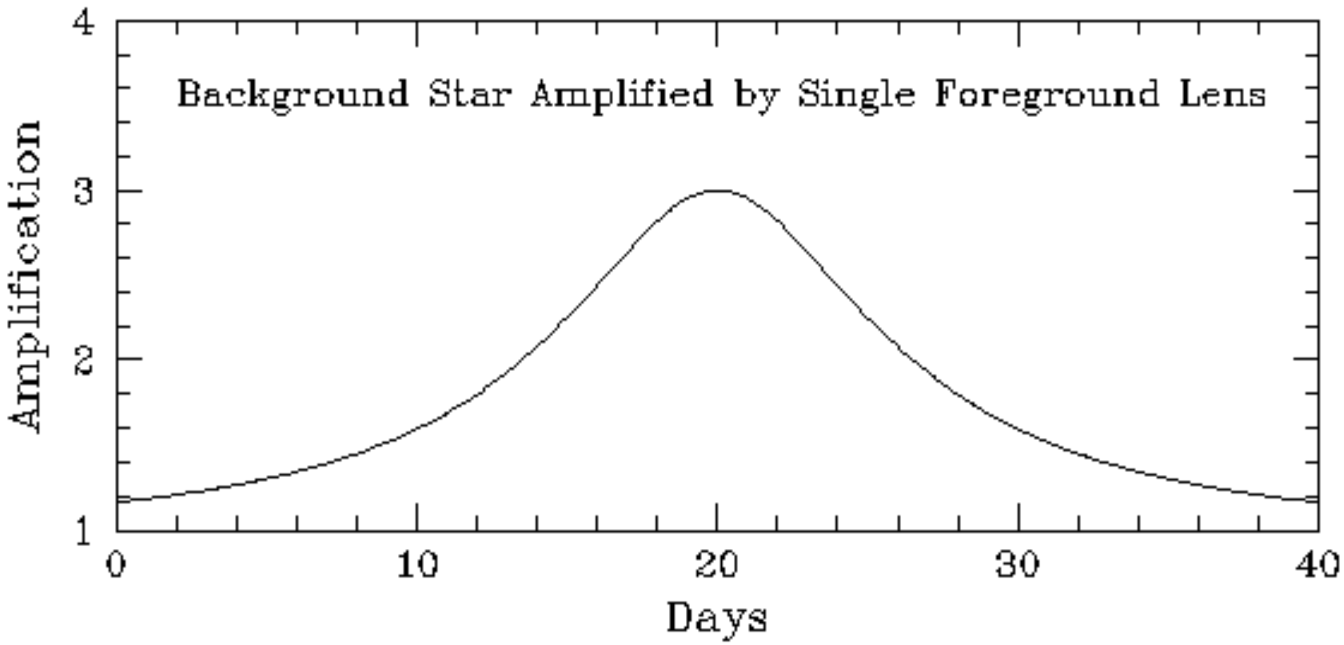
- Definition: measures the brightness of a star.
- Basic Idea: look for variations in a star’s brightness caused by transiting planets
- make sure the orbital plane is oriented correctly
- Bad News: requires precision of 1 part in 100 000 and lots of time.
- Good News: we can actually do this with current technology
- Better News: some astronomers are doing it right now.

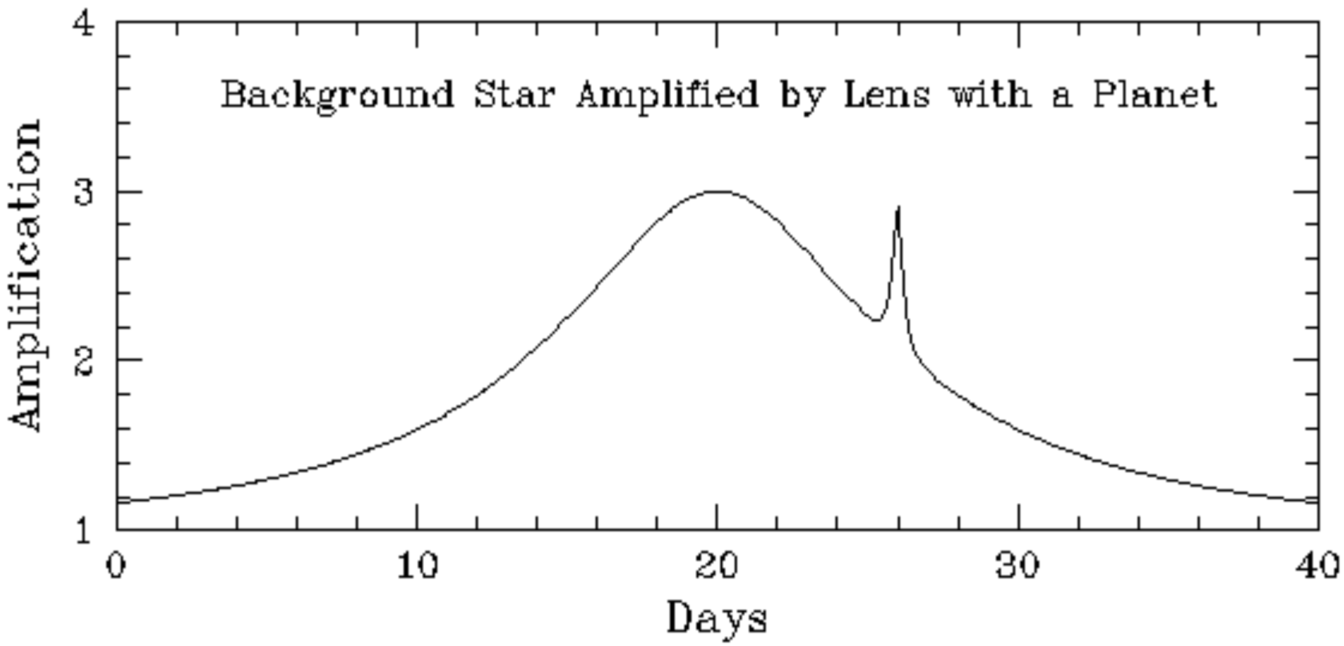
Gravitational Microlensing

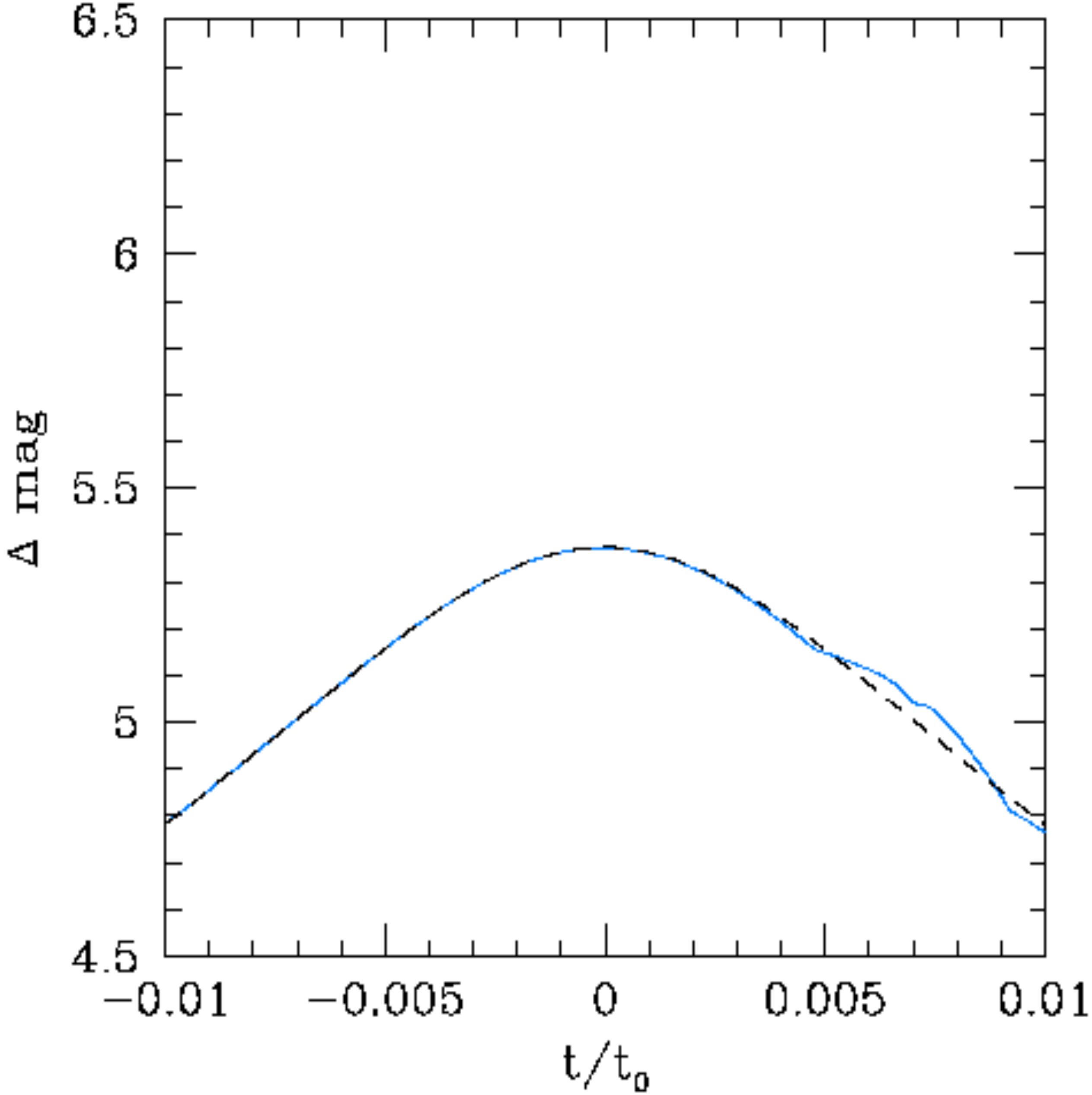
-

- Basic Idea: A star passing in front of a more distant object will act as a lens.

- A planet orbiting the lensing star will leave a special signature in the light profile.


Background Star Amplified by Single Foreground Lens
Amplification
Days
1
2
3
4
0
10
20
30
40


Background Star Amplified by Lens with a Planet
Amplification
Days
1
2
3
4
0
10
20
30
40



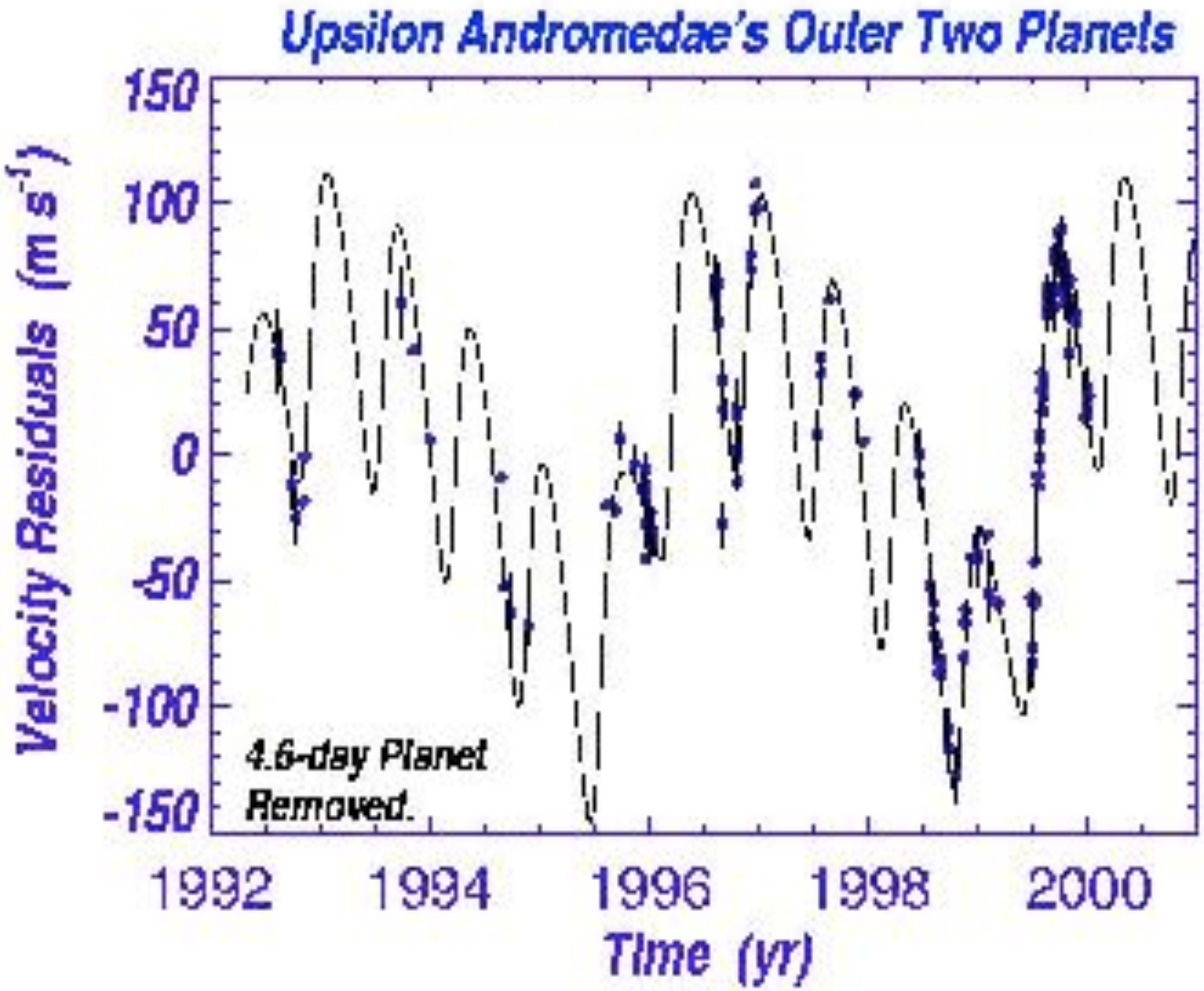
6.5
6
5.5
5
4.5
Δ mag
−0.01
−0.005
0
0.005
0.01
t/t₀

Multiple Planets.

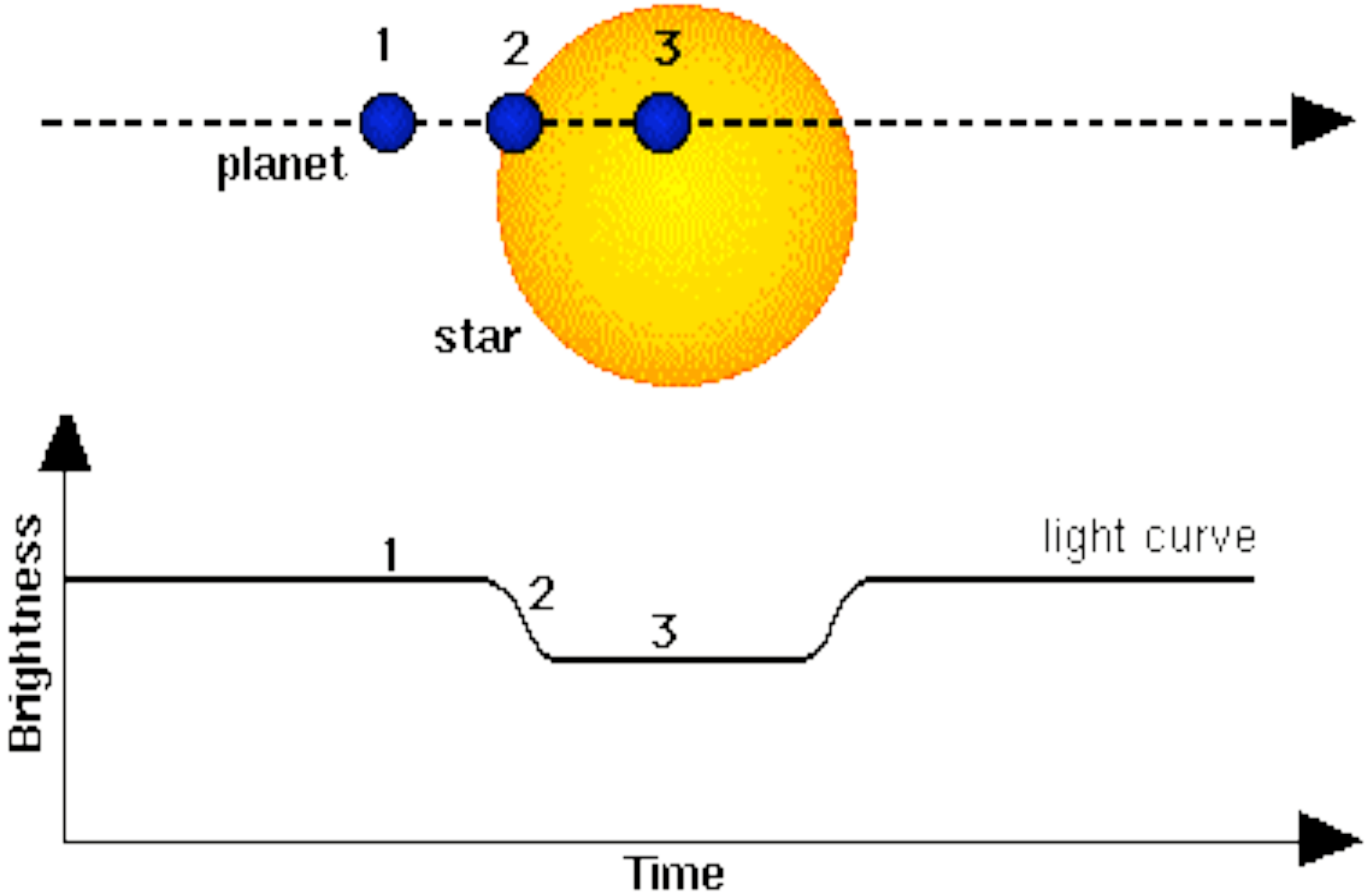
- Five stars have now been found with complex wobbles
- multiple planets.
- All in resonances
- Best example: Upsilon Andromedae

Jiggling Motion.

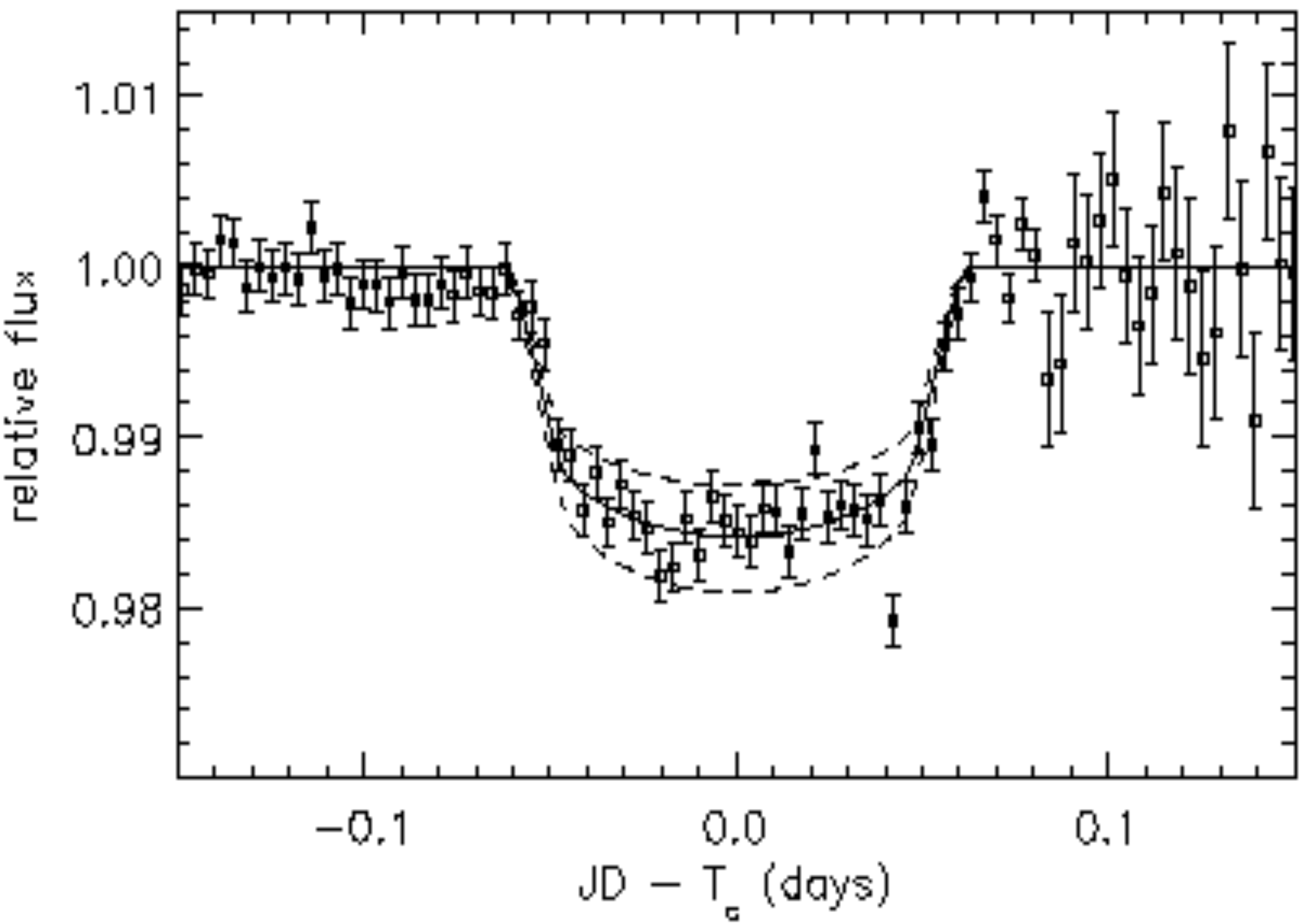
- Here is a graph of its changes in velocity (as measured by the Doppler shift of its spectrum). Note the complex pattern - evidence for at least three planets.



Eclipsing planet: HD 209458

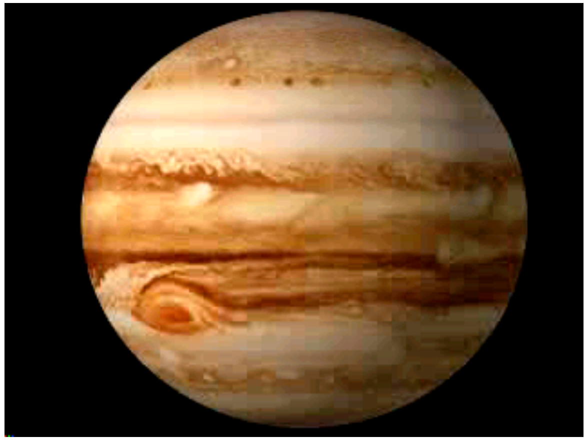


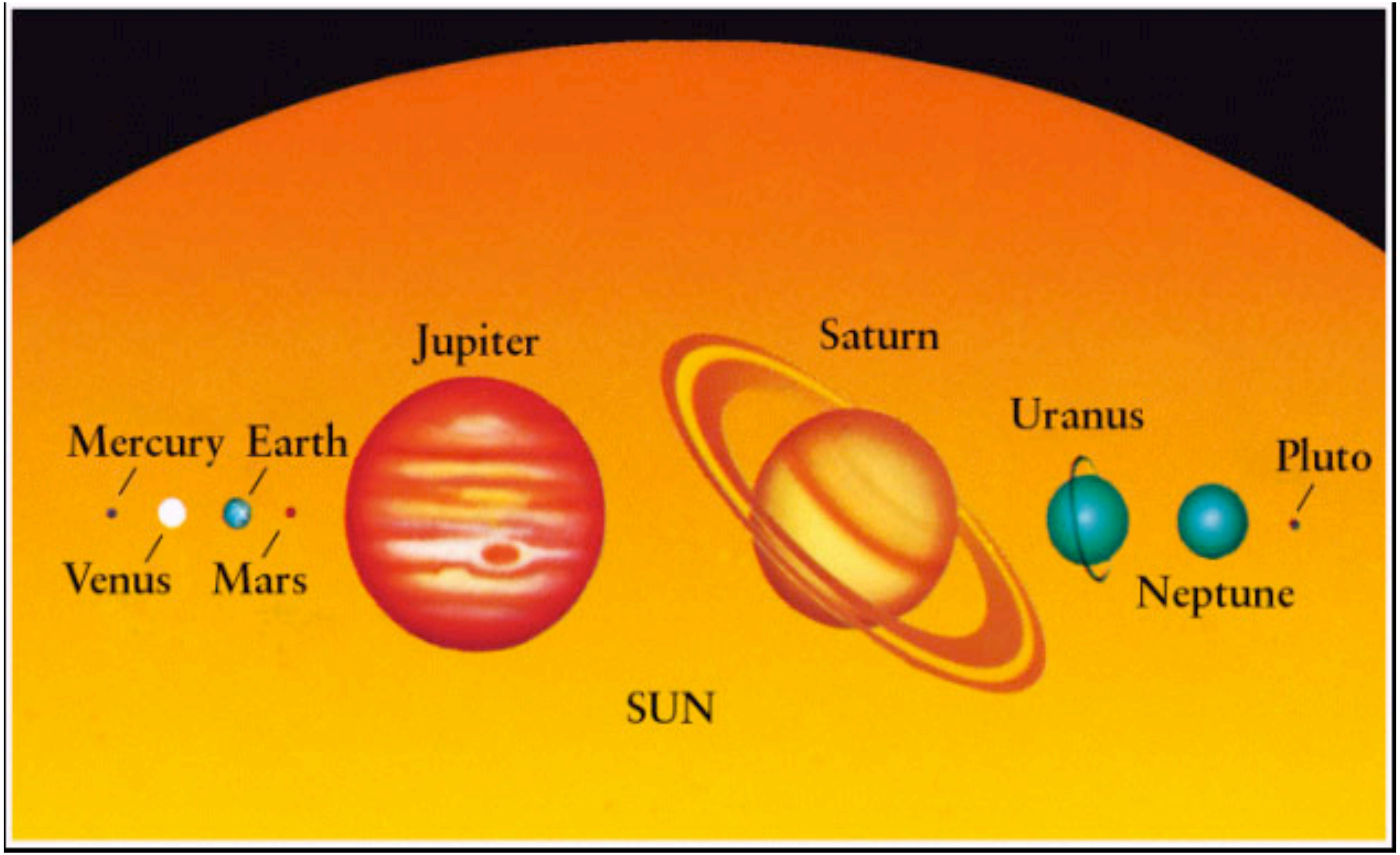
Transit of planet across HD 209458



Implications

- Best studied extrasolar planet so far!. Because of eclipse we know precisely mass, radius, and all orbital parameters.
- Its size is slightly greater than Jupiter, yet it is less massive, implying that it's density must be very low - lower even than that of Saturn (which is the least dense planet in our solar system).
- Could it have formed there? Migration?
- Tidal heating? (e.g. Gu et al 2003)
- Strange surface conditions: Tidally locked → Strong T contrasts (1000K vs. 400K) → strong winds → observable consequences?
- Therefore: "Hot Jupiter" must be a gas giant planet - no rocky world would have such a low density.




Jupiter
Saturn
Uranus
Pluto
Mercury
Earth
Venus
Mars
Neptune
SUN

(Why not imaging?)

Competition between:

- sensitivity (planet-star contrast)
- resolution (planet-star distance)

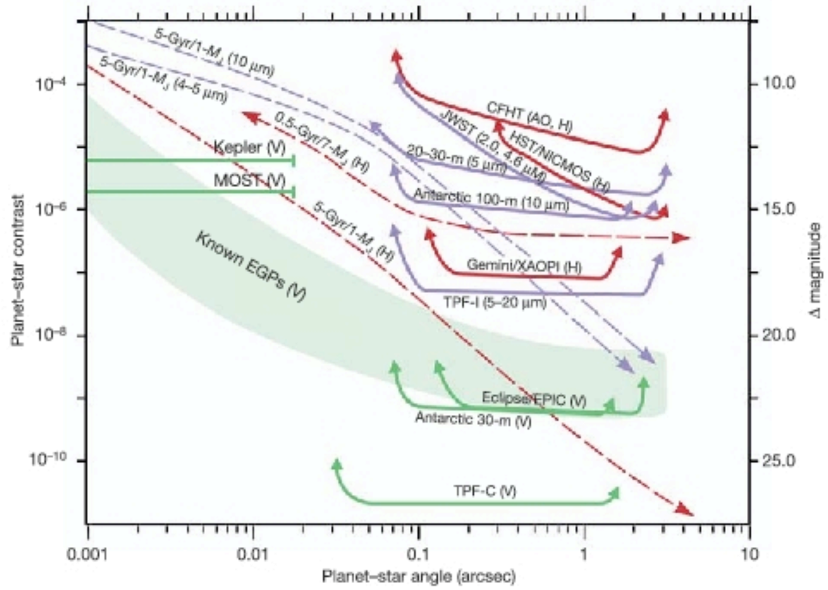


Figure 5 A comparison of the planet/star contrast ratios (and contrast magnitudes = −2.5 log(*f*)) versus angular separation (in arcsec) achievable for some proposed planet imaging systems. A distance of 10 pc is assumed. Integration times and signal-to-noise ratios assumed vary and are taken from preliminary studies by the associated instrument teams. At *H* band (red), the imaging telescopes represented include the Canada/France/Hawaii Telescope (CFHT)[69], HST/NICMOS and the Gemini/XAOPI. Not shown on this plot is the MMT (AO) system, which should achieve, at a wavelength of 5 μm, *f* values from 10^{-4} to a few $\times 10^{-6}$ for angular separations of 0.3" to 1.0", respectively. The LBT (also not shown) should achieve, at a wavelength of 10 μm, an approximately ten times better performance than this. At 5 μm, a notional curve for a 20- or 30-m telescope in Antarctica and the JWST (in fact, at 4.6 μm) are provided. At 10 μm, a notional curve for a 100-m telescope in Antarctica is given. Also included on this plot is the interferometric version of TPF (TPF-I/Darwin), which might have a sensitivity of one part in 10^7 from 5 to 20 μm. All the mid-infrared curves are in purple. In the optical (green, *V*), putative sensitivities for the EPIC, ECLIPSE and TPF-C instruments are plotted. Superposed are corresponding 'phase-averaged' theoretical curves (dashed) for a 5-Gyr/1-M_J EGP around a G2V star in the *H* band (~1.65 μm), in the 4–5-μm band, and at 10 μm (see Fig. 2). Also included are a theoretical curve in the *H* band (dashed red) for a 0.5-Gyr/7-M_J EGP around a G2V star and a green swathe where the known EGPs may reside in the optical (*V* band). Note that the theoretical curves for more massive and younger EGPs than represented on this plot can be considerably higher. Orientation effects have been ignored. Each curve is for a given wavelength or bandpass and the imager and theory must be compared at the same wavelength. Very generous error bars should be assumed. The photometric sensitivity curves for MOST and Kepler are also superposed. See text for details.

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Theories

1. Solid core formation from agglomeration of dust grains, to rocks to planetesimals.

- Gas accretion onto these solid cores.
- Orbital migration to smaller radii due to local "clearing" of the gas disc (because of gas accretion), formation of gaps around the planet.

BUT: require too long a timescale, especially for the formation of the solid core plus planets do not migrate nor grow as close as observations suggest (gas disc vanishes).

- Latest model, allows planet to form a circum-planetary disc which enhances accretion rates.

Theories

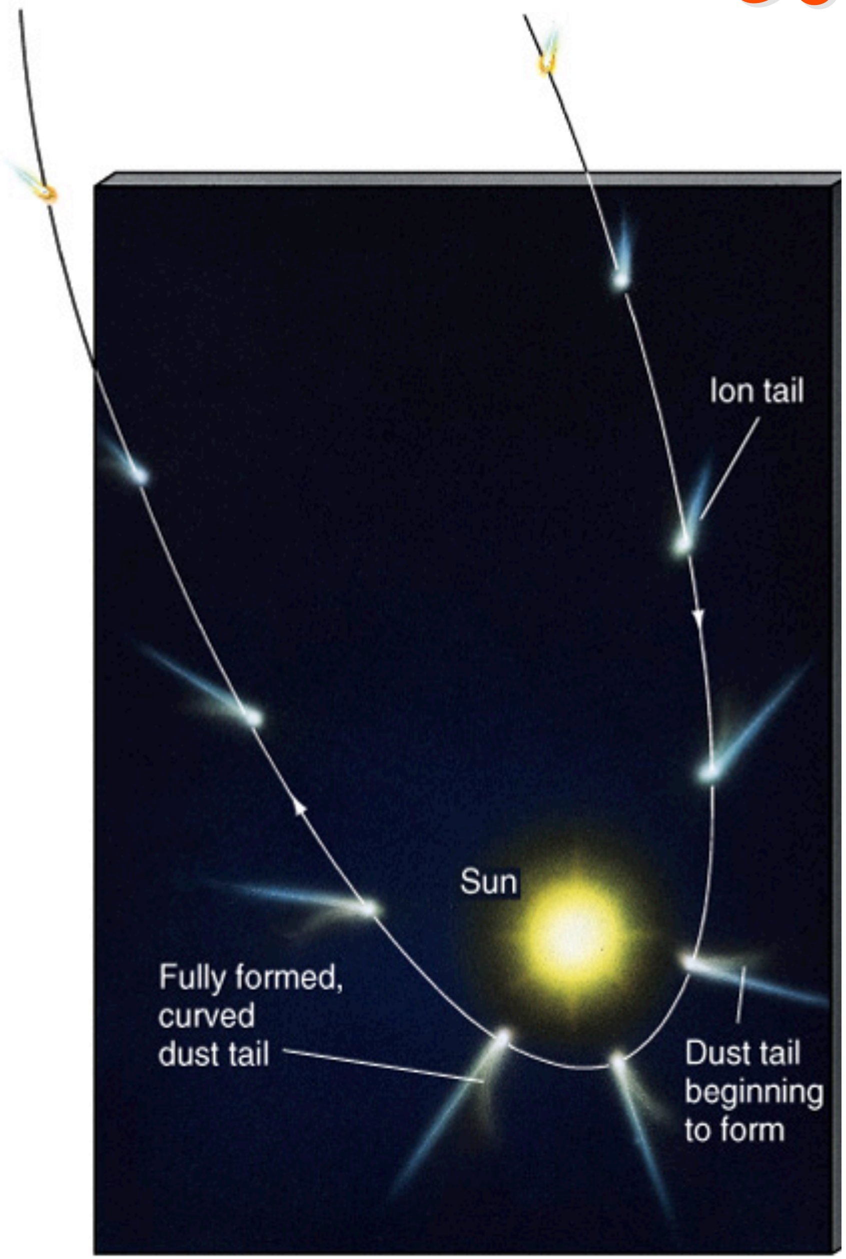
2. Fragmentation of the gas disc, i.e. planet forms with the same mechanism that companions to the star form, but in this case the final mass is lower (maybe depend on time of fragmentation and the state of the dynamical properties of the disc at this stage). Problem with frequency plus mass and radius distributions?

Debris objects

- **Asteroids** – fragments of rocky objects
  - Range in size up to 100 km in diameter.
  - Irregularly shaped, and cratered.
  - Similar in composition to outer layers of terrestrial planets.
- **Comets** – small icy bodies (dirty snowballs).
  - Large elliptical orbits can bring comets in close to the Sun.
  - Recent studies suggest they are at least 50% rock and dust.
- **Meteoroids** – specks of dust and rock similar in composition to Asteroids, but much smaller (less than 100 m in diameter).

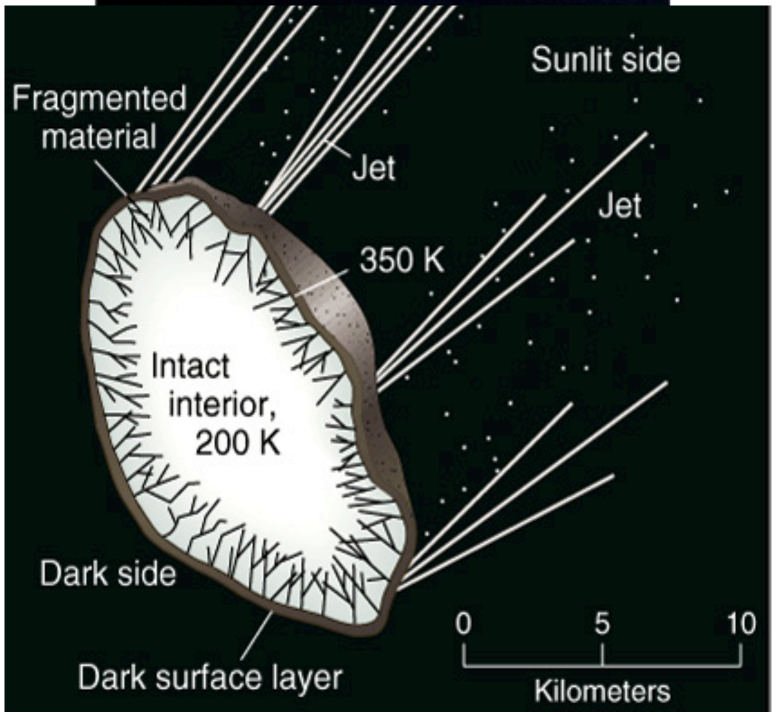
Comets

Comets



- Comets have two tails:
  - Gas (ion) tail (type I)
    - Ionized gas carried away by the solar wind.
    - Generally points away from the Sun.
  - Dust tail (type II)
    - Dust loosened by vaporizing ice, pushed away be solar wind.
    - Follows orbital path of comet.
- Coma – halo of gas and dust surrounding the nucleus.
  - Nucleus ~ 10 – 100 km
  - Coma ~ 10^5 km

Comet nuclei

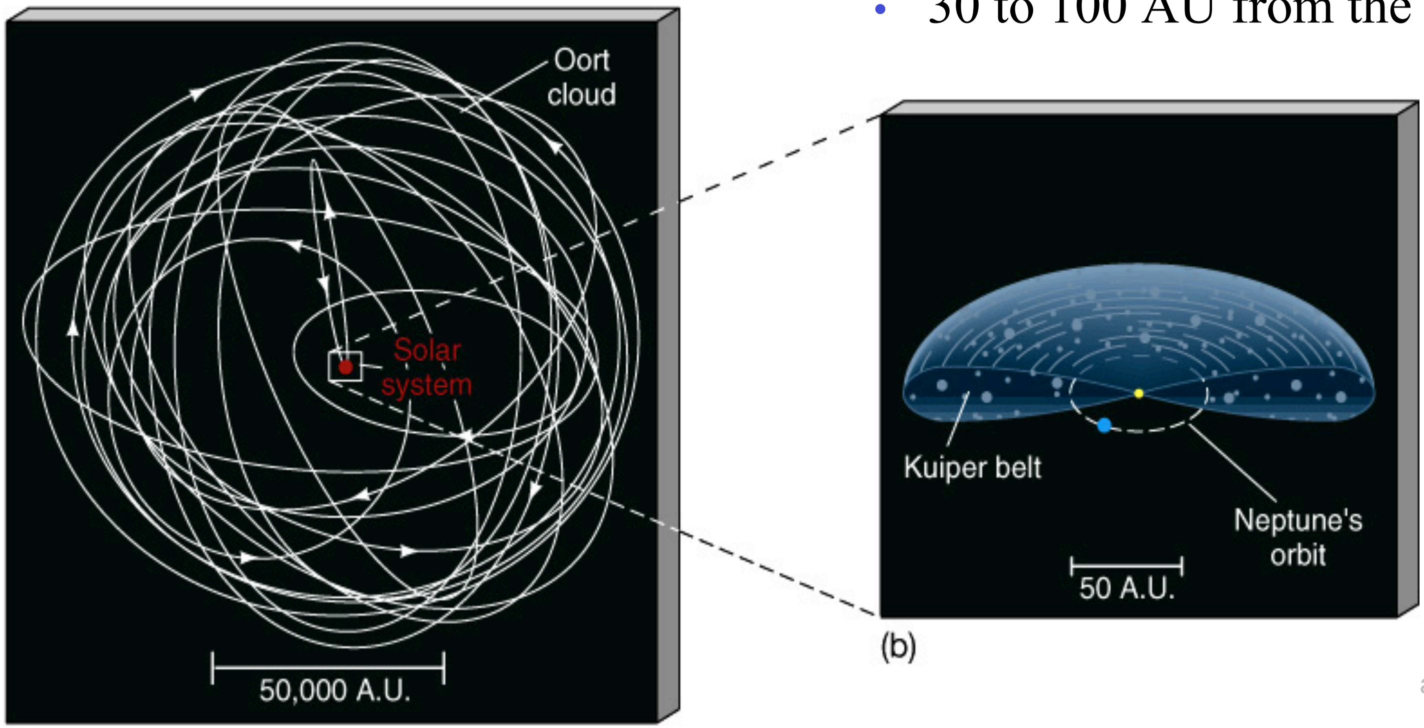


- Comet nuclei
  - Porous rock, irregular in shape.
  - Ices (H_2O, CO_2, ammonia, etc.)
  - Density ~ 0.1 – 0.25 g/cm^3
- As comet nears the sun, ices sublime (change directly from solid to gas).
- Jets of material give off gases and dust.
  - Probably faults or vents in surface of nucleus.

The Origin of Comets

- Long period comets (P > 200 yrs.)
  - Randomly inclined orbits.
  - Random direction and revolution.
- Oort Cloud
  - Spherical cloud of icy bodies.
  - 10^4 to 10^5 AU in radius.

- Short period comets (P < 200 yrs.)
  - Orbits lie within 30° of the plane of the Solar System.
  - Most revolve counterclockwise.
- Kuiper Belt
  - Disk of icy planetesimals.
  - 30 to 100 AU from the Sun.



The planetary system