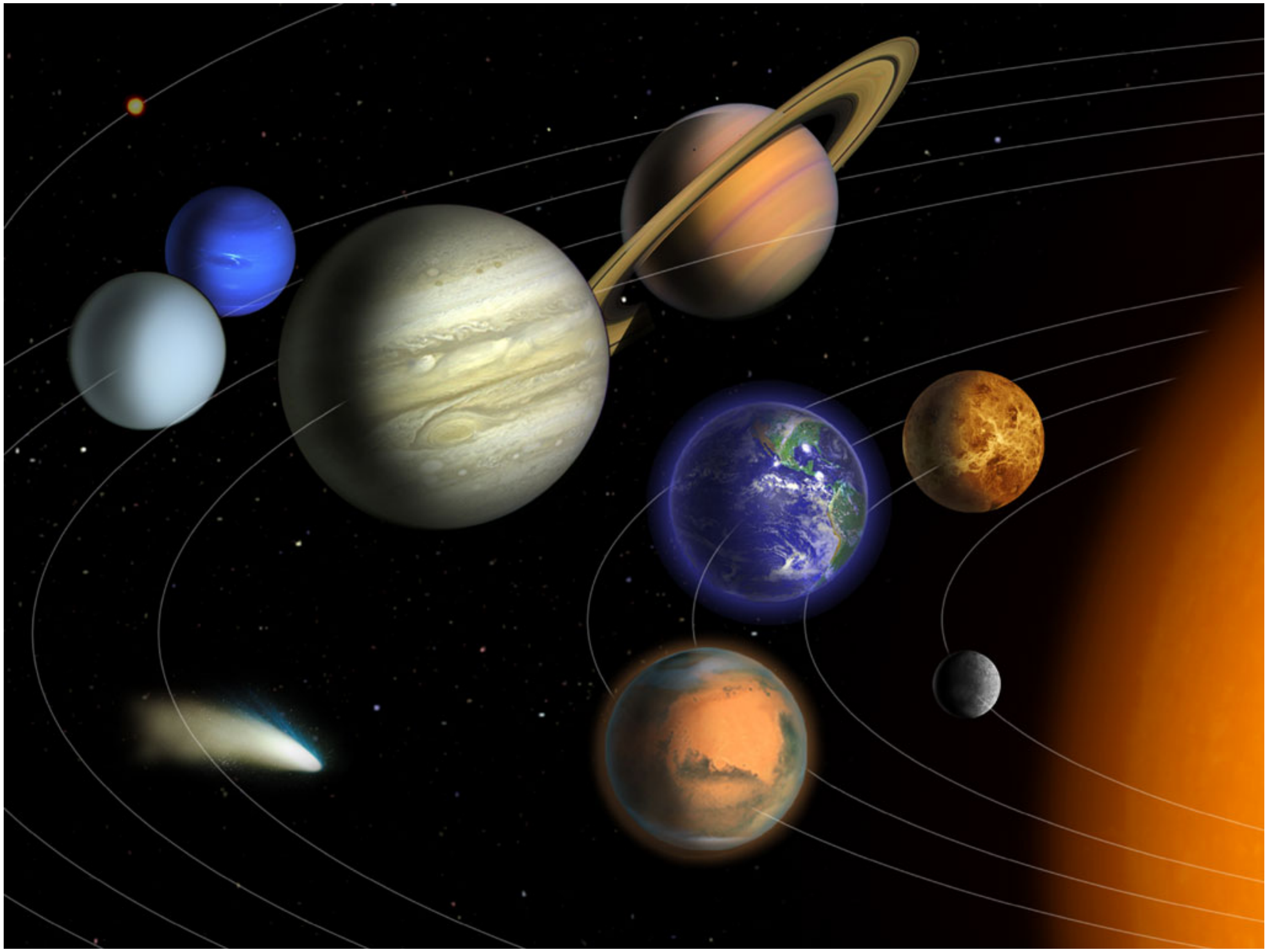
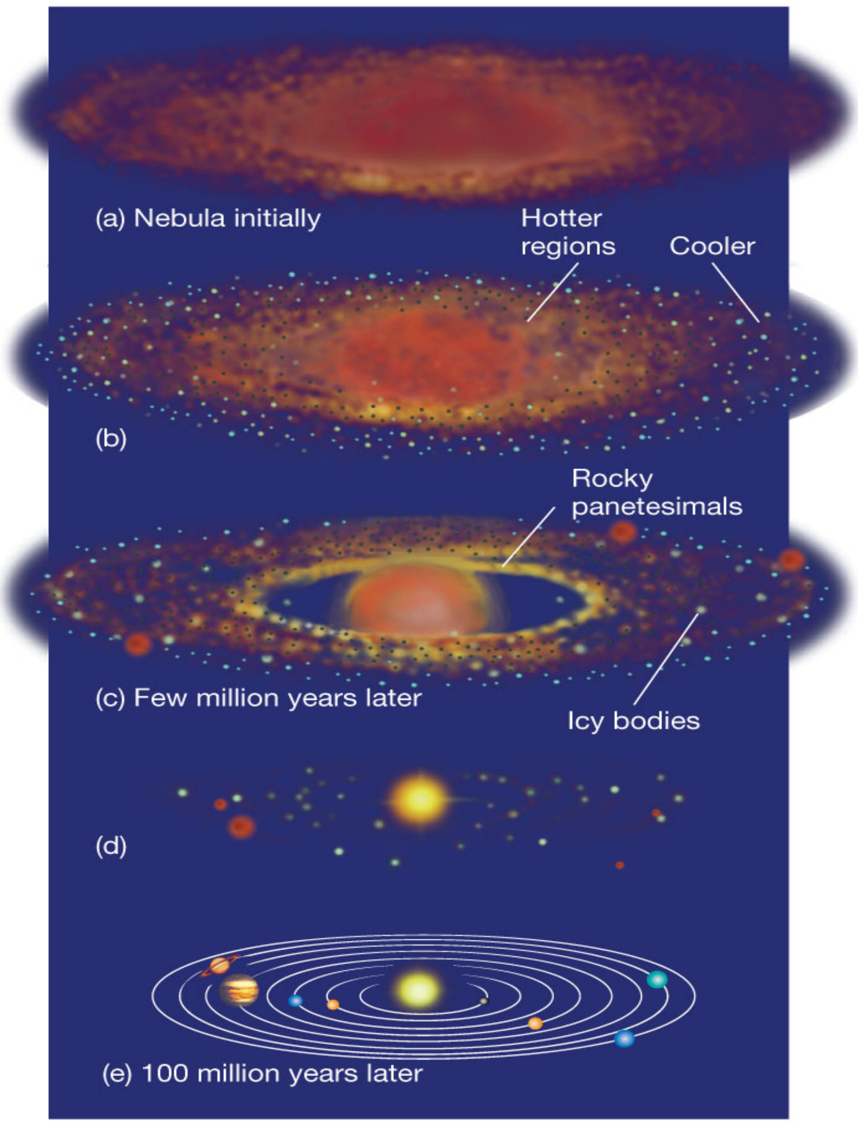
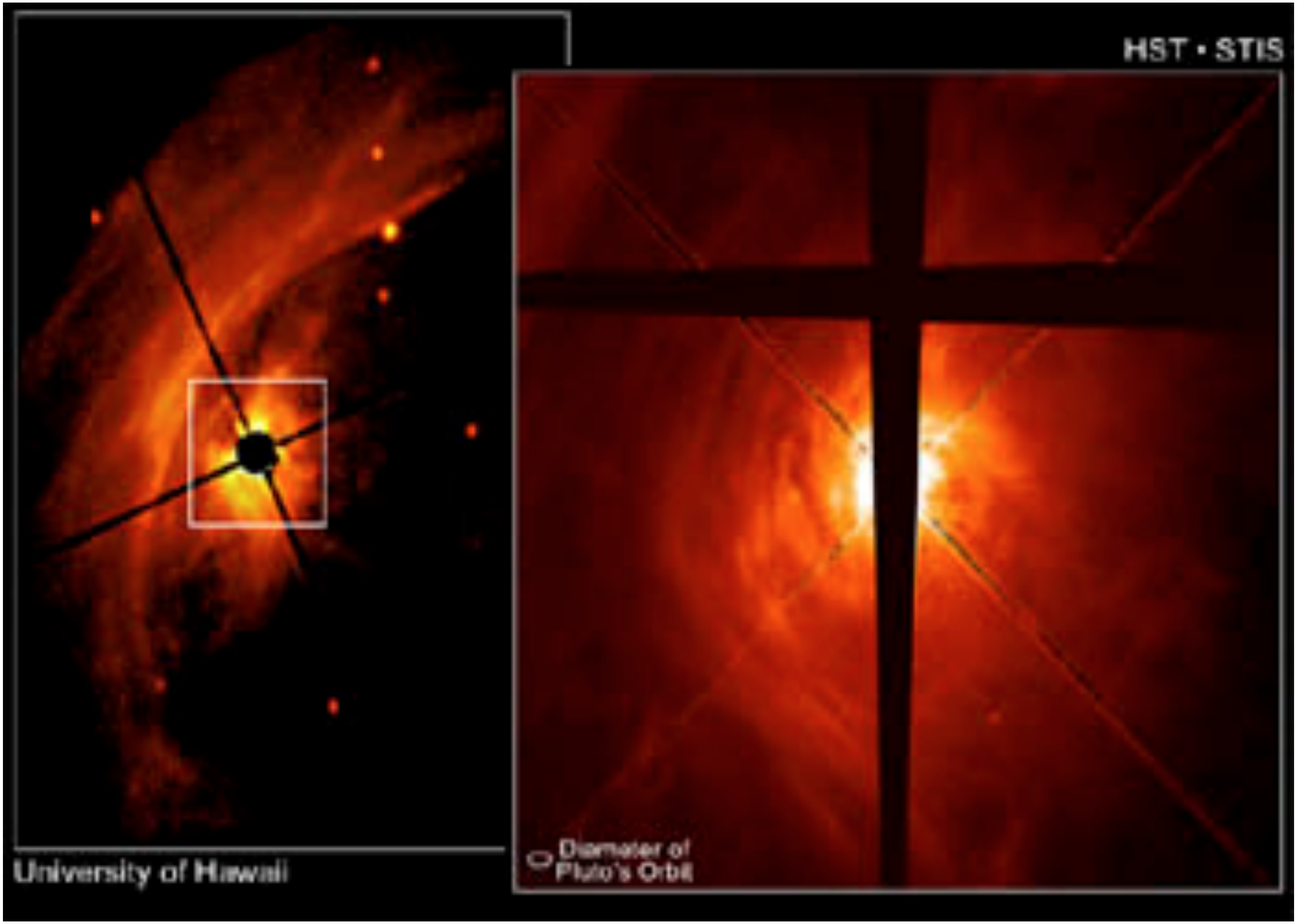
An overview of the Solar System and other worlds



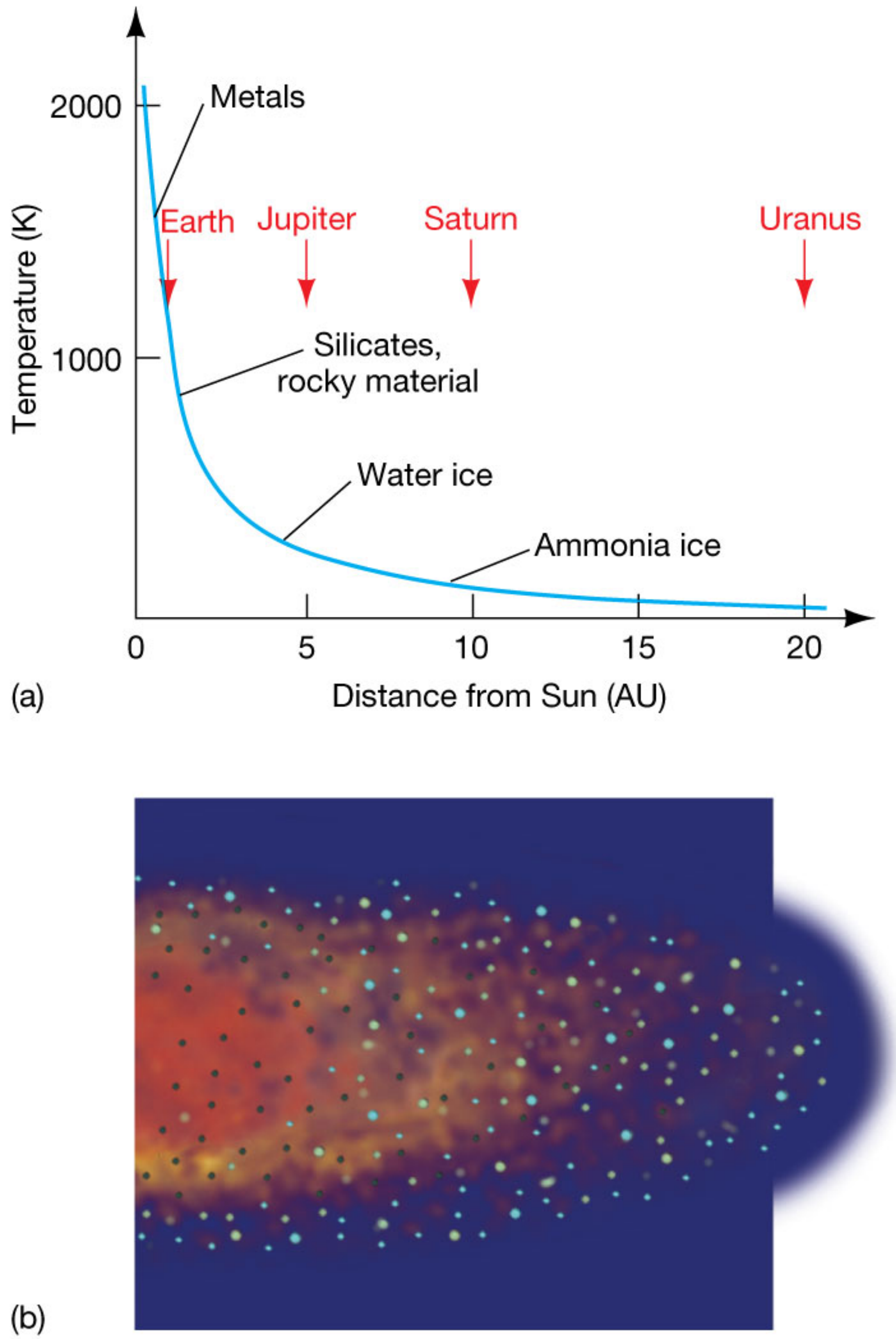
C&M Chaps. 6, 14 & 15

The Formation of the Solar System

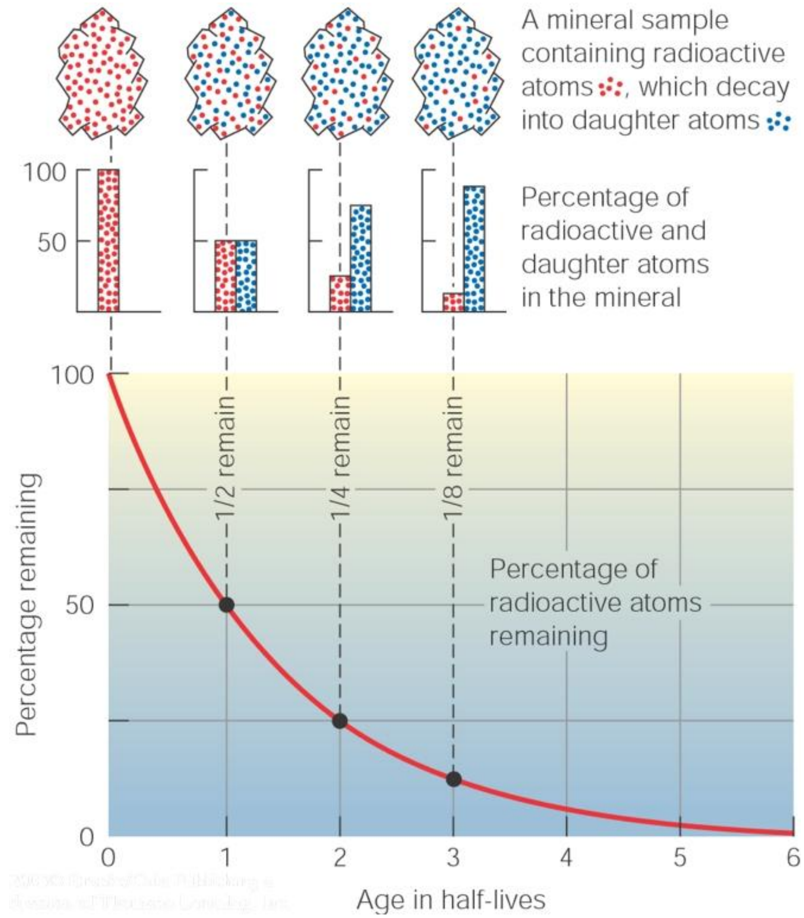



HST • STIS
Diameter of
Pluto's Orbit
University of Hawaii

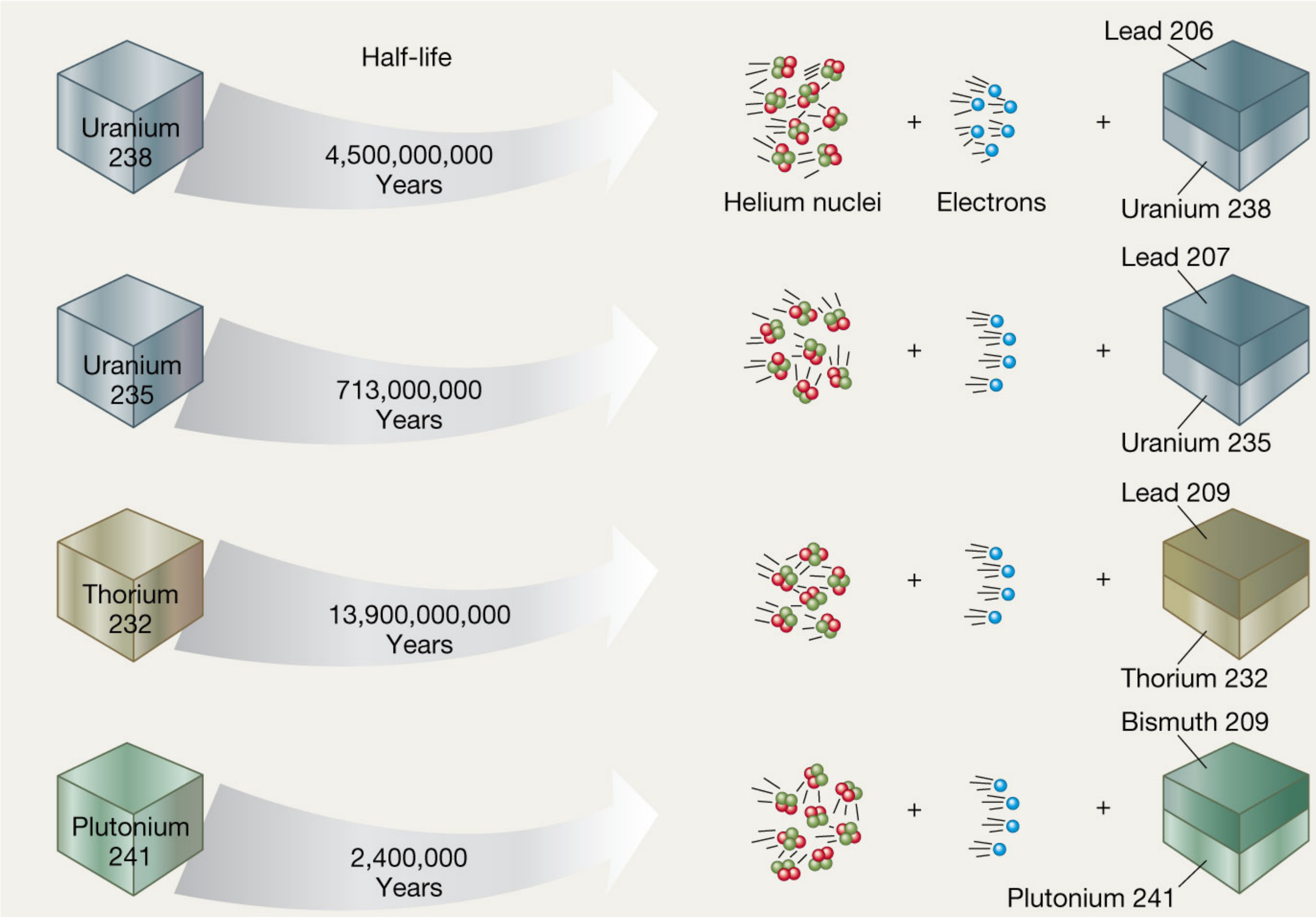
Differentiation:



The Age of the Solar System



Fraction of material remaining = $0.5^{t/T}$ where T=half life and t=time.


Half-life
Uranium 238
4,500,000,000 Years
Helium nuclei
+
Electrons
+
Lead 206
Uranium 238
Uranium 235
713,000,000 Years
+
+
Lead 207
Uranium 235
Thorium 232
13,900,000,000 Years
+
+
Lead 209
Thorium 232
Plutonium 241
2,400,000 Years
+
+
Bismuth 209
Plutonium 241

Example: In a certain rock sample it is found that 31% of uranium-238 has decayed to lead-206. Estimate the age of the rock sample.

Fraction of material remaining = $0.5^{t/T}$ where T=half life and t=time.

$0.69 = 0.5^{t/4.5e9}$

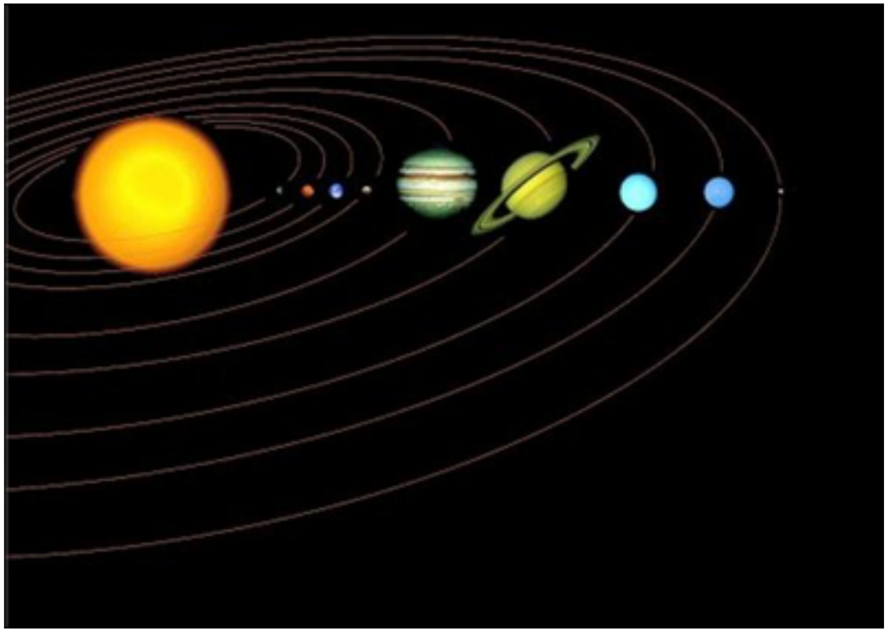
$\text{Log } 0.69 = (t/4.5\times10^9) \times \log 0.5$

$t = 2.4\times10^9$ years = 2.4 billion years

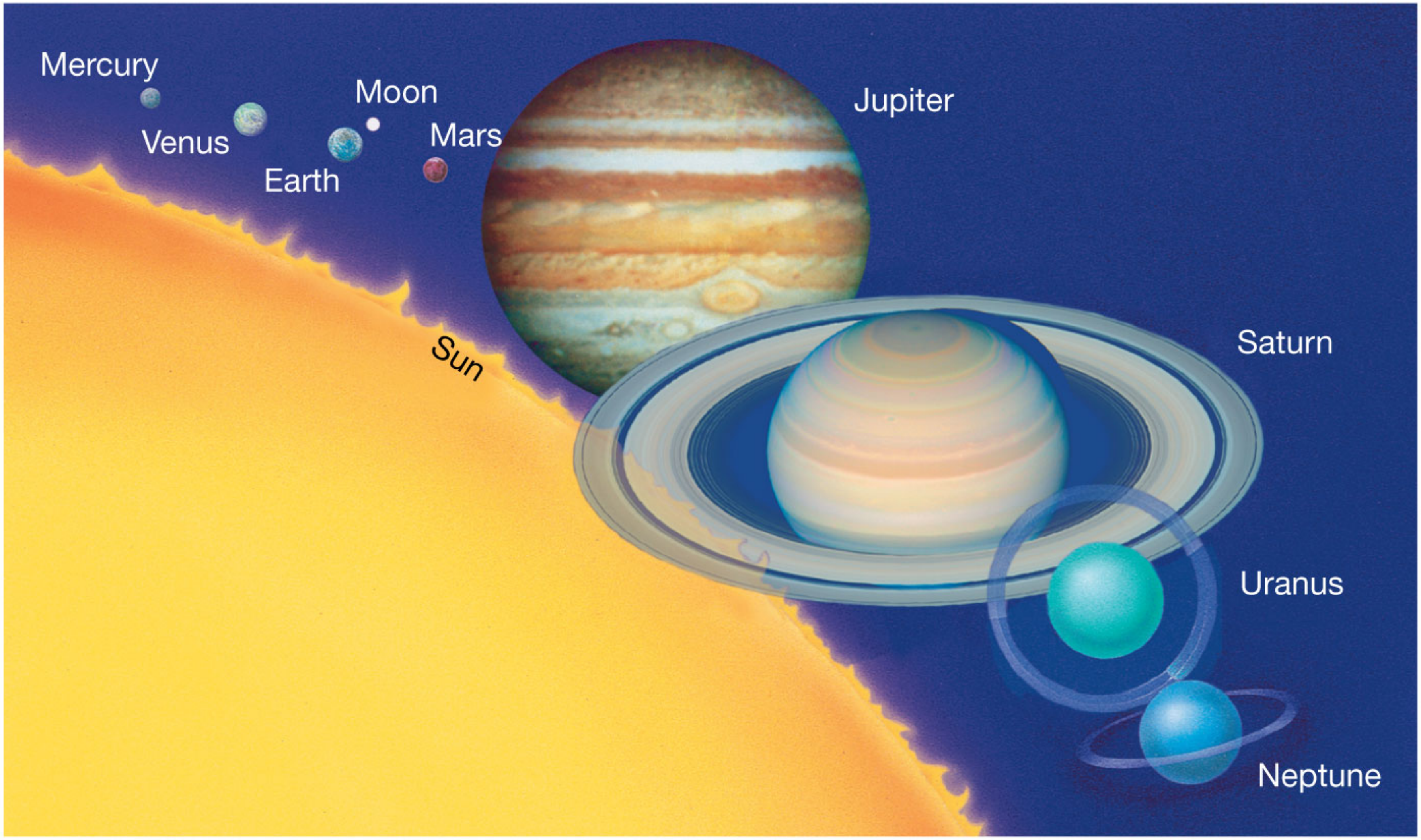
The Composition of The Solar System

The solar system has 5 main components:

1. The sun (obviously)
2. The planets (8 in total) orbiting the sun
3. Asteroids, mostly in the asteroid belt
4. Comets mostly in the Oort cloud.
5. Dwarf planets



The planets to scale.



Planetary Motion

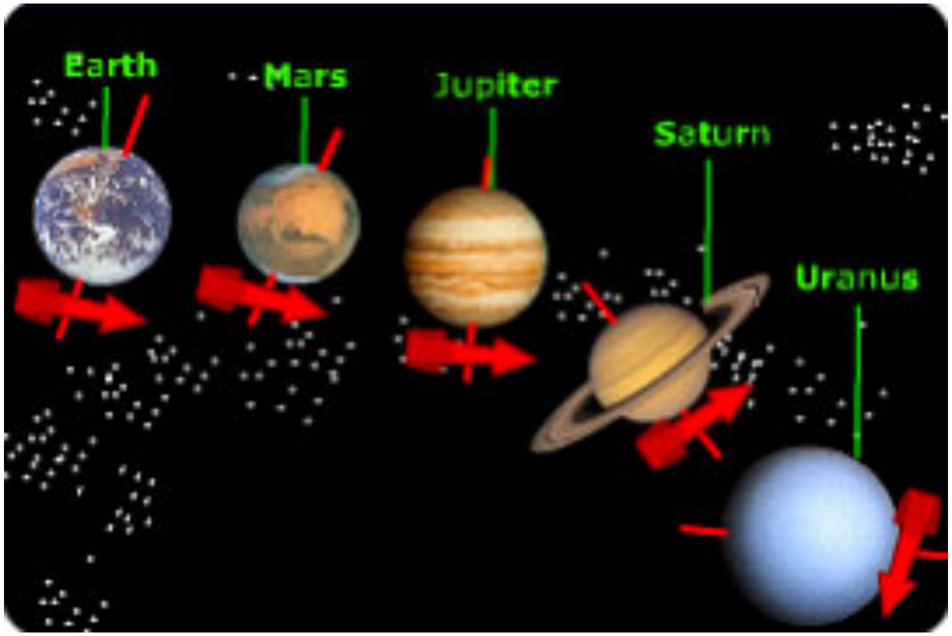
TABLE 6.1 Properties of Some Solar System Objects

Object	Orbital Semimajor Axis (AU)	Orbital Period (Earth Years)	Mass (Earth Masses)	Radius (Earth Radii)	Number of Known Satellites	Rotation Period * (days)	Average Density (kg/m^3)	Average Density (g/cm^3)
Mercury	0.39	0.24	0.055	0.38	0	59	5400	5.4
Venus	0.72	0.62	0.82	0.95	0	–243	5200	5.2
Earth	1.0	1.0	1.0	1.0	1	1.0	5500	5.5
Moon	—	—	0.012	0.27	—	27.3	3300	3.3
Mars	1.52	1.9	0.11	0.53	2	1.0	3900	3.9
Ceres (asteroid)	2.8	4.7	0.00015	0.073	0	0.38	2700	2.7
Jupiter	5.2	11.9	318	11.2	63	0.41	1300	1.3
Saturn	9.5	29.4	95	9.5	56	0.44	700	0.7
Uranus	19.2	84	15	4.0	27	–0.72	1300	1.3
Neptune	30.1	164	17	3.9	13	0.67	1600	1.6
Pluto (Kuiper belt object)	39.5	248	0.002	0.2	3	–6.4	2100	2.1
Hale-Bopp (comet)	180	2400	1.0×10^{-9}	0.004	—	0.47	100	0.1
Sun	—	—	332,000	109	—	25.8	1400	1.4

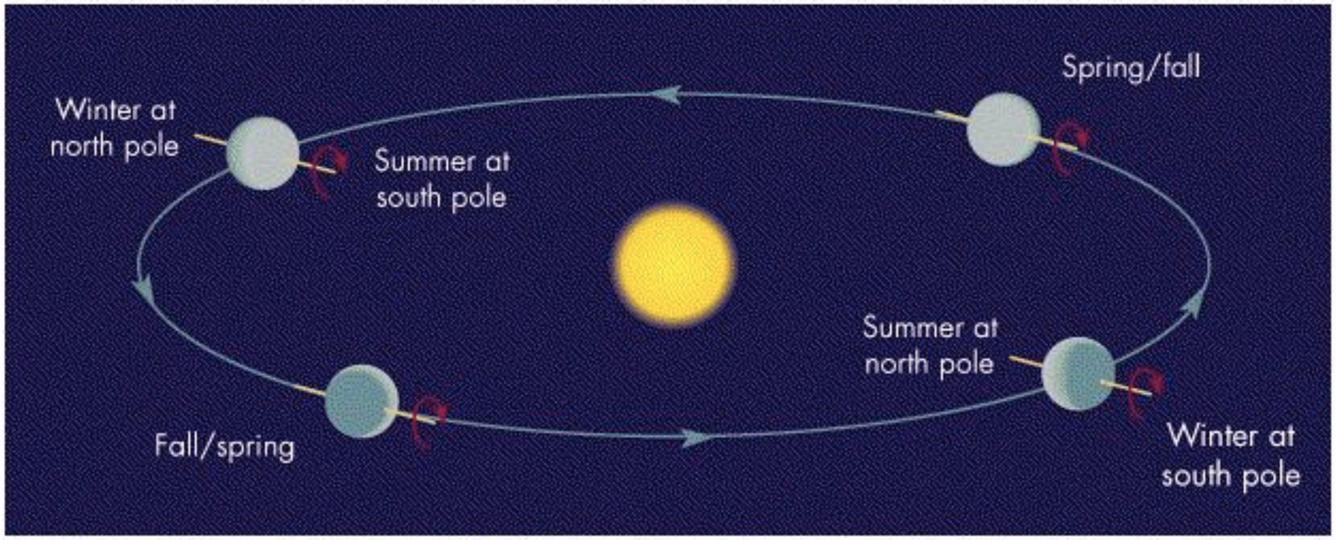
**A negative rotation period indicates retrograde (backward) rotation relative to the sense in which all planets orbit the Sun.*

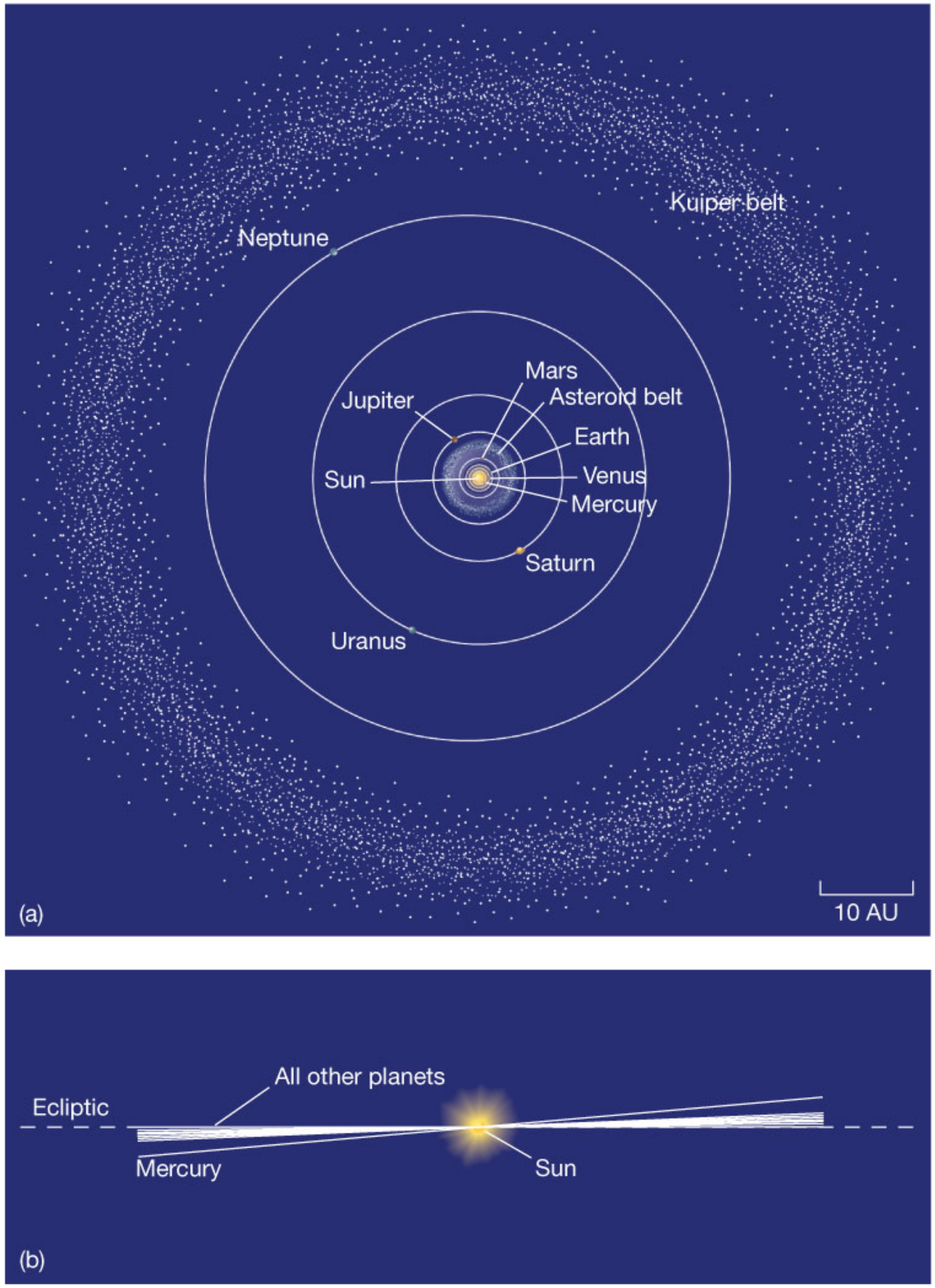
Length of a year depends on distance from sun. Length of day does not.

Most planets have their rotation axis tilted compared to their orbit.



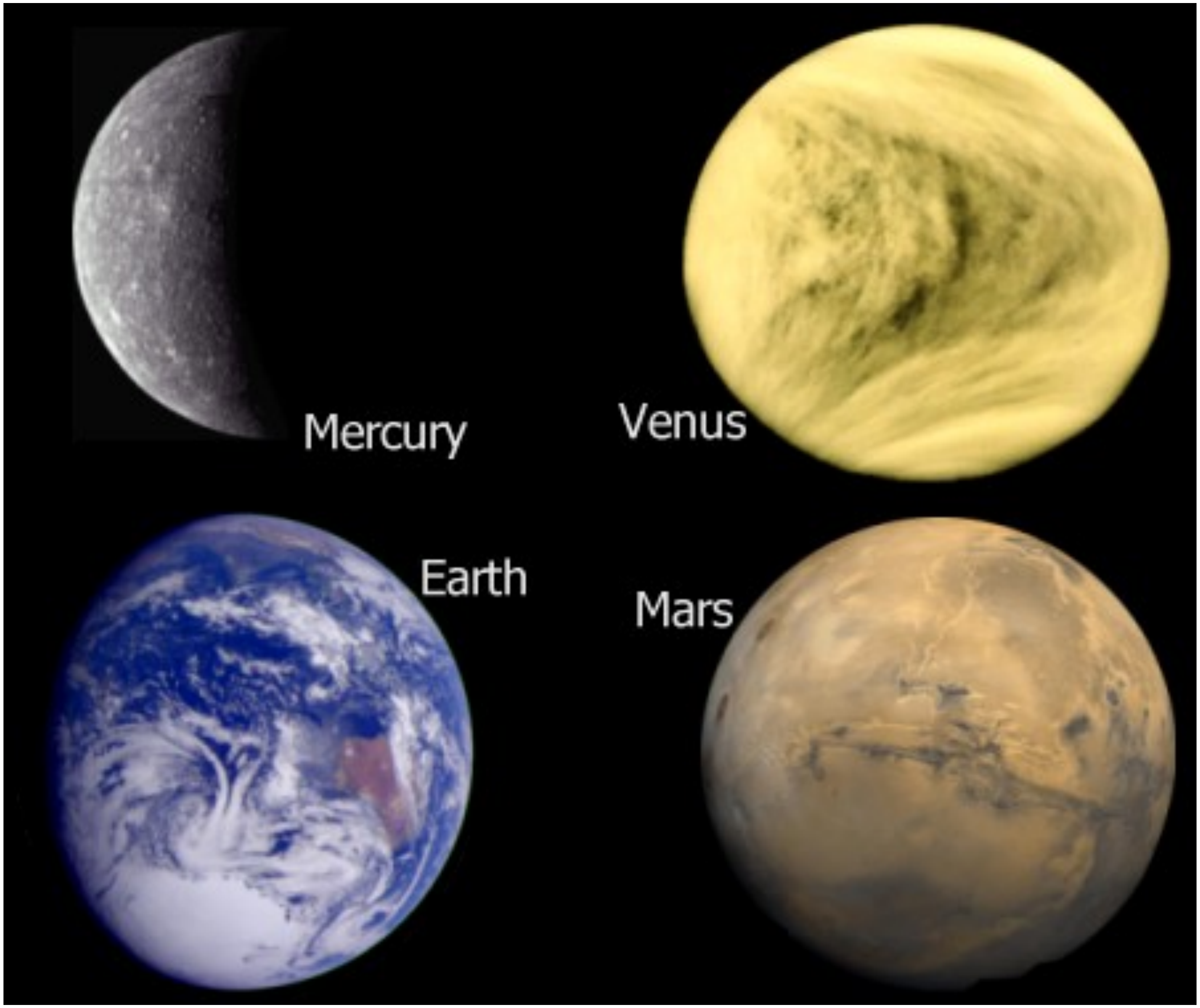
Seasons on Uranus:





Kuiper belt
Neptune
Mars
Asteroid belt
Jupiter
Earth
Sun
Venus
Mercury
Saturn
Uranus
(a)
10 AU
All other planets
Ecliptic
Mercury
Sun
(b)

The Terrestrial Planets



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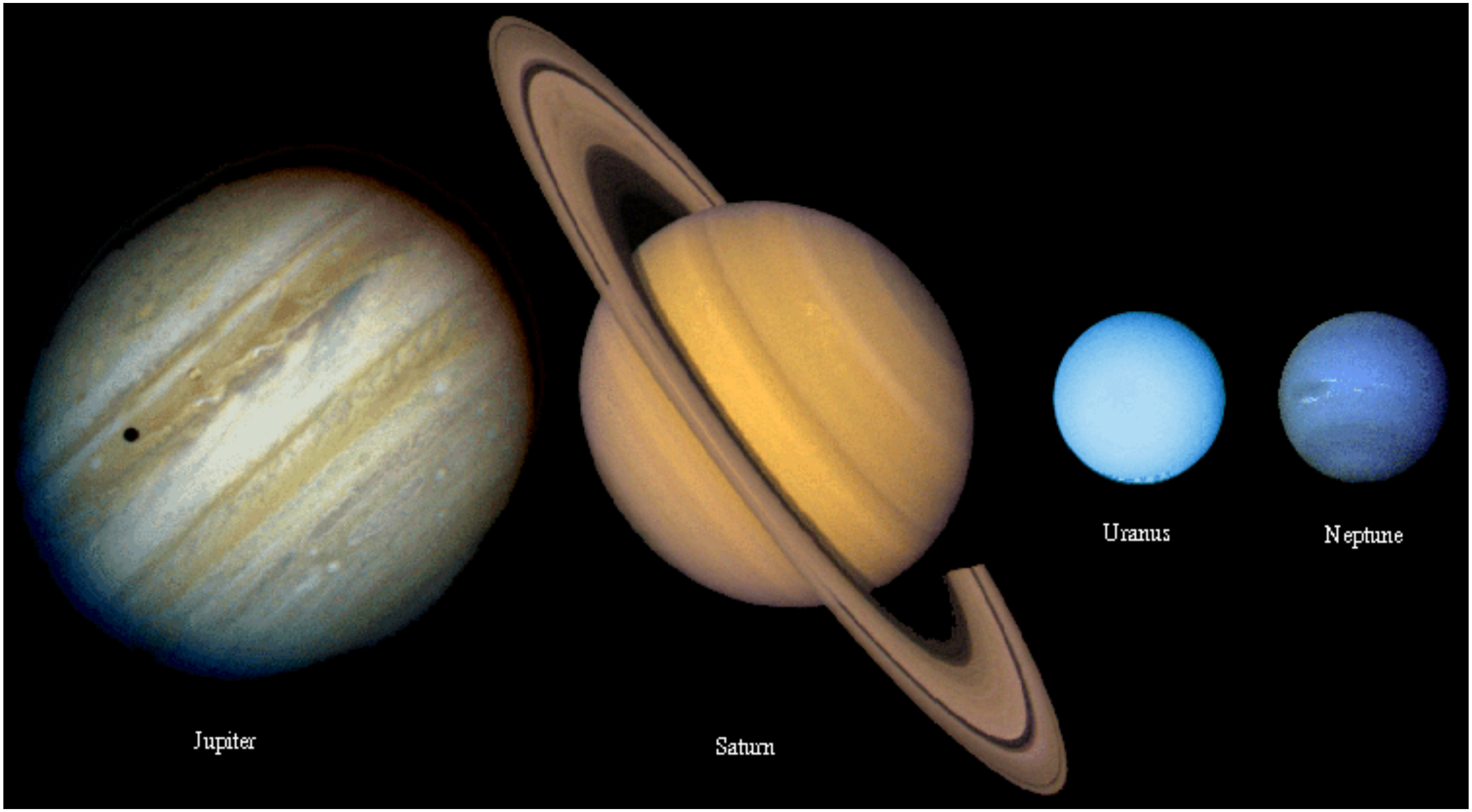
Sun	—	—	332,000	109	—	25.8	1400	1.4

**A negative rotation period indicates retrograde (backward) rotation relative to the sense in which all planets orbit the Sun.*

Small, rocky, dense, few satellites.

Jovian Planets



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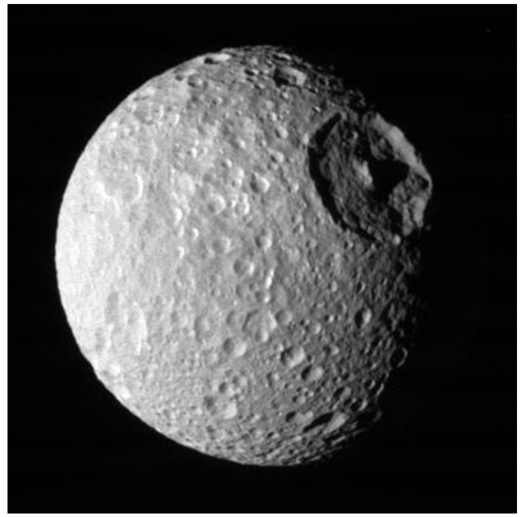
**A negative rotation period indicates retrograde (backward) rotation relative to the sense in which all planets orbit the Sun.*

Large, gaseous, low density, many satellites.

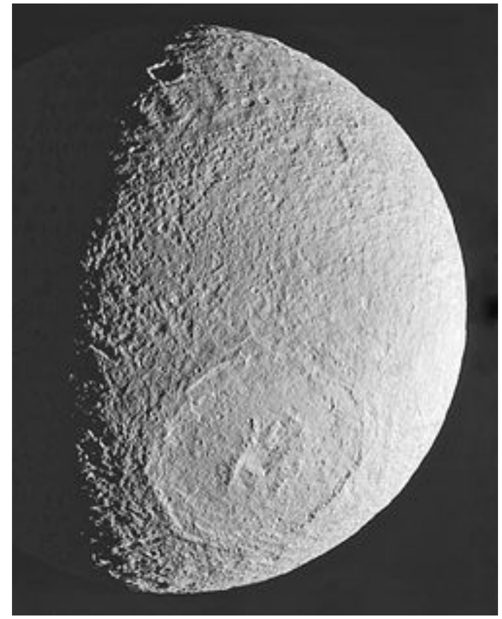
Planetary Features

Impact craters need rocky surface and little atmosphere to survive

Barringer crater 1.2 km, Arizona



Saturn's moon Mimas. 139 km across.

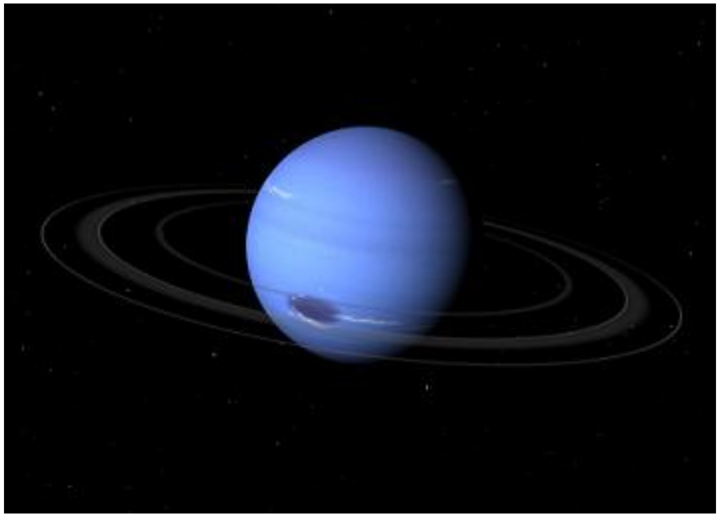


Saturn's moon Tethys. 445 km across.

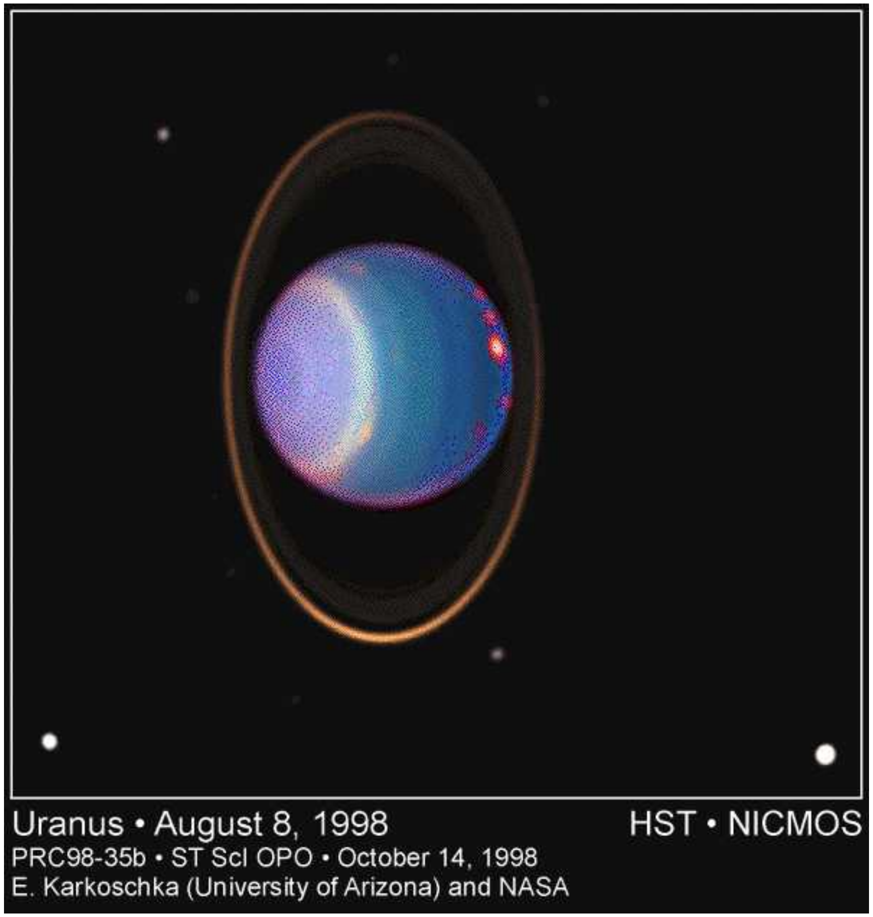
http://en.wikipedia.org/wiki/Larger_craters_in_the_Solar_System

Planetary Features

Rings: Saturn has very obvious rings, but all of the Jovian planets have rings. None of the terrestrial planets have rings.



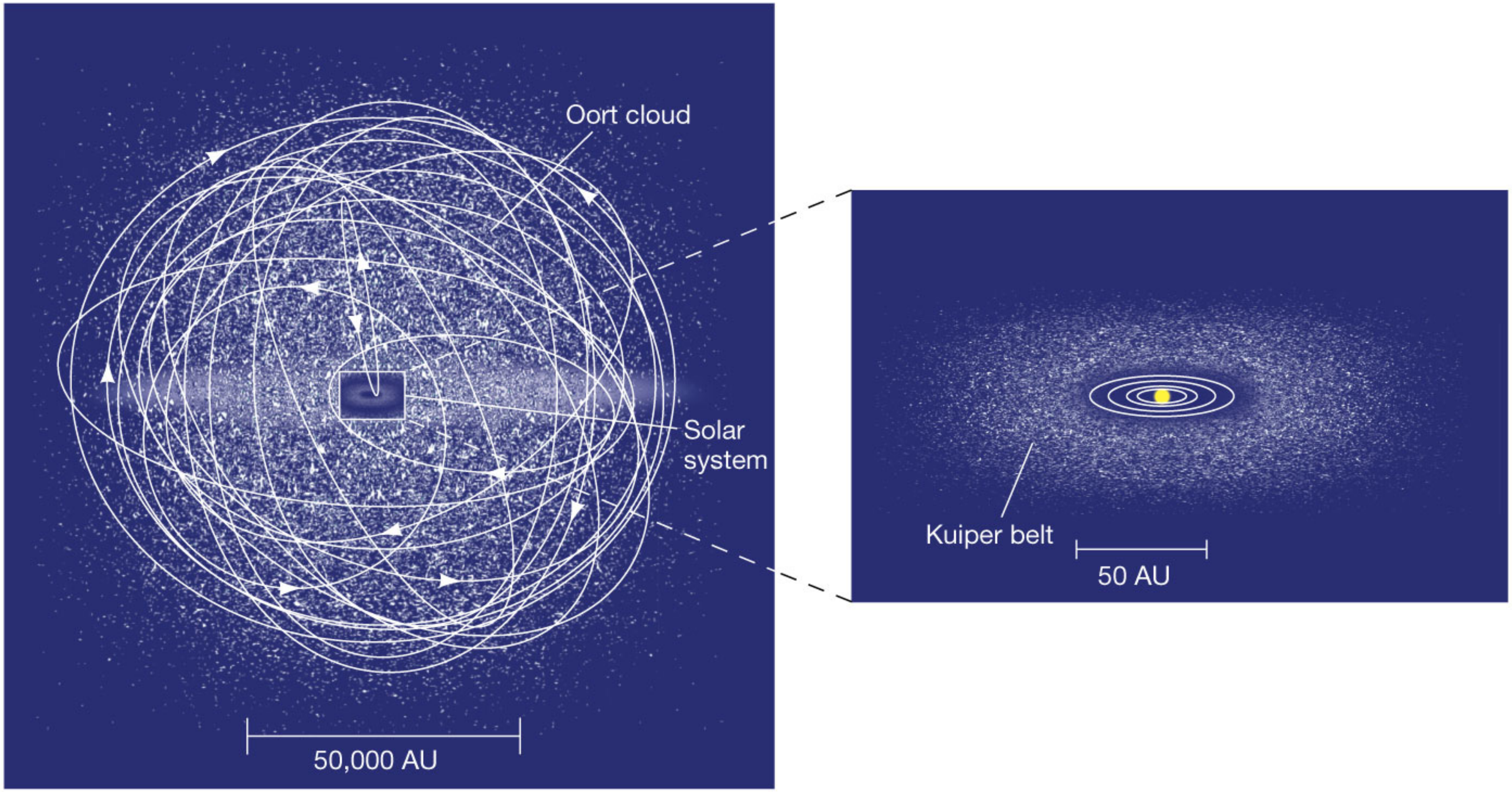
Neptune

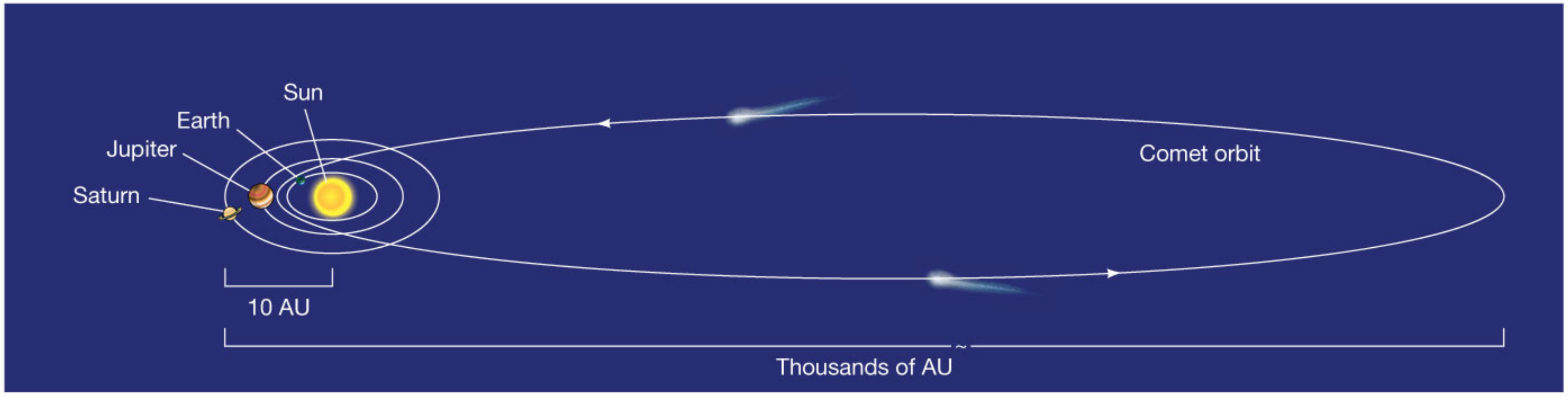


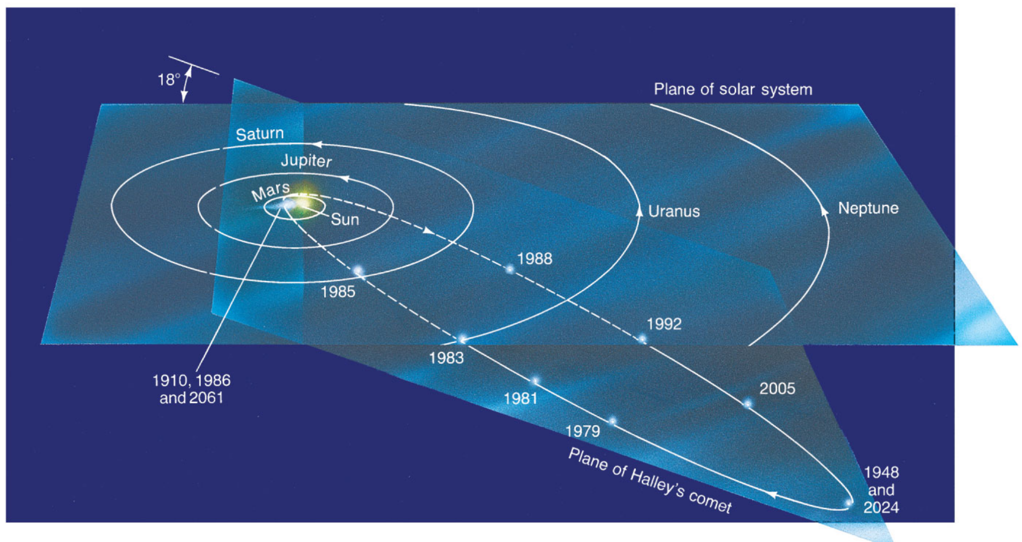
Planetary Features

Some of the Jovian satellites are larger than small planets!

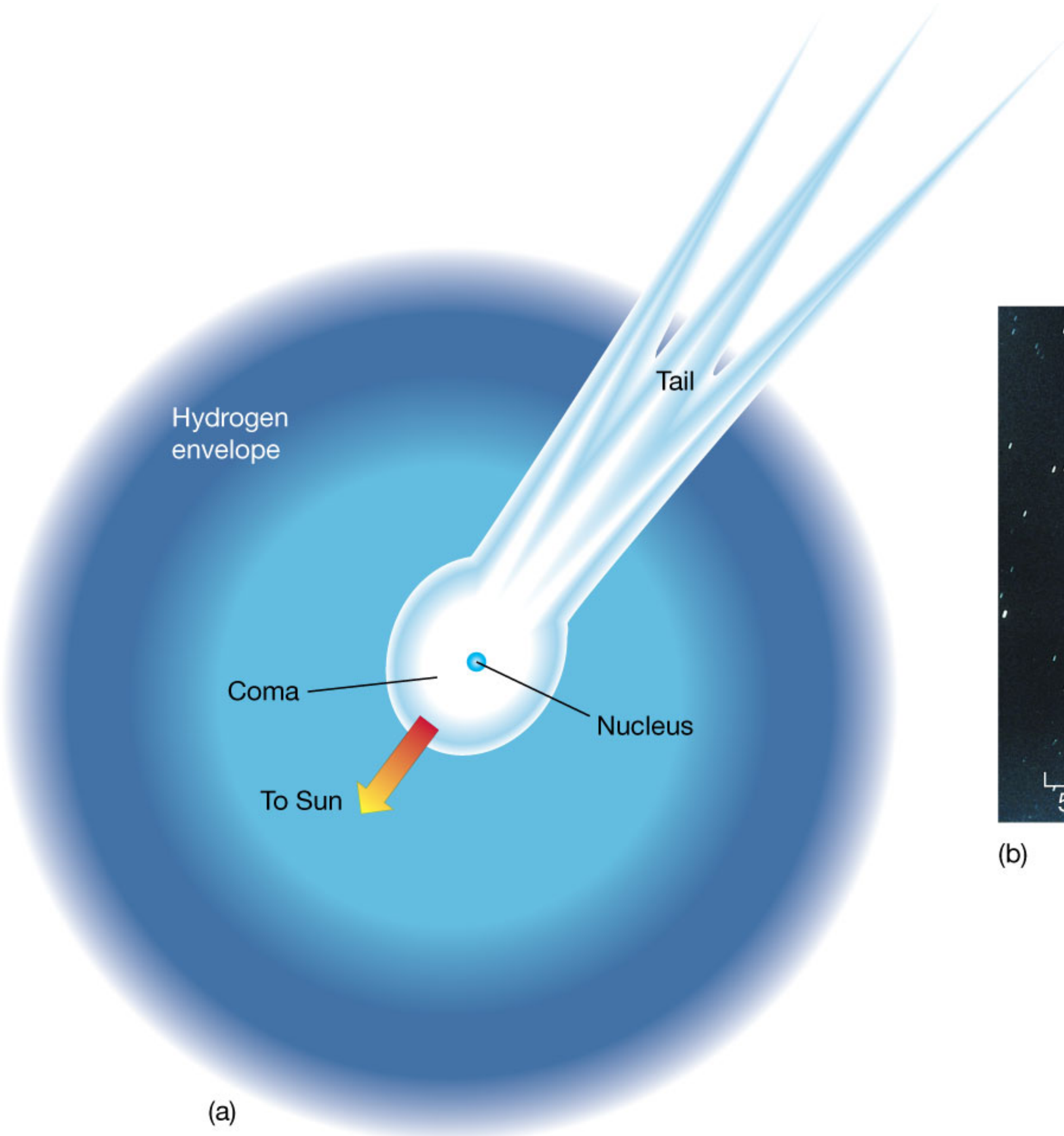
Comets



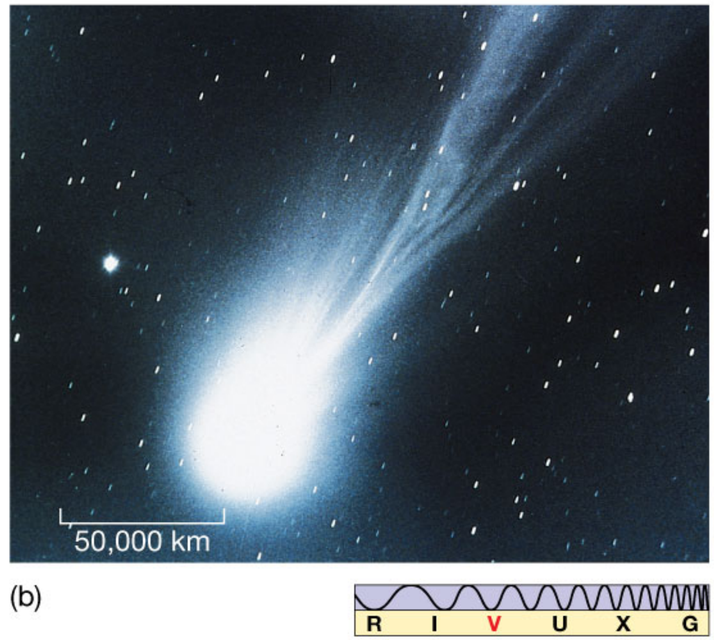




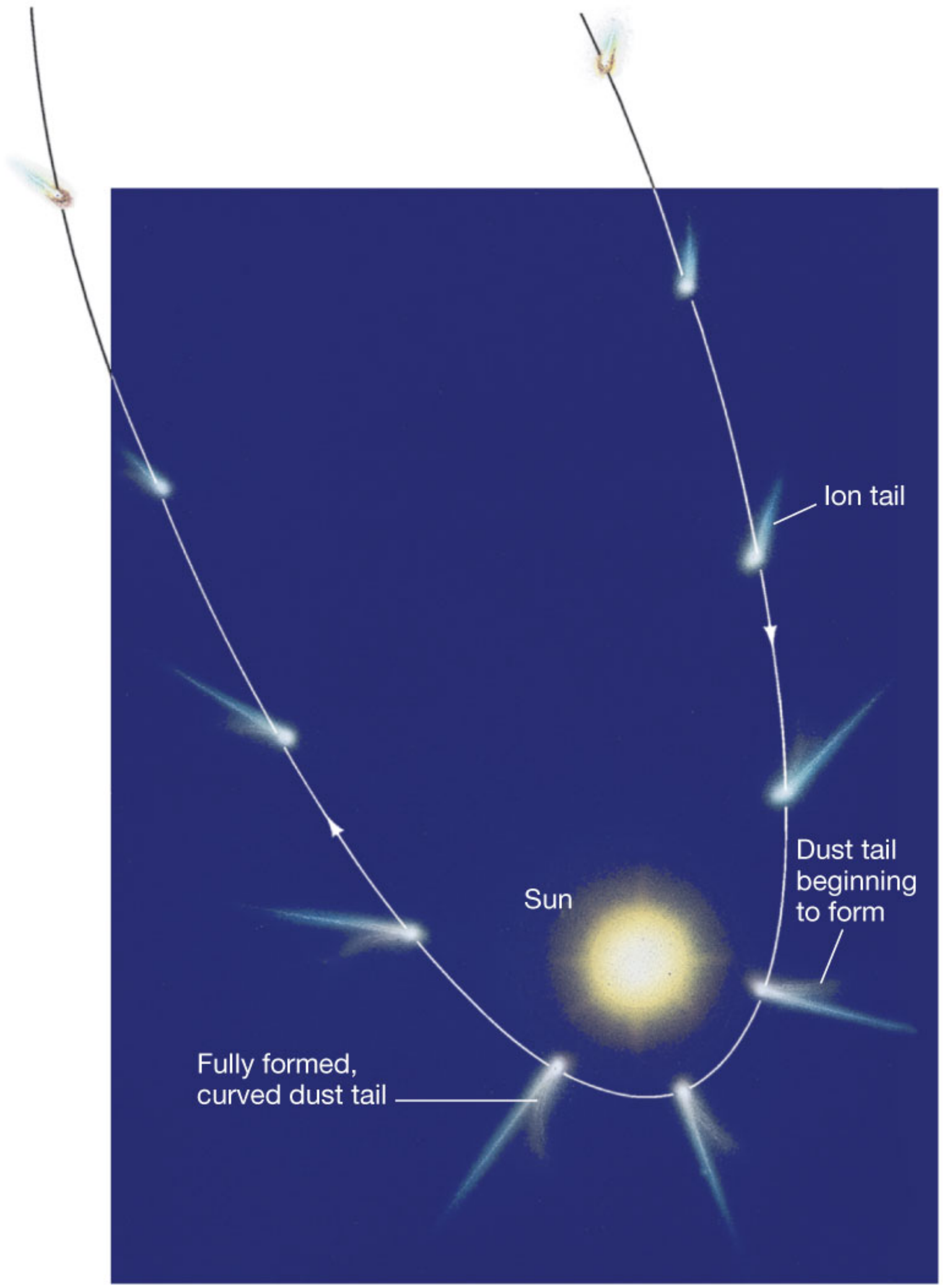
Cometary orbits are both eccentric and can be highly inclined.



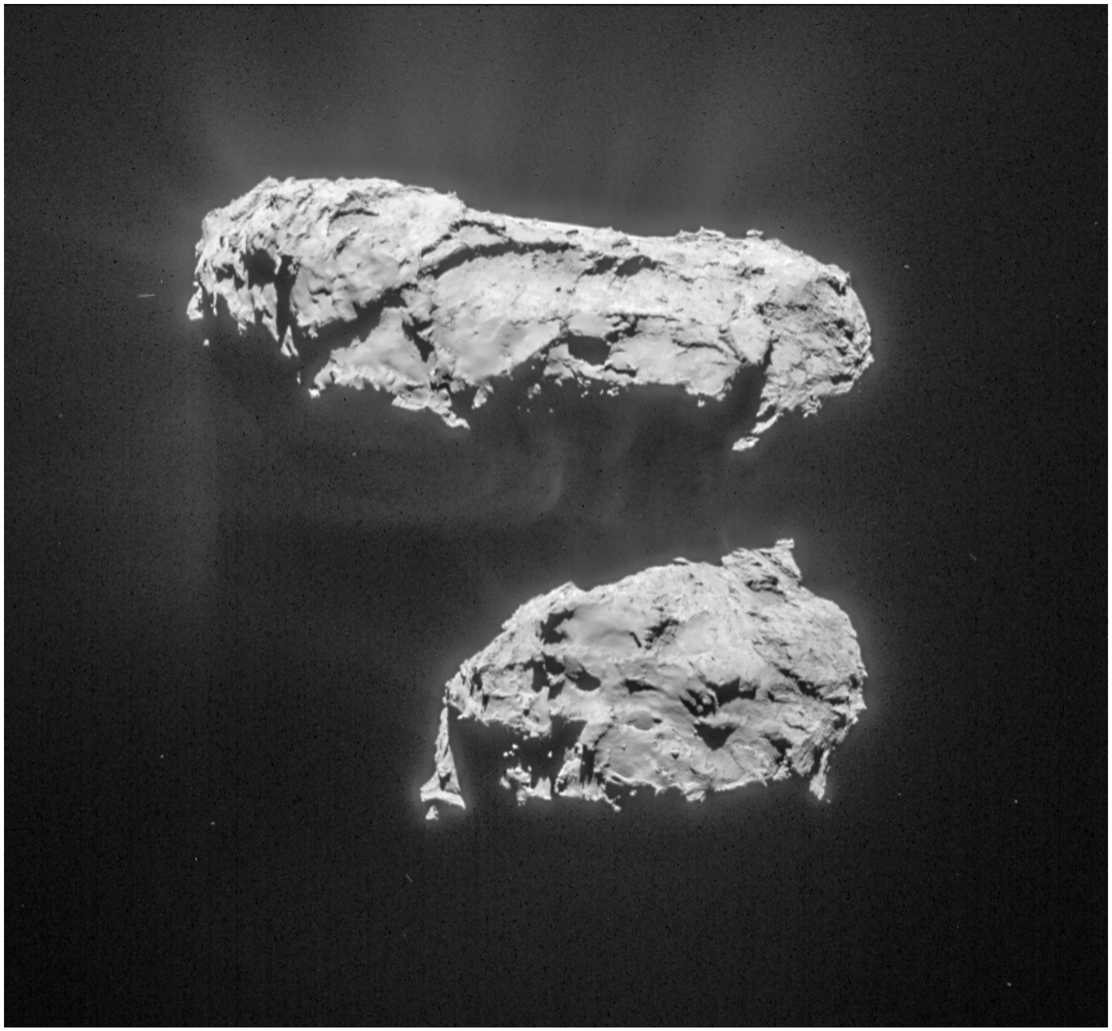
(a)



(b)


Ion tail
Dust tail beginning to form
Sun
Fully formed, curved dust tail

In 2014, ESA's Rosetta mission put its Philae lander on the surface of 67P/Churyumov-Gerasimenko.



Meteors

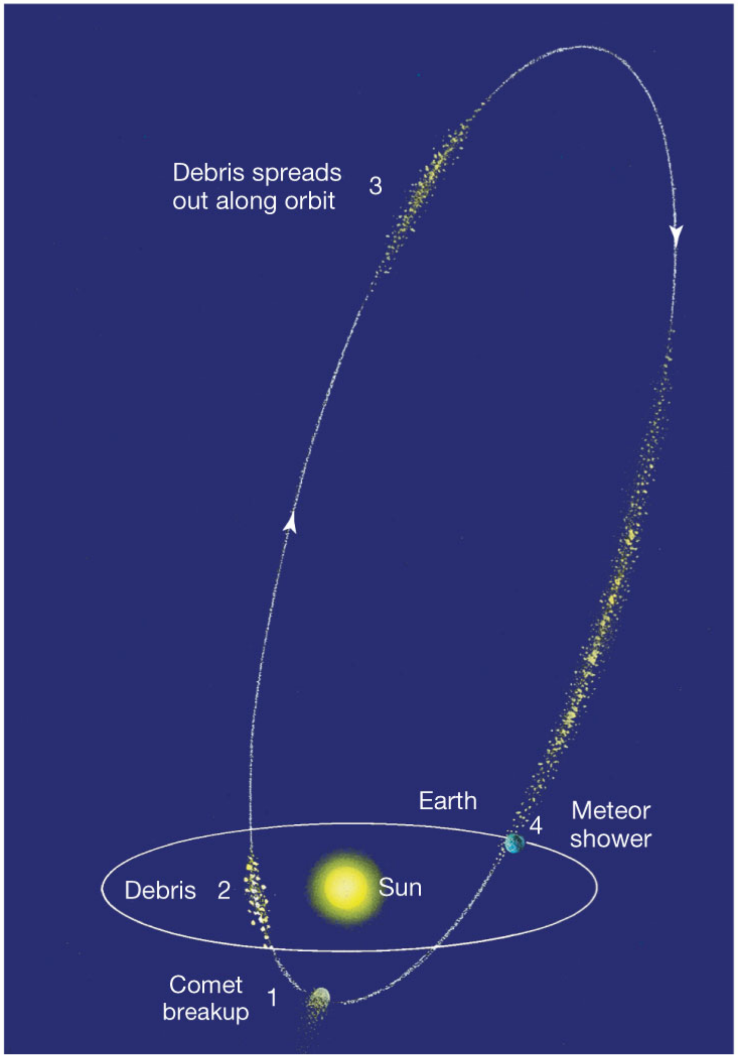


TABLE 14.1 Some Prominent Meteor Showers

Morning of Maximum Activity	Name of Shower	Rough Hourly Count	Parent Comet
Jan. 3	Quadrantid	40	—
Apr. 21	Lyrid	10	1861I (Thatcher)
May 4	Eta Aquarid	20	Halley
June 30	Beta Taurid	25‡	Encke
July 30	Delta Aquarid	20	—
Aug. 11	Perseid	50	1862III (Swift-Tuttle)
Oct. 9	Draconid	up to 500	Giacobini-Zinner
Oct. 20	Orionid	30	Halley
Nov. 7	Taurid	10	Encke
Nov. 16	Leonid	12*	1866I (Tuttle)
Dec. 13	Geminid	50	3200 (Phaeton)†

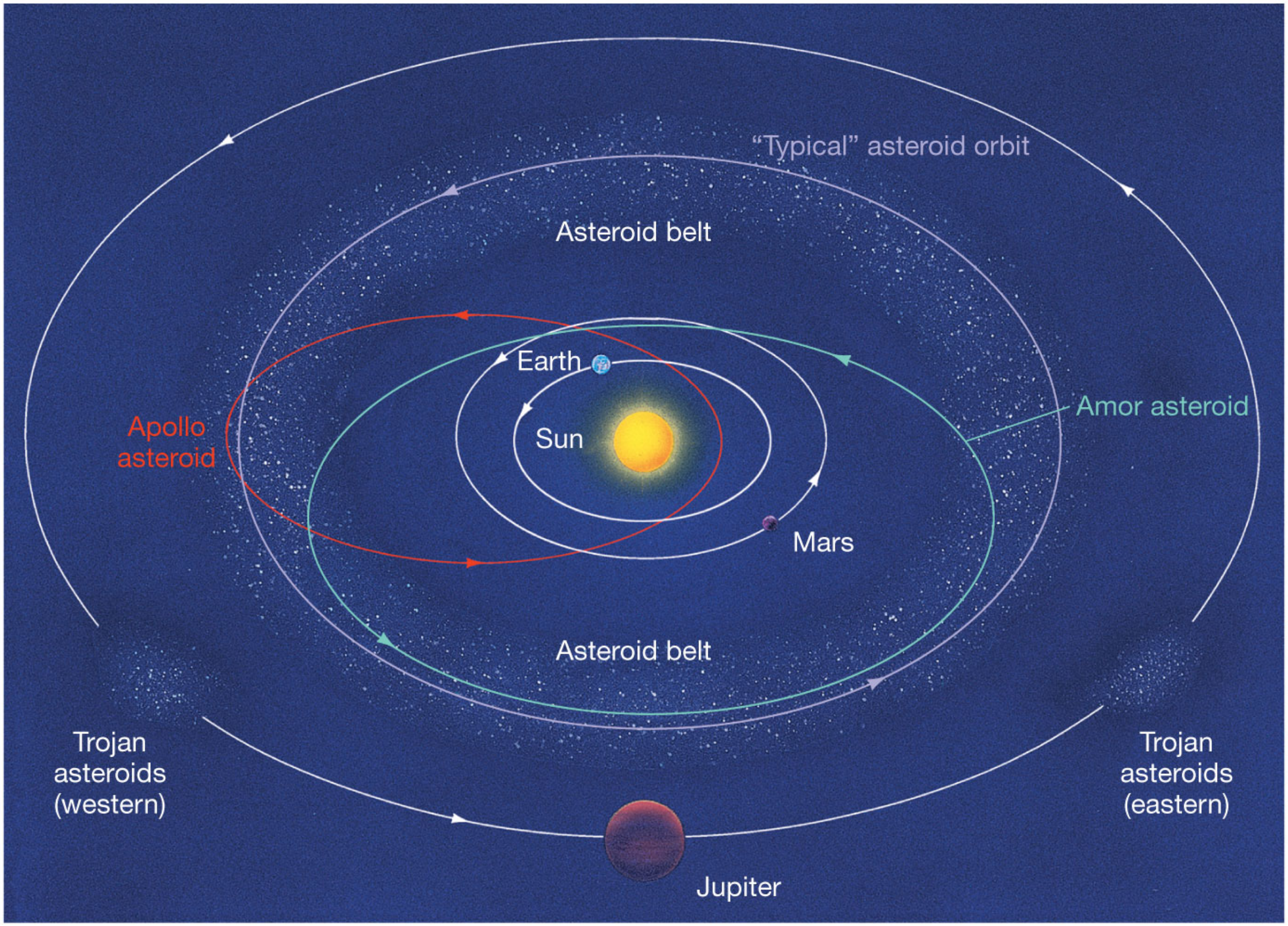
**Every 33 years, as Earth passes through the densest region of this meteoroid swarm, we see intense showers that can exceed 1000 meteors per minute for brief periods. This intense activity is next expected to occur in 2032.*

†Phaeton is actually an asteroid and shows no signs of cometary activity, but its orbit matches the meteoroid paths very well.

‡Meteor count peaks after sunrise.

Meteorites

Asteroids



"Typical" asteroid orbit
Asteroid belt
Earth
Apollo
asteroid
Sun
Amor asteroid
Mars
Asteroid belt
Trojan
asteroids
(western)
Trojan
asteroids
(eastern)
Jupiter

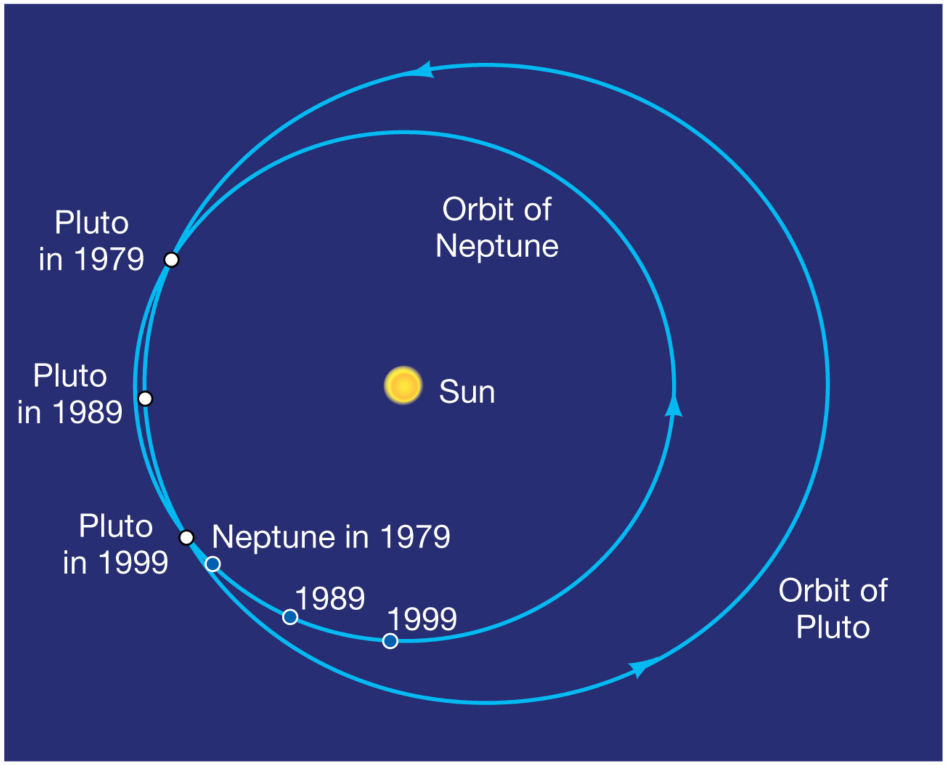
(a)

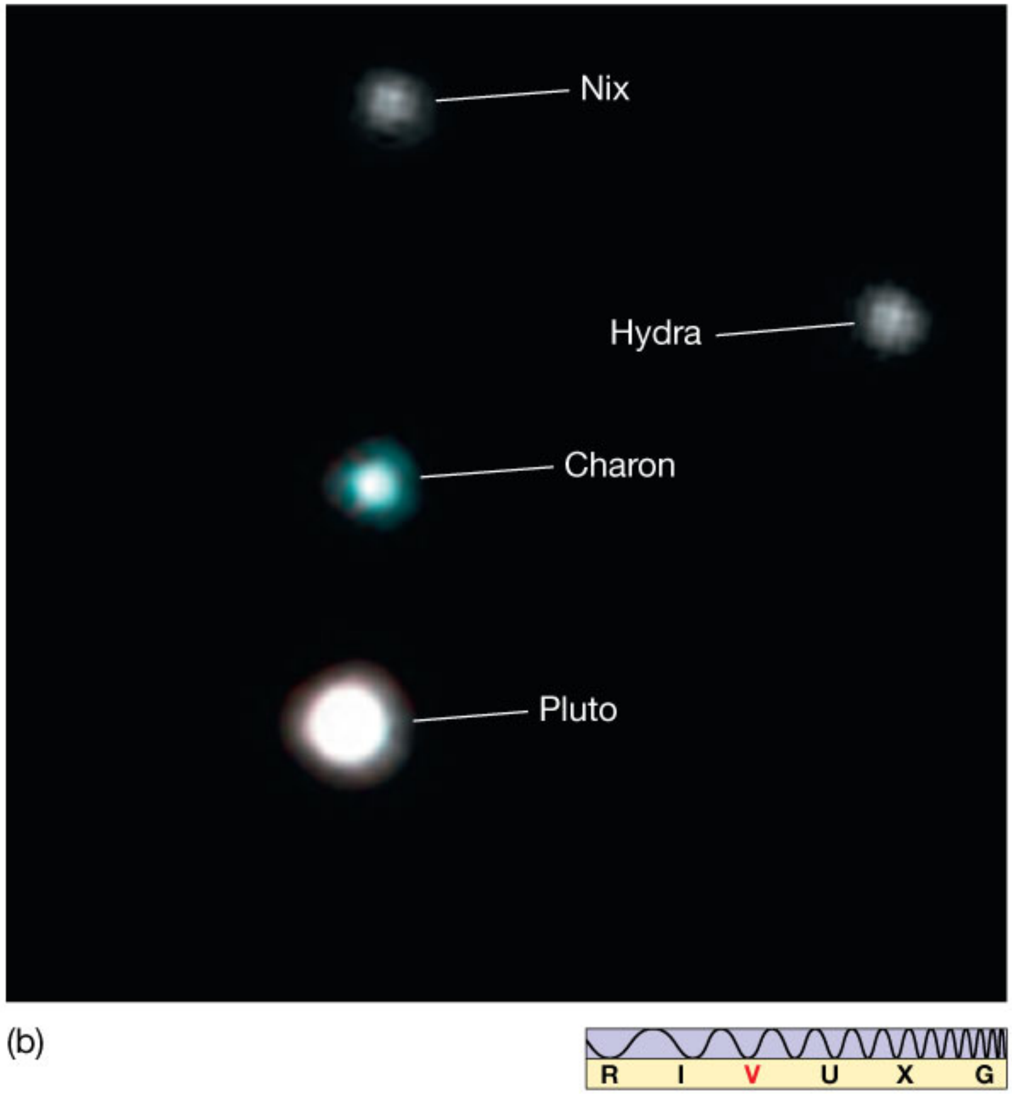

M0151295144F4
December 3 2000 23:08:30 21° 146°

Outer Solar System Objects

Pluto: a planetary oddity.

- Neptune crossing orbit.
- Highly inclined orbit (17 degrees).
- Eccentric orbit (e=0.25)
- Resonant orbit with Neptune 3:2.
- At the distance of the Jovian planets, but more like a terrestrial planet in its characteristics (no rings, small, few satellites).

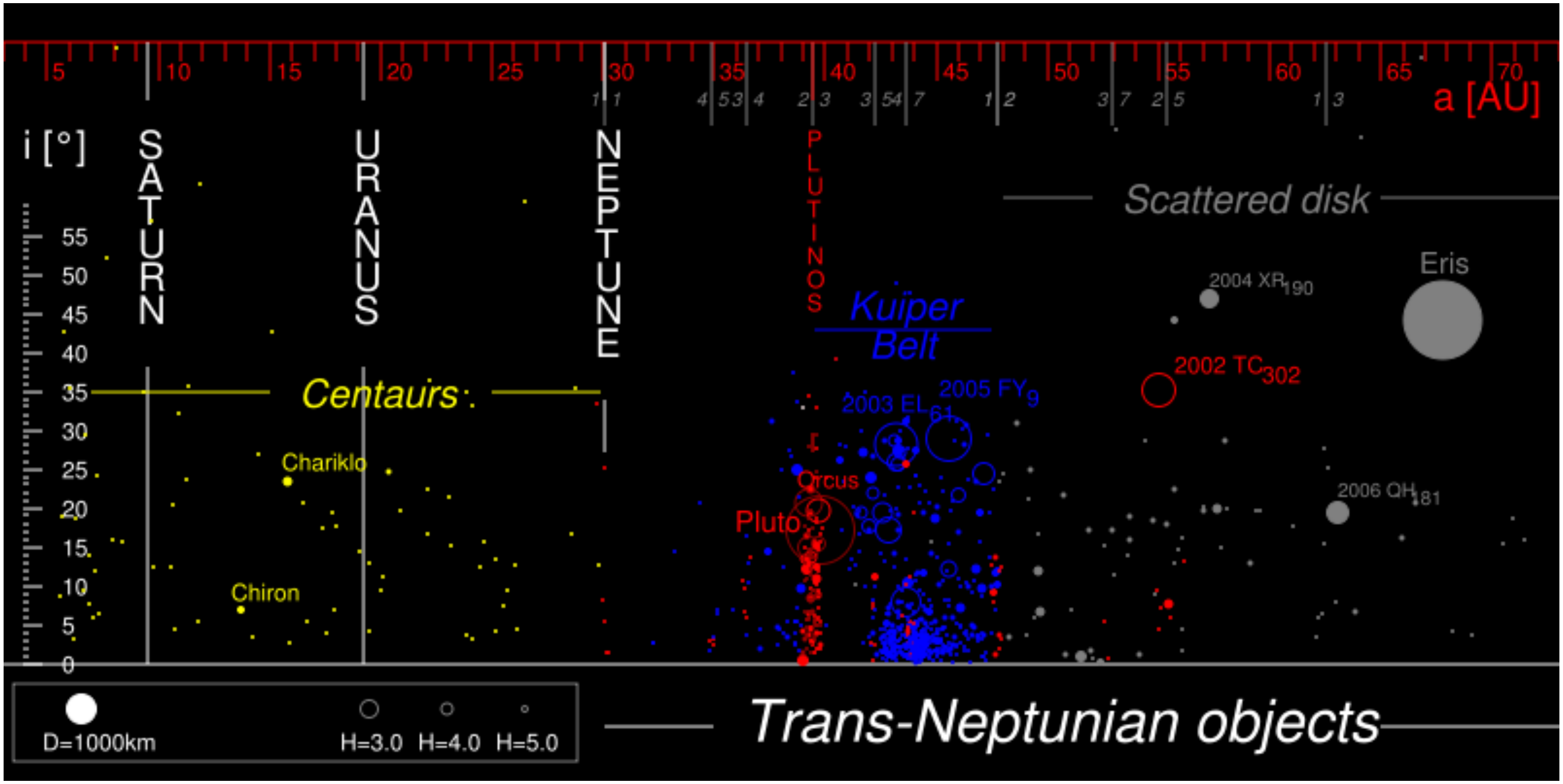


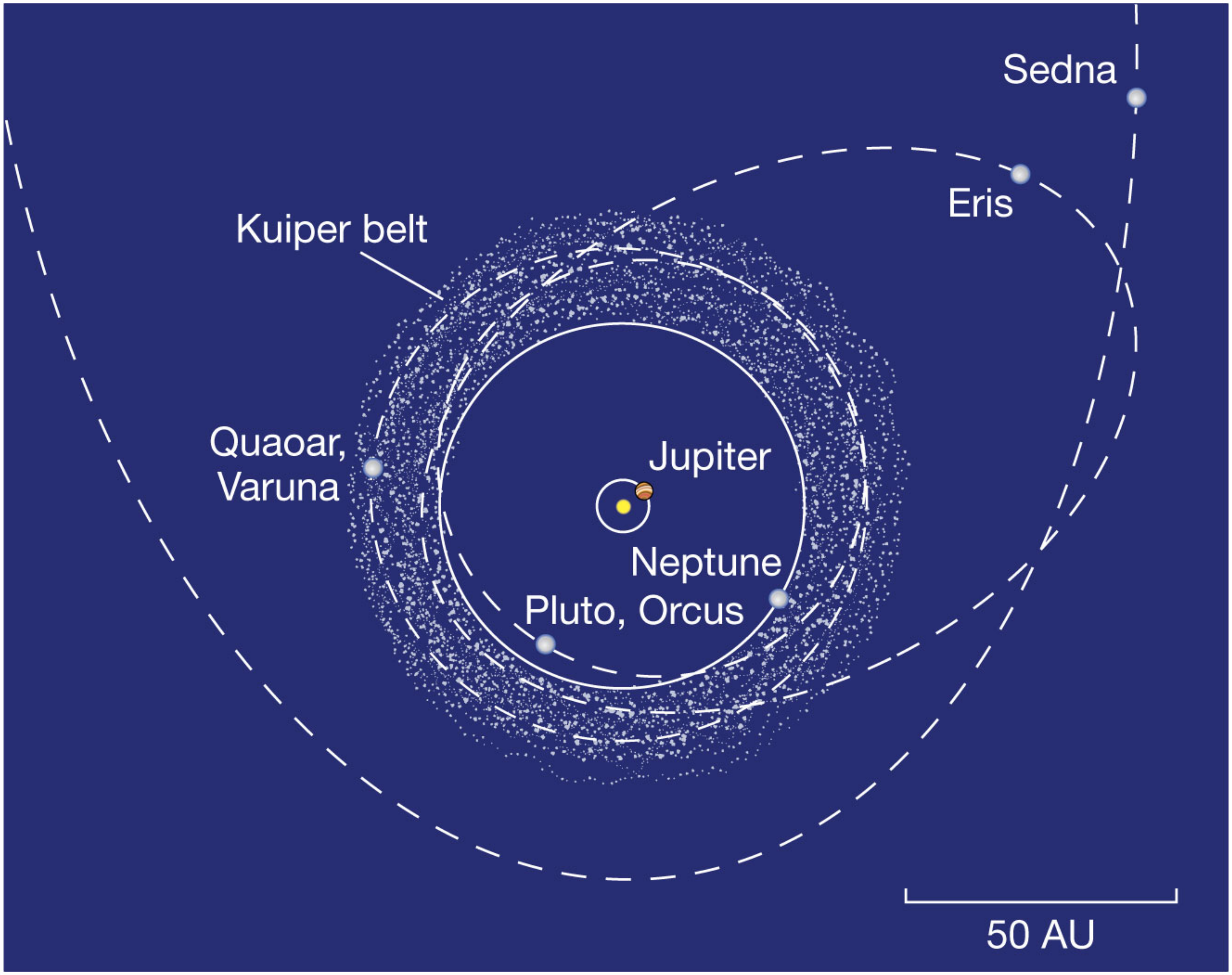


(b)

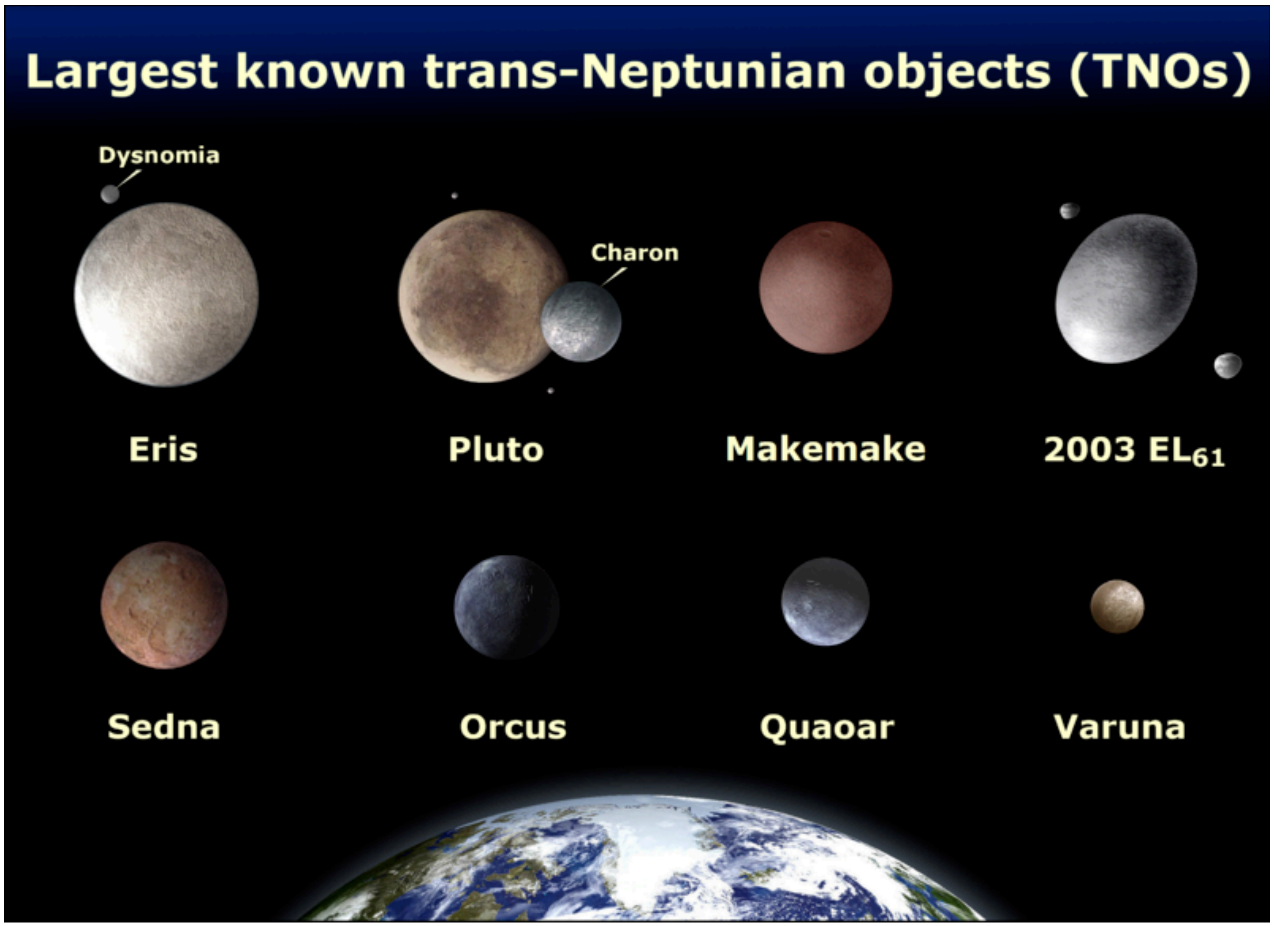
Charon discovered in 1978, Hydra and Nix in 2005.

Trans-Neptunian Objects



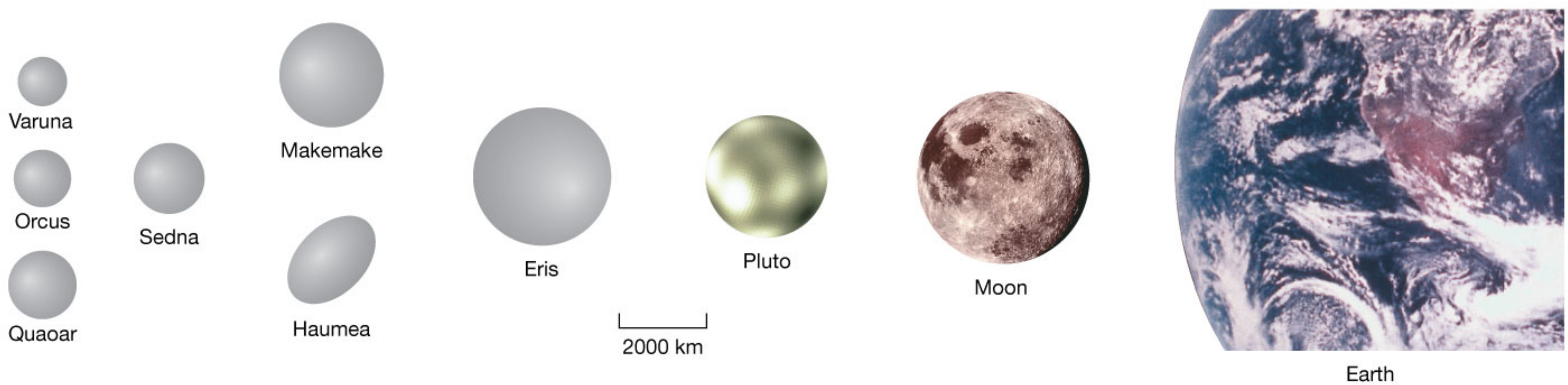

Sedna
Eris
Kuiper belt
Quaoar,
Varuna
Jupiter
Neptune
Pluto, Orcus
50 AU

Lots of new TNOs being discovered. Pluto is even smaller than the largest TNO (Eris), so whilst it had been considered a planet since its discovery in 2006, the IAU decided a new classification was required.



Planet: An object that

- Orbits the sun (and is not a satellite)
- Is large enough to be round under its own gravity
- Has cleared is `lane' of other material



Under this definition there are 8 planets, since Pluto has not fully cleared its region of space of planetesimals. It also does not include Eris, any of the Kuiper Belt Objects or more distant objects such as Sedna, for the same reason.

In order to recognise the difference between objects such as Pluto and Eris and other bodies in solar system that are clearly "unplanet" like, such as the majority of the asteroids and comets, in 2006 we defined a new term: dwarf planet.

Dwarf planet: An object that

- Orbits the sun (and is not a satellite)
- Is large enough to be round under its own gravity
- Has NOT cleared is `lane' of other material

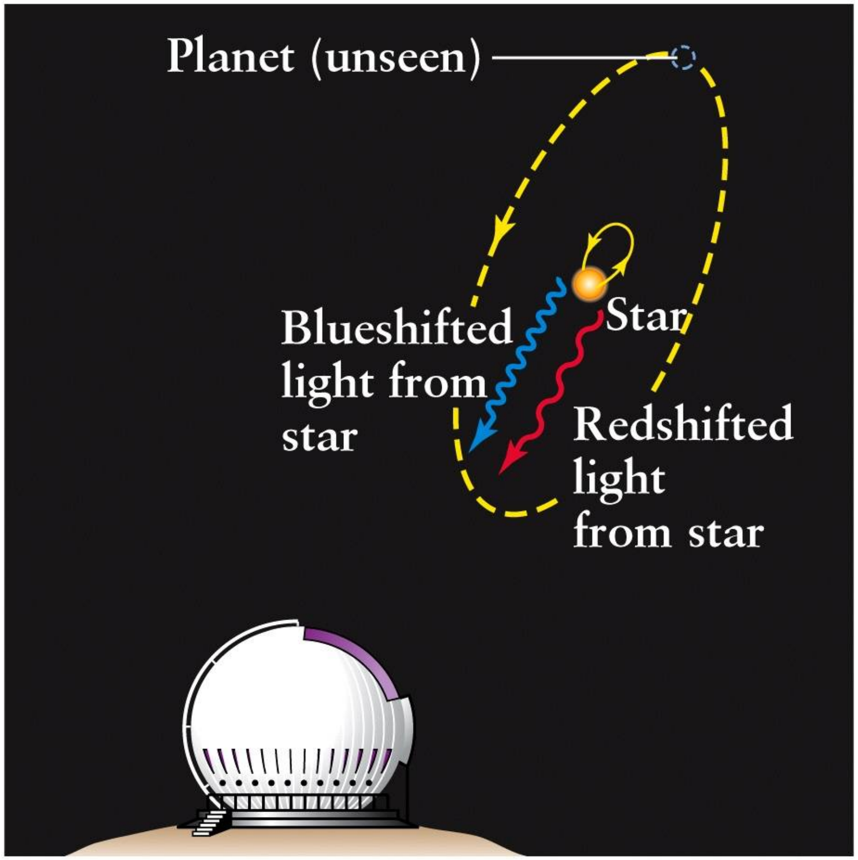
Confirmed members are Pluto, Eris, Ceres (an asteroid) and Makemake. Candidates (pending confirmation of their shape) include Sedna and Orcus.

http://www.minorplanetcenter.net/iau/info/HowNamed.html

5. Certain classes of names are to be applied to specific orbital classes of minor planets.
   - Objects in the classical TNO belt are to receive names of creation deities.
   - Objects in orbits in 3:2 resonance with Neptune are to receive names of underworld deities.
   - Objects in orbits between the orbits of Jupiter and Neptune, and not in 1:1 resonance with any major planet, are to receive names of centaurs.
   - Objects in 1:1 resonance with Jupiter are to receive names associated with the Trojan War. Objects at the preceding L4 point are named for Greeks, objects at the trailing L5 point are named for Trojans.
   - Near-Earth Objects are to receive names from mythology, except names associated with creation or underworld themes.

Extra-solar Planets

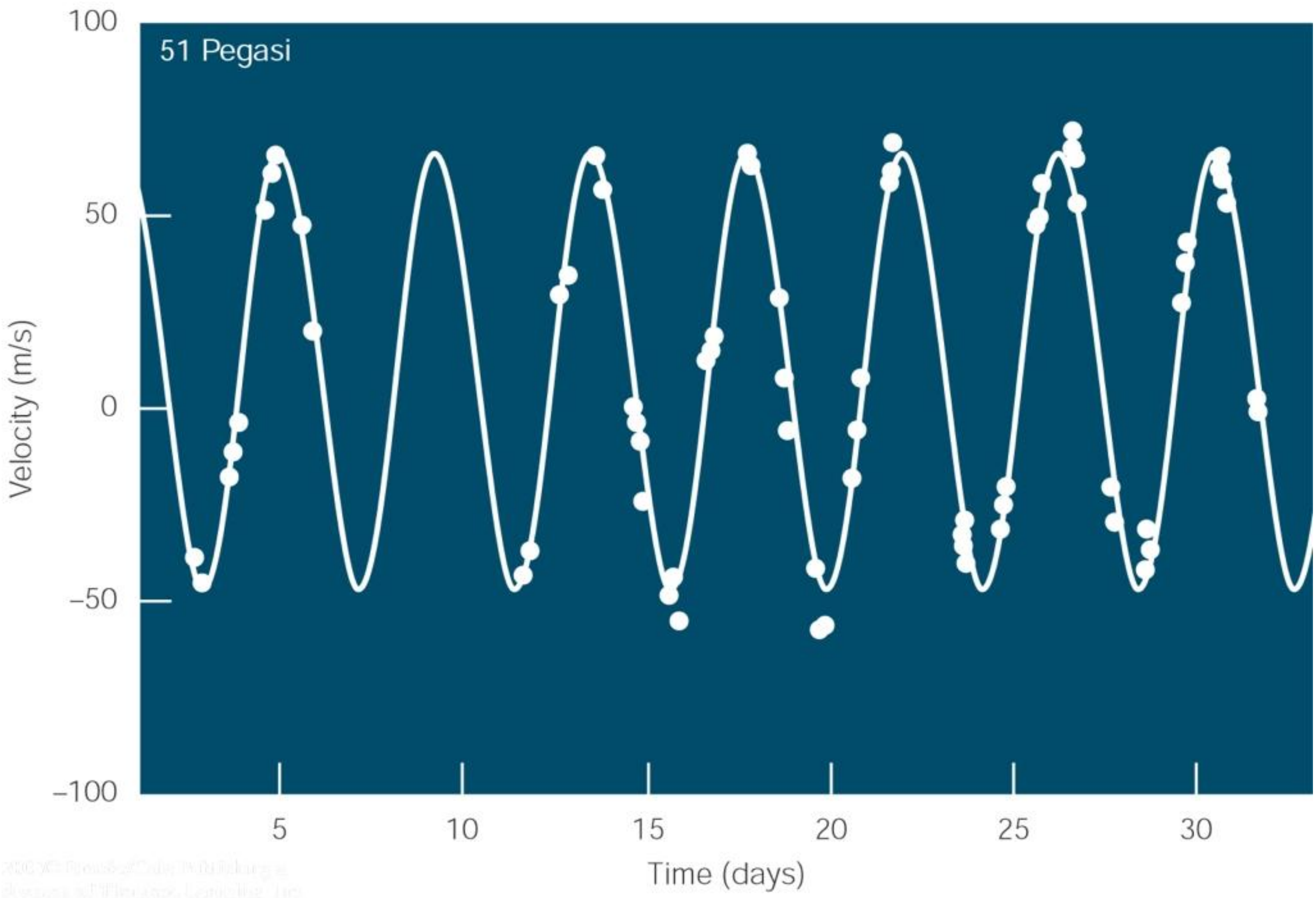
Detection methods: Doppler shifts (radial velocity).

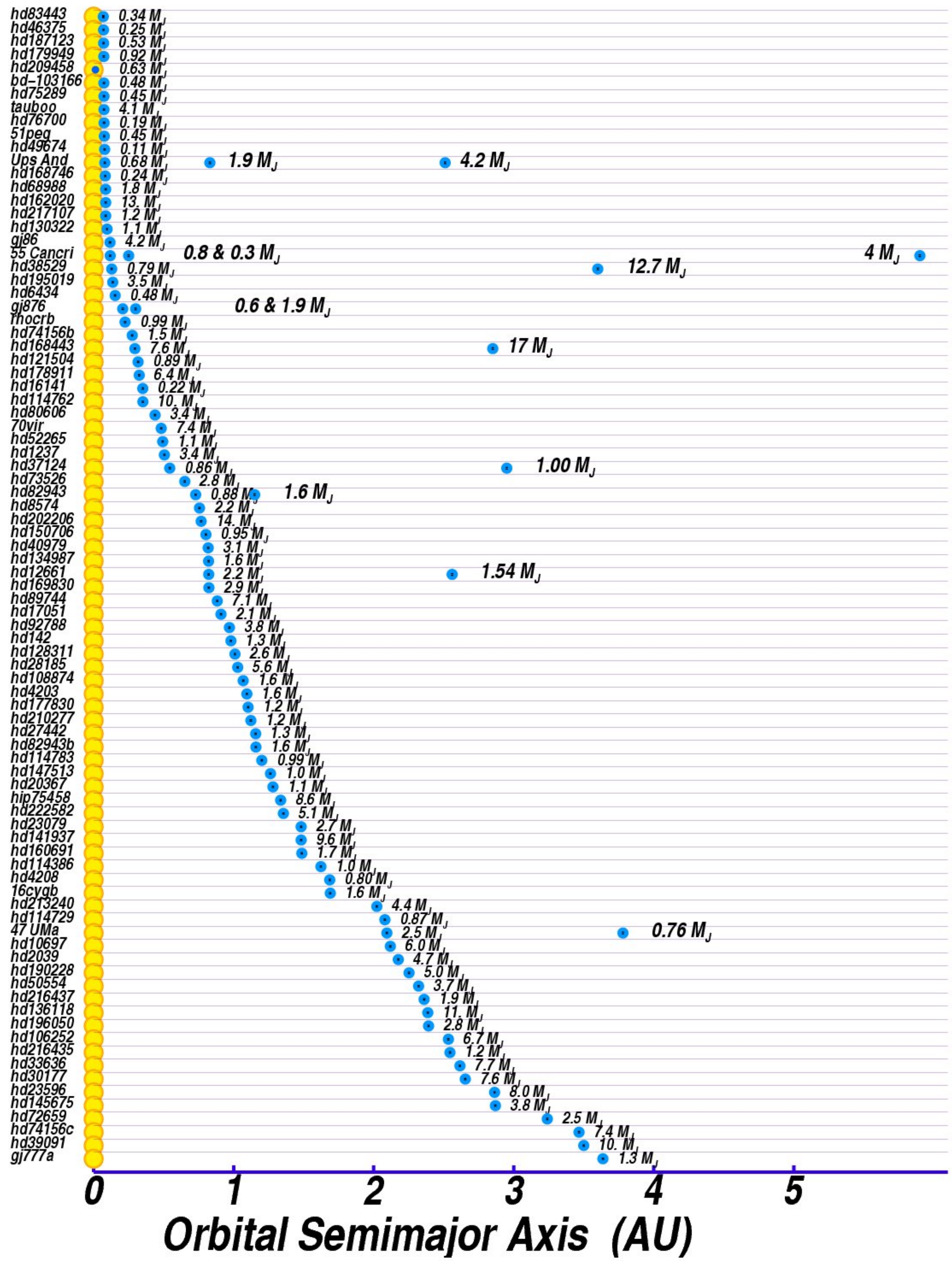


c

Wikipedia: "The first published discovery to receive subsequent confirmation was made in 1988 by the Canadian astronomers Bruce Campbell, G. A. H. Walker, and Stephenson Yang of University of Victoria and University of British Columbia"

A light curve of 51 Peg, one of the first extra-solar planets found




hd83443
hd46375
hd187123
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bd-103166
hd75289
tauboo
hd76700
51peg
hd49674
Ups And
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hd68988
hd162020
hd217107
hd130322
gj86
55 Cancri
hd38529
hd195019
hd6434
gj876
rhocrb
hd74156b
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hd16141
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hd23079
hd141937
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hd114386
hd4208
16cygb
hd213240
hd114729
47 UMa
hd10697
hd2039
hd190228
hd50554
hd216437
hd136118
hd196050
hd106252
hd216435
hd33636
hd30177
hd23596
hd145675
hd72659
hd74156c
hd39091
gj777a
0.34 M_J
0.25 M_J
0.53 M_J
0.92 M_J
0.63 M_J
0.48 M_J
0.45 M_J
4.1 M_J
0.19 M_J
0.45 M_J
0.11 M_J
0.68 M_J
1.9 M_J
4.2 M_J
0.24 M_J
1.8 M_J
13. M_J
1.2 M_J
1.1 M_J
4.2 M_J
0.8 & 0.3 M_J
4 M_J
0.79 M_J
12.7 M_J
3.5 M_J
0.48 M_J
0.6 & 1.9 M_J
0.99 M_J
1.5 M_J
7.6 M_J
17 M_J
0.89 M_J
6.4 M_J
0.22 M_J
10. M_J
3.4 M_J
7.4 M_J
1.1 M_J
3.4 M_J
0.86 M_J
1.00 M_J
2.8 M_J
0.88 M_J
1.6 M_J
2.2 M_J
14. M_J
0.95 M_J
3.1 M_J
1.6 M_J
2.2 M_J
1.54 M_J
2.9 M_J
7.1 M_J
2.1 M_J
3.8 M_J
1.3 M_J
2.6 M_J
5.6 M_J
1.6 M_J
1.6 M_J
1.2 M_J
1.2 M_J
1.3 M_J
1.6 M_J
0.99 M_J
1.0 M_J
1.1 M_J
8.6 M_J
5.1 M_J
2.7 M_J
9.6 M_J
1.7 M_J
1.0 M_J
0.80 M_J
1.6 M_J
4.4 M_J
0.87 M_J
2.5 M_J
0.76 M_J
6.0 M_J
4.7 M_J
5.0 M_J
3.7 M_J
1.9 M_J
11. M_J
2.8 M_J
6.7 M_J
1.2 M_J
7.7 M_J
7.6 M_J
8.0 M_J
3.8 M_J
2.5 M_J
7.4 M_J
10. M_J
1.3 M_J
0
1
2
3
4
5
Orbital Semimajor Axis (AU)

Radial velocity score-card

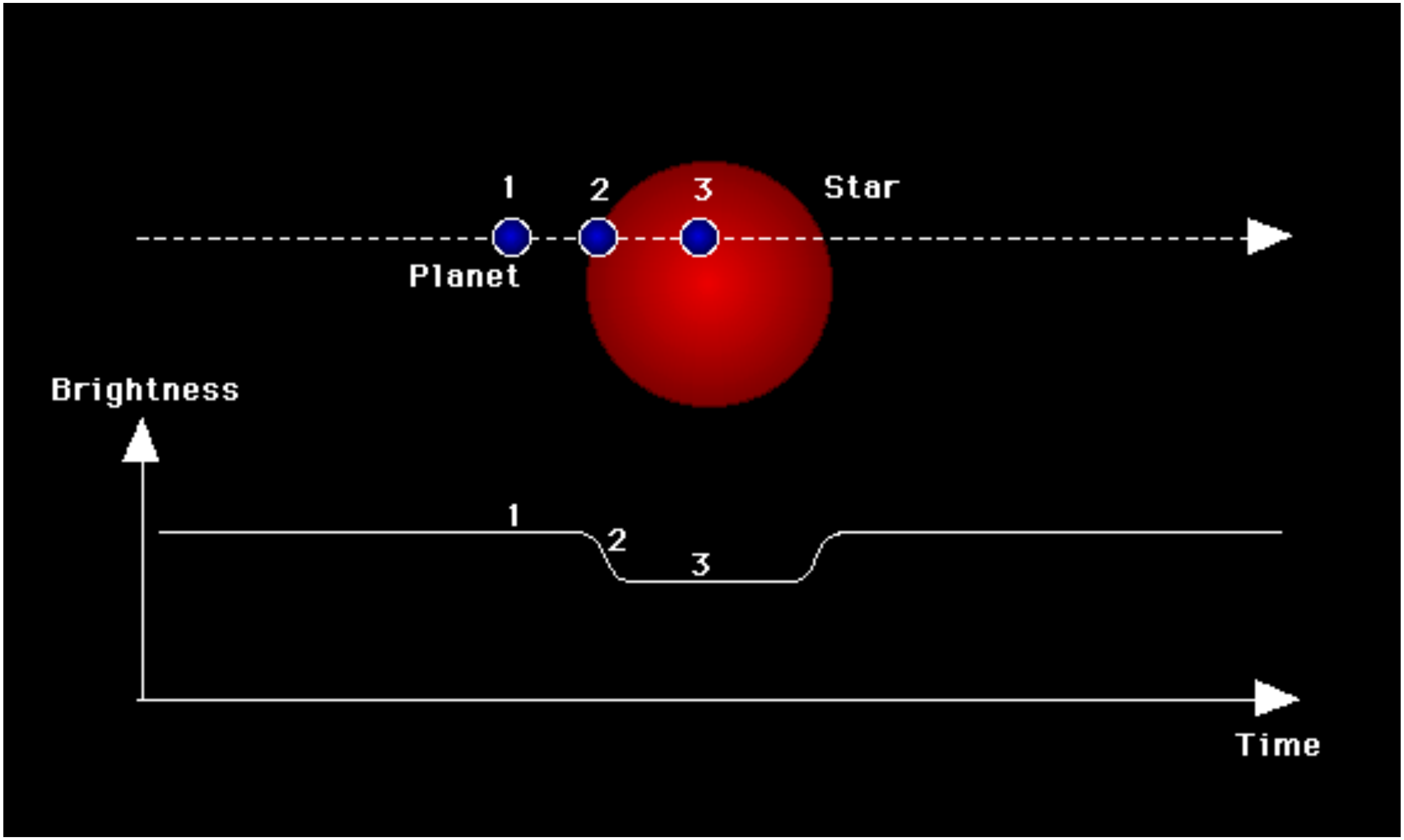
Advantages:

- False detections fairly unlikely
- Orbits do not have to be (fully) edge-on, just need part radial component
- Technology now fairly routine (hundreds of planets found this way): very successful

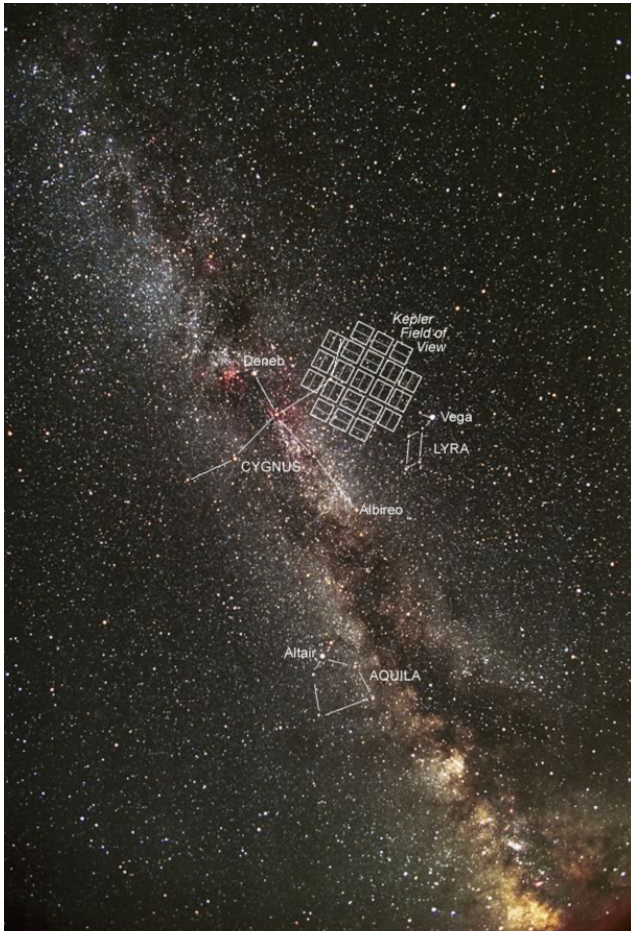
Disadvantages:

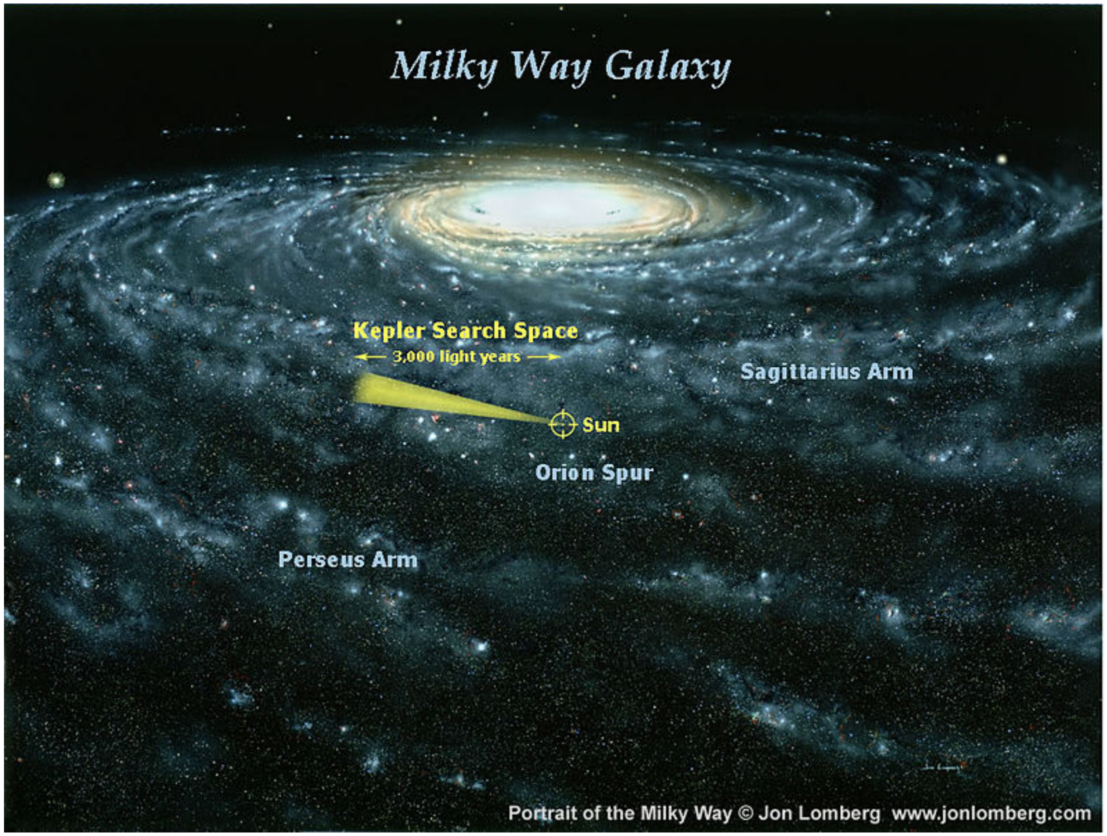
- Uncertainty in inclination angle of mass
- Bias towards high mass, close-in planets
- Requires high signal-to-noise, so larger telescopes

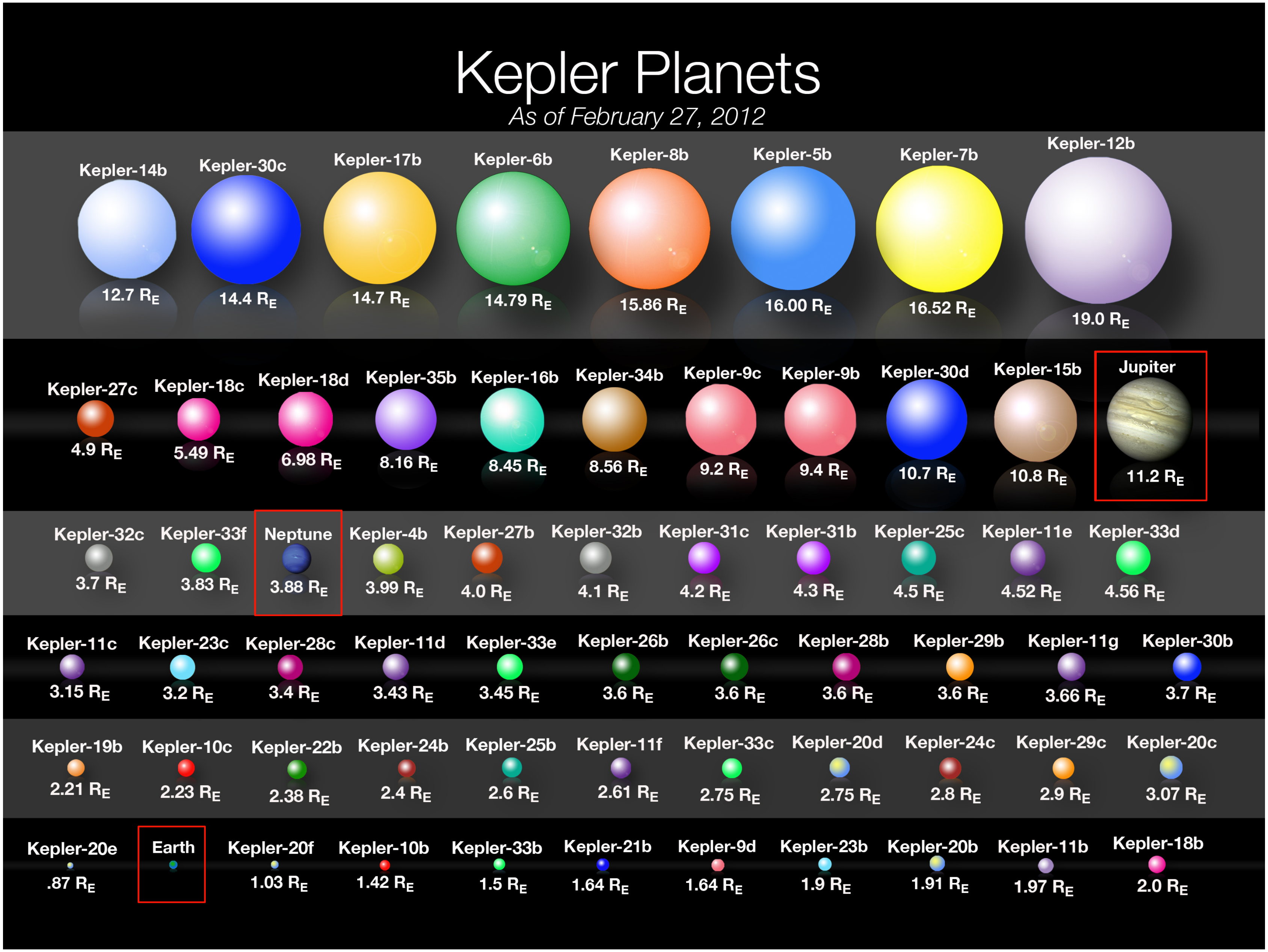
Detection methods: Transits



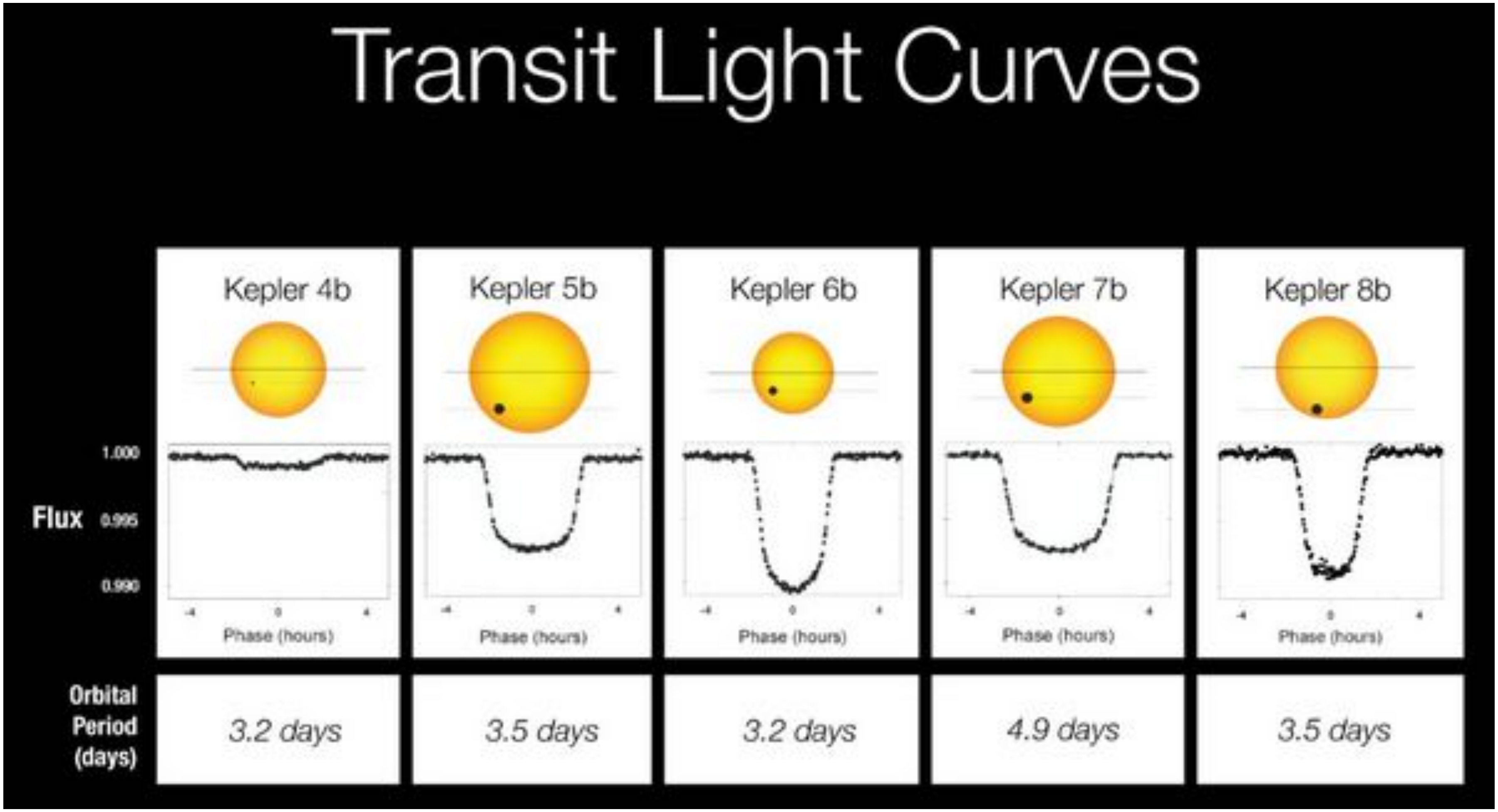
NASA's Kepler mission launched in 2009 is in heliocentric orbit (p=372 days) and continuously observes over 150,000 stars over an area of 115 sq. degrees.






Kepler Planets
As of February 27, 2012
Kepler-14b 12.7 R_E
Kepler-30c 14.4 R_E
Kepler-17b 14.7 R_E
Kepler-6b 14.79 R_E
Kepler-8b 15.86 R_E
Kepler-5b 16.00 R_E
Kepler-7b 16.52 R_E
Kepler-12b 19.0 R_E
Kepler-27c 4.9 R_E
Kepler-18c 5.49 R_E
Kepler-18d 6.98 R_E
Kepler-35b 8.16 R_E
Kepler-16b 8.45 R_E
Kepler-34b 8.56 R_E
Kepler-9c 9.2 R_E
Kepler-9b 9.4 R_E
Kepler-30d 10.7 R_E
Kepler-15b 10.8 R_E
Jupiter 11.2 R_E
Kepler-32c 3.7 R_E
Kepler-33f 3.83 R_E
Neptune 3.88 R_E
Kepler-4b 3.99 R_E
Kepler-27b 4.0 R_E
Kepler-32b 4.1 R_E
Kepler-31c 4.2 R_E
Kepler-31b 4.3 R_E
Kepler-25c 4.5 R_E
Kepler-11e 4.52 R_E
Kepler-33d 4.56 R_E
Kepler-11c 3.15 R_E
Kepler-23c 3.2 R_E
Kepler-28c 3.4 R_E
Kepler-11d 3.43 R_E
Kepler-33e 3.45 R_E
Kepler-26b 3.6 R_E
Kepler-26c 3.6 R_E
Kepler-28b 3.6 R_E
Kepler-29b 3.6 R_E
Kepler-11g 3.66 R_E
Kepler-30b 3.7 R_E
Kepler-19b 2.21 R_E
Kepler-10c 2.23 R_E
Kepler-22b 2.38 R_E
Kepler-24b 2.4 R_E
Kepler-25b 2.6 R_E
Kepler-11f 2.61 R_E
Kepler-33c 2.75 R_E
Kepler-20d 2.75 R_E
Kepler-24c 2.8 R_E
Kepler-29c 2.9 R_E
Kepler-20c 3.07 R_E
Kepler-20e .87 R_E
Earth
Kepler-20f 1.03 R_E
Kepler-10b 1.42 R_E
Kepler-33b 1.5 R_E
Kepler-21b 1.64 R_E
Kepler-9d 1.64 R_E
Kepler-23b 1.9 R_E
Kepler-20b 1.91 R_E
Kepler-11b 1.97 R_E
Kepler-18b 2.0 R_E

Light curves provide a measurement of radius (and other orbital parameters).



Transit method score-card

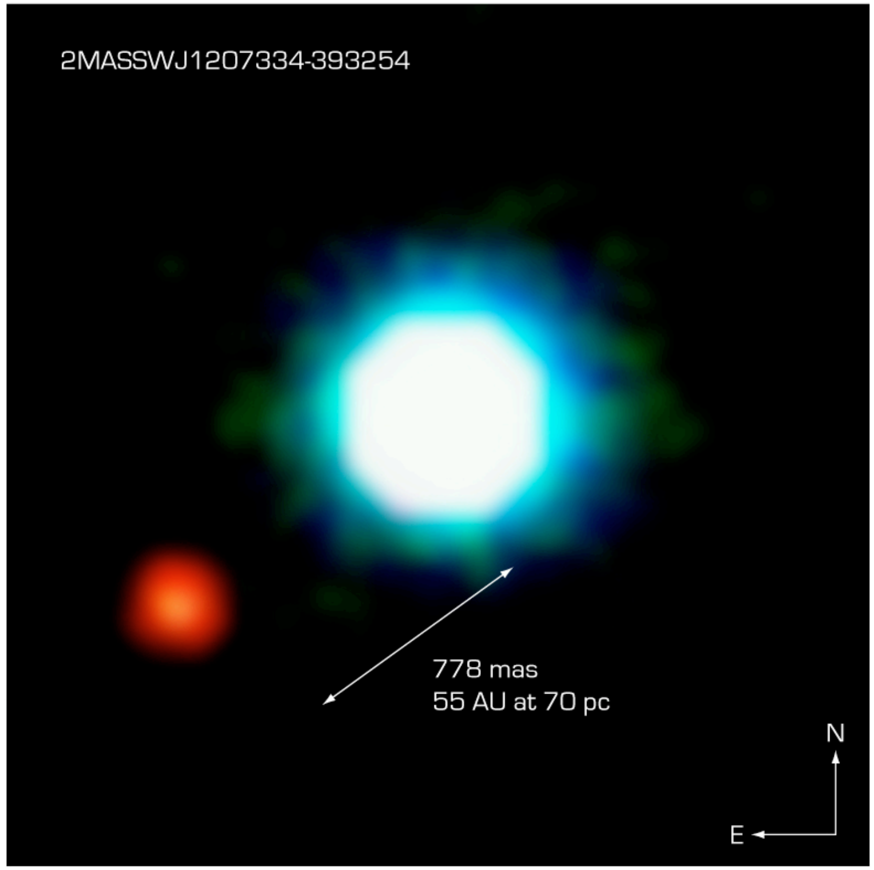
Advantages:

- Large numbers of stars can be observed at once
- Requires relatively small telescopes
- Radius can be determined from shape of light curve
- Possible follow-up to look at planetary atmosphere
- Kepler revealing large numbers

Disadvantages:

- System needs to be edge-on
- Lots of false alarms (e.g. variability)
- Requires spectroscopic confirmation

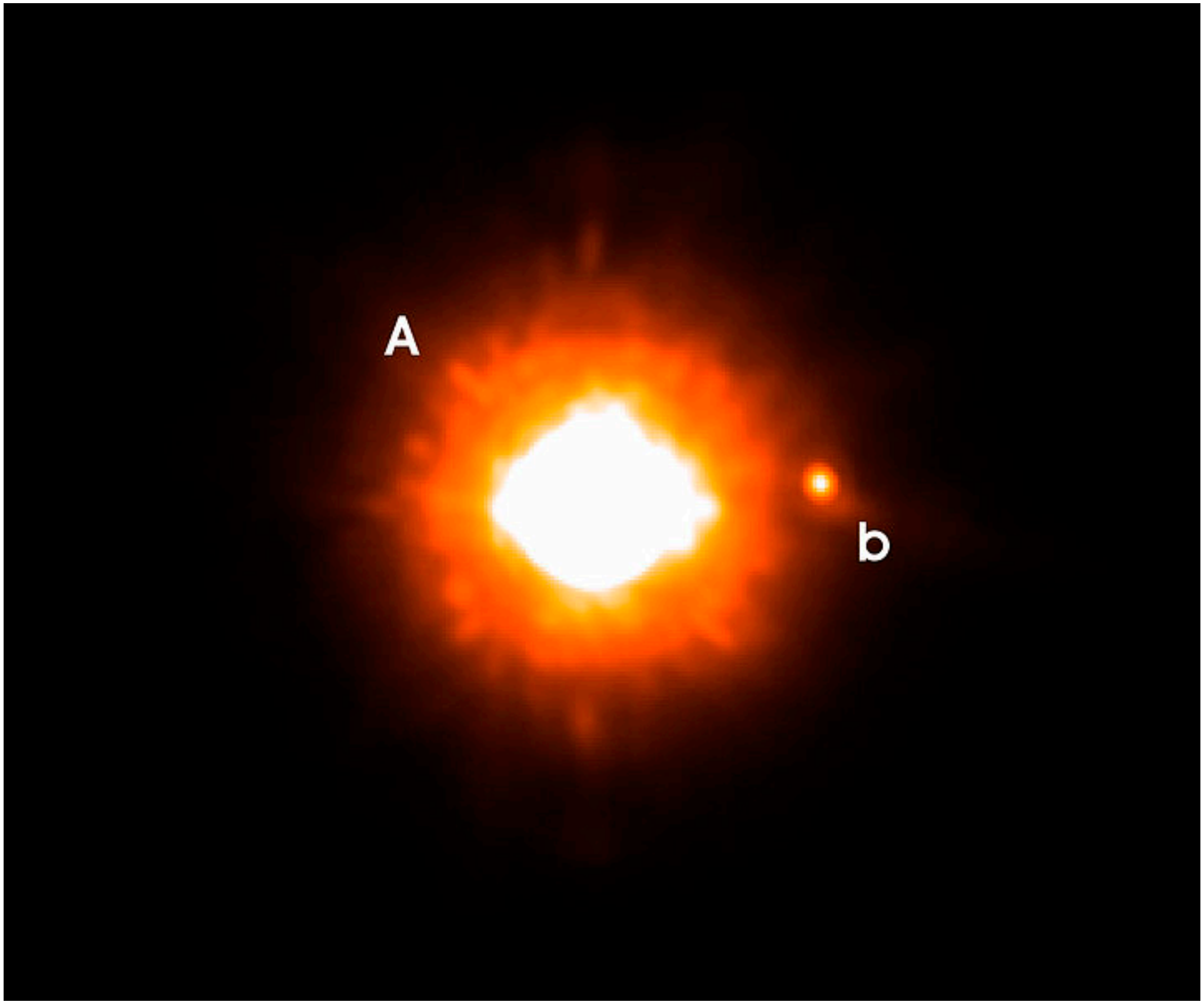
Detection methods: direct imaging.



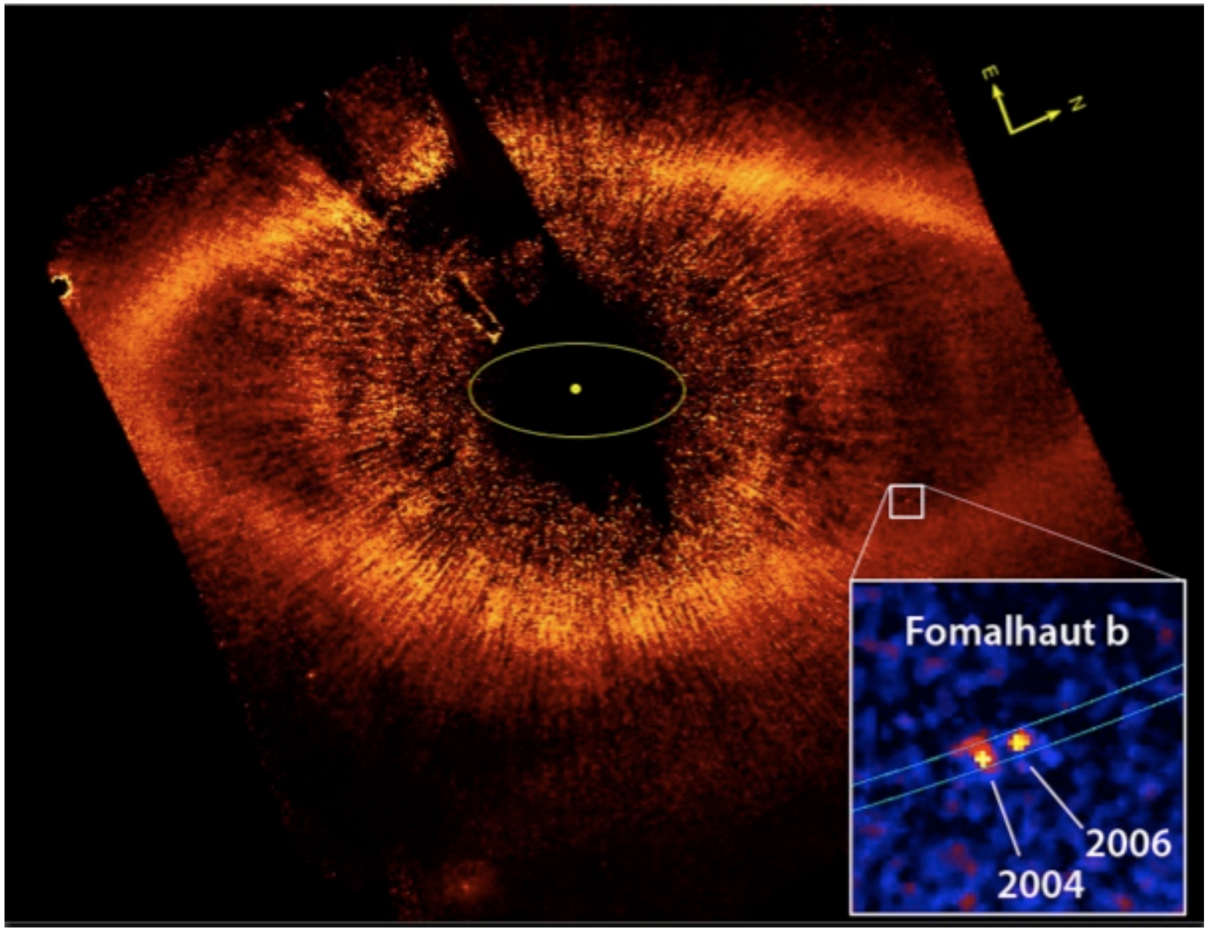
NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004)

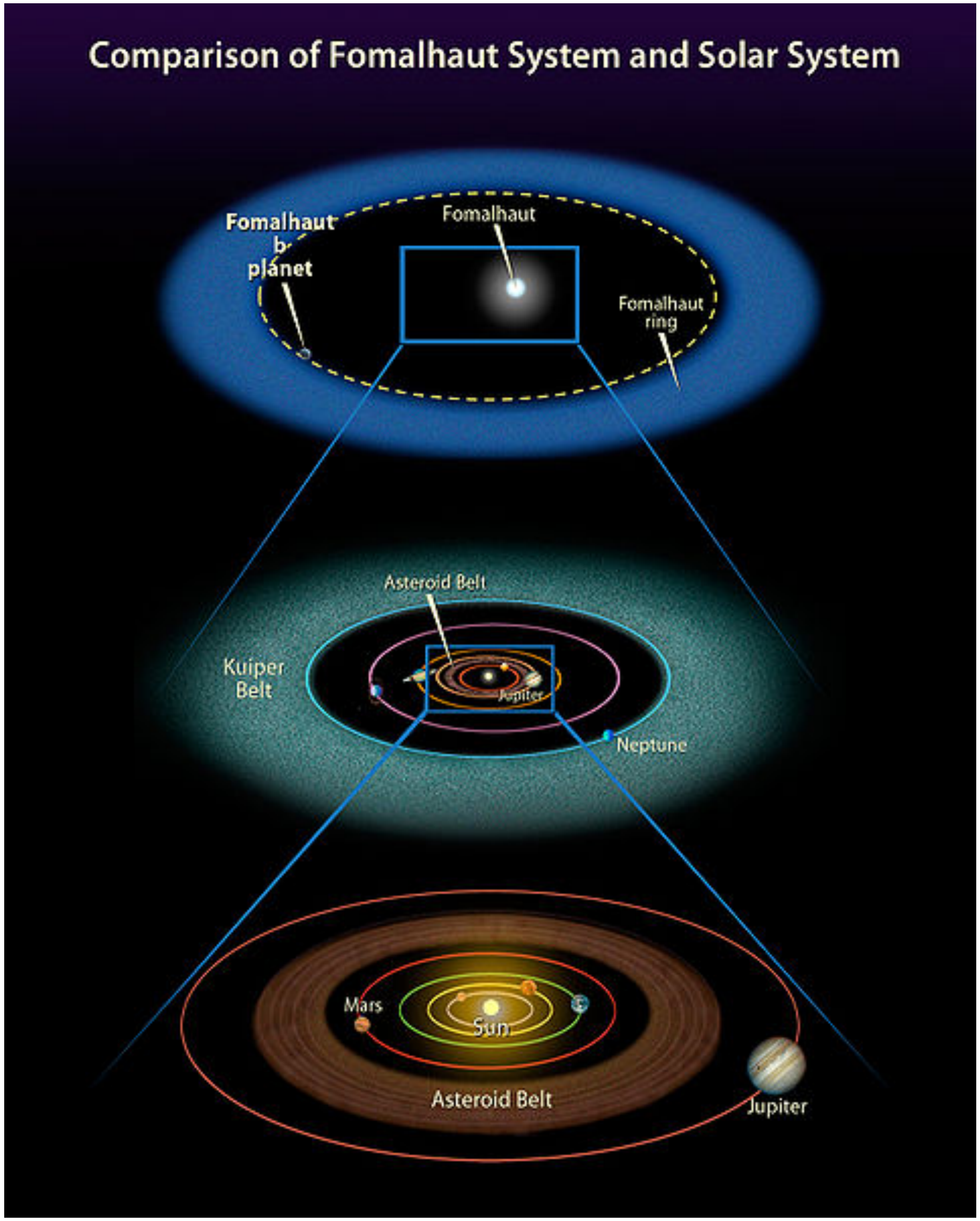
2004: First direct imaging of planetary mass companion. But around a brown dwarf, not a fully fledged star. Bright blue object is the brown dwarf. Red object claimed to be about 5 Jupiter masses.



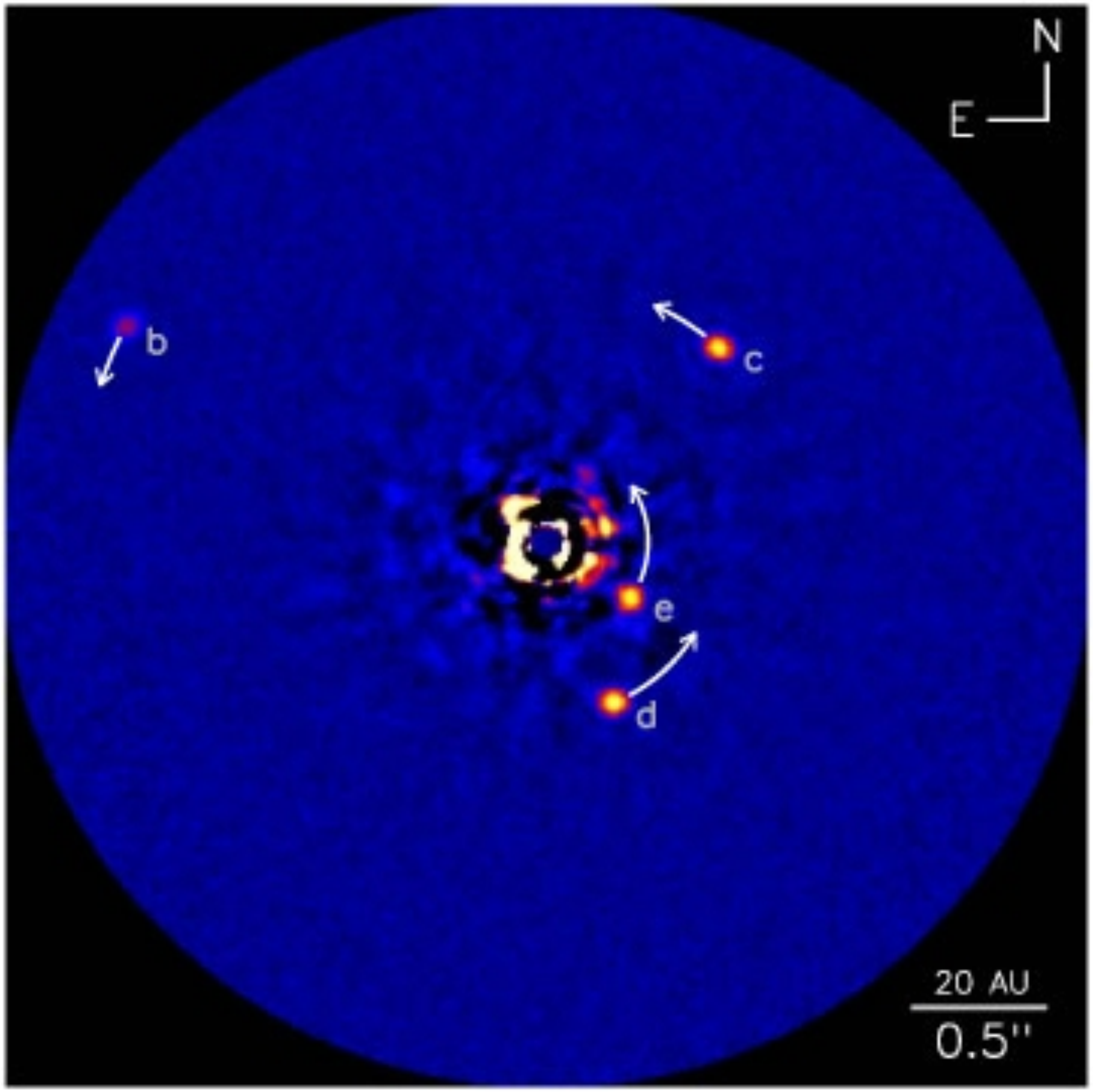
2005: GQ Lupi's companion: ~100 AU, 1-2 Jupiter masses, but maybe as much as 40 Jupiter masses (making it a brown dwarf).



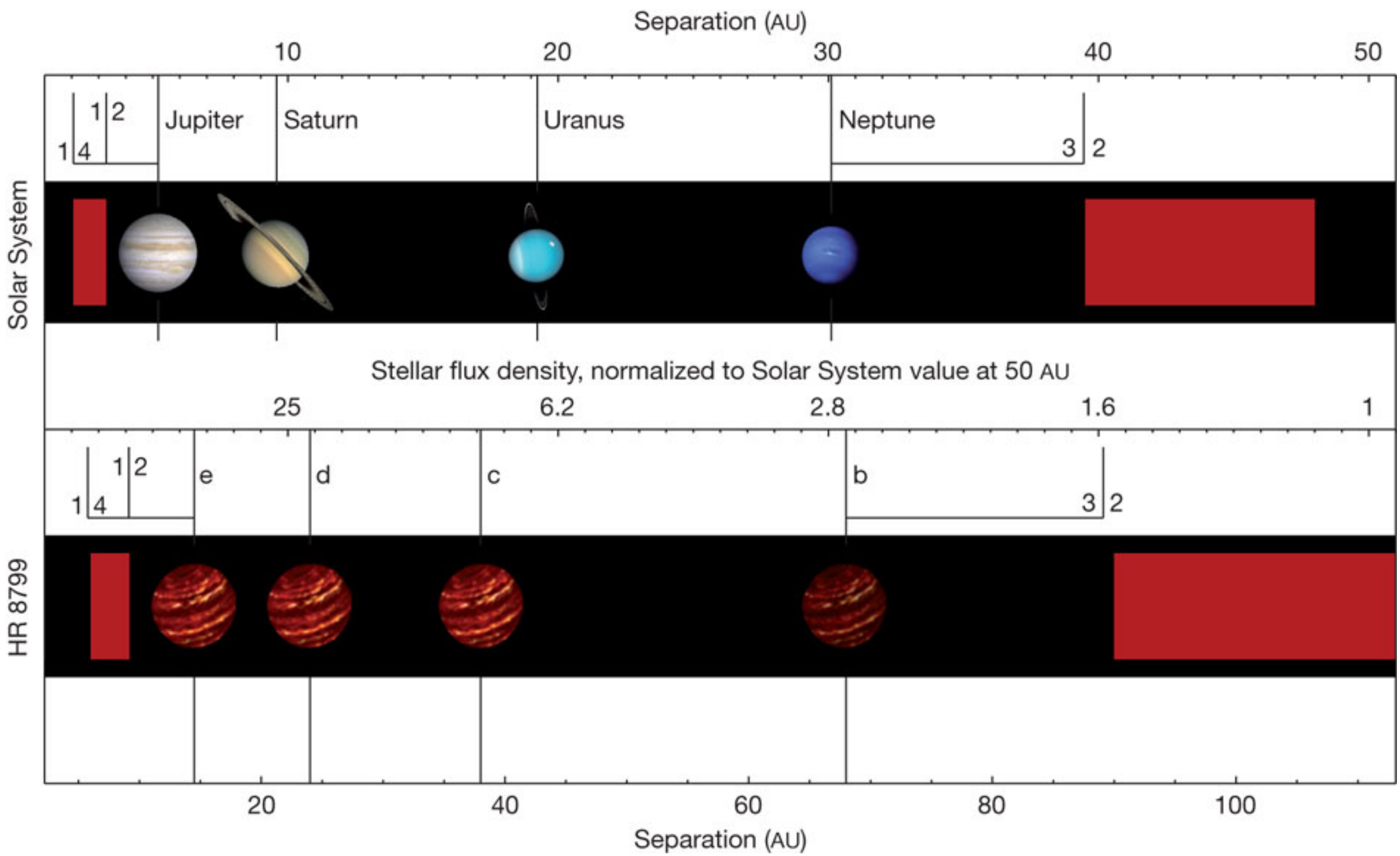
2008: detection around star Fomalhaut in its dust/debris ring, but some suggestions that it may just be scattered light, or rubble pile.



Comparison of Fomalhaut System and Solar System
Fomalhaut
b
planet
Fomalhaut
Fomalhaut
ring
Asteroid Belt
Kuiper
Belt
Jupiter
Neptune
Mars
Sun
Asteroid Belt
Jupiter



2008: HR8799 discovery of 3 (then 4!) planets by team based in Victoria!



HR 8799's planets present on a similar scale to our solar system.

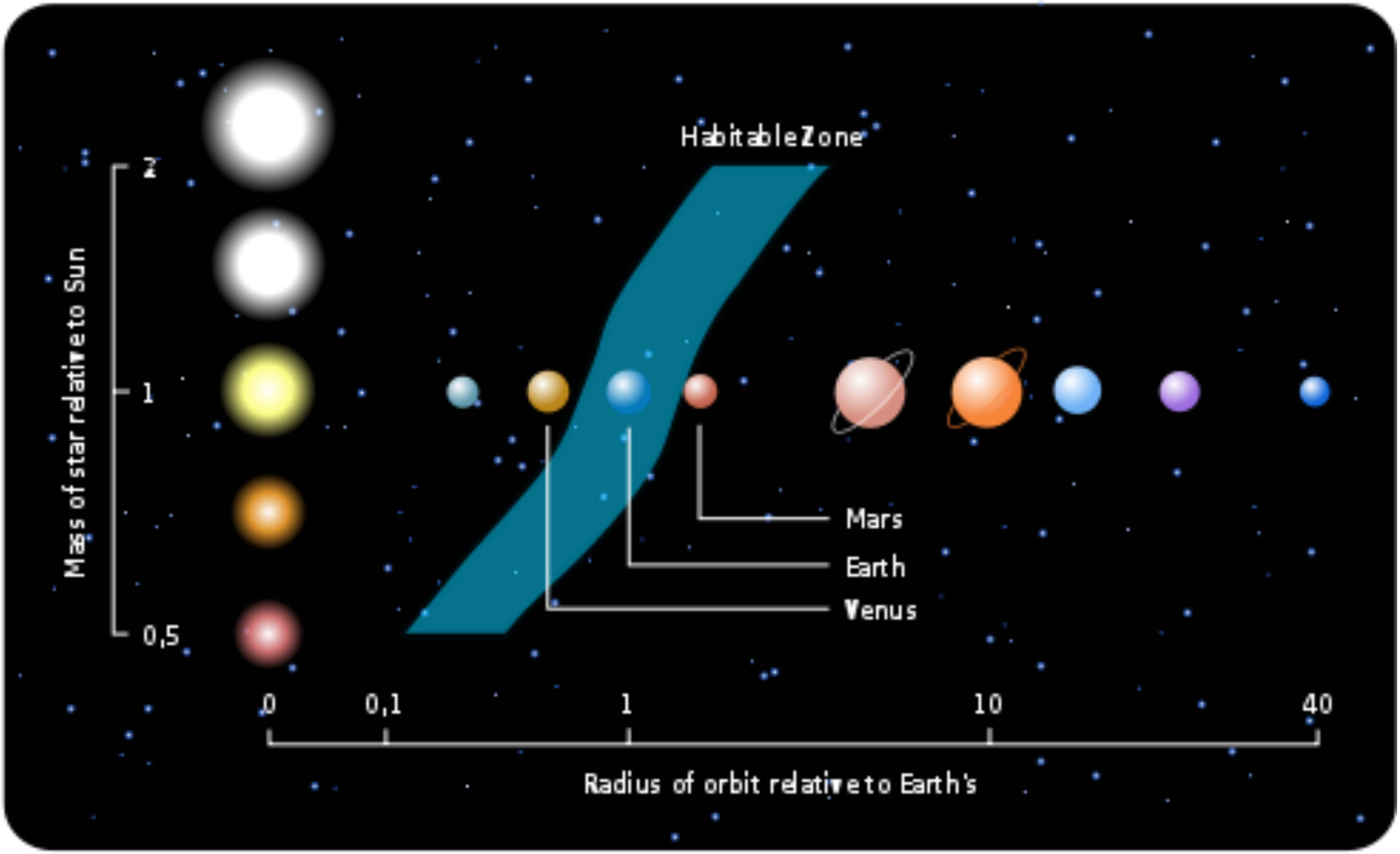
Direct imaging score-card

Advantages:

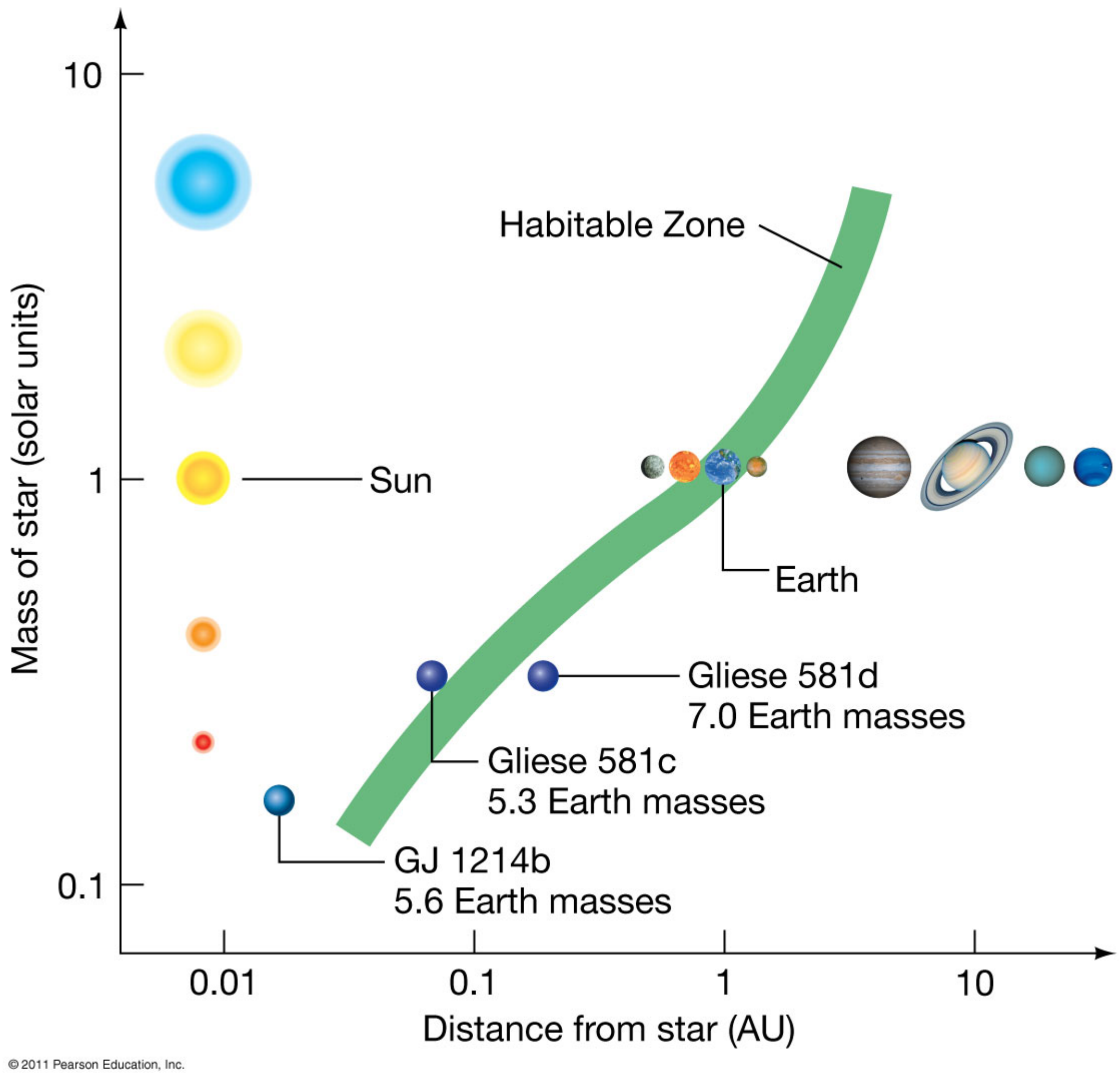
- We all like to see pictures…

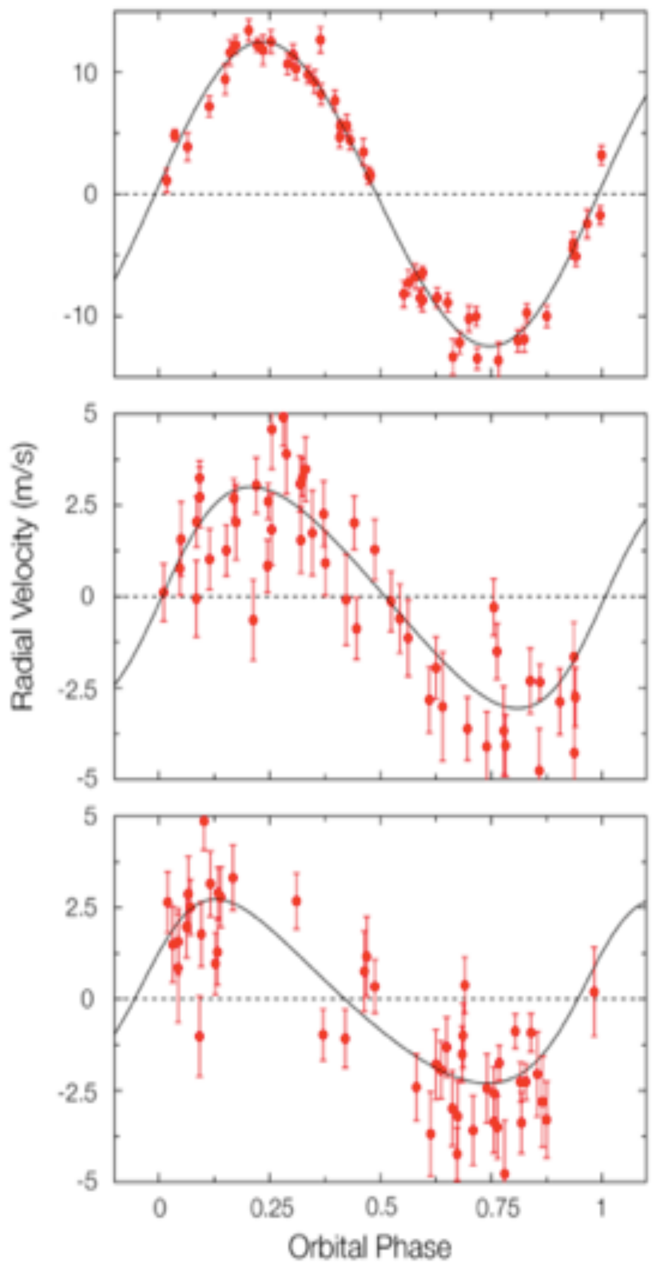
Disadvantages:

- Still extremely challenging observationally
- Must prove that object is not in projection
- Biased towards high mass, (moderately) large separations


Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

A fast changing field: status when textbook went to press in 2009:

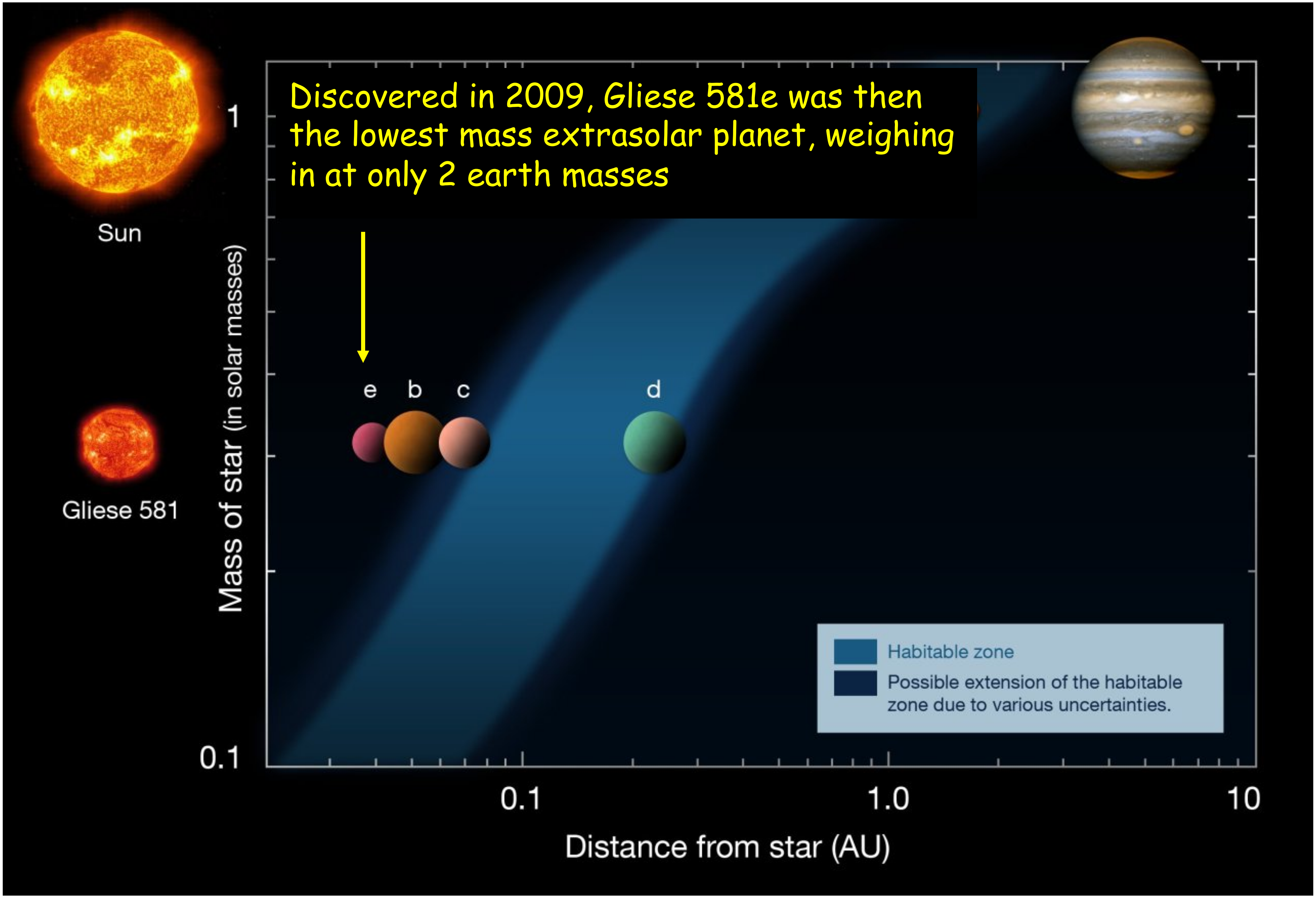




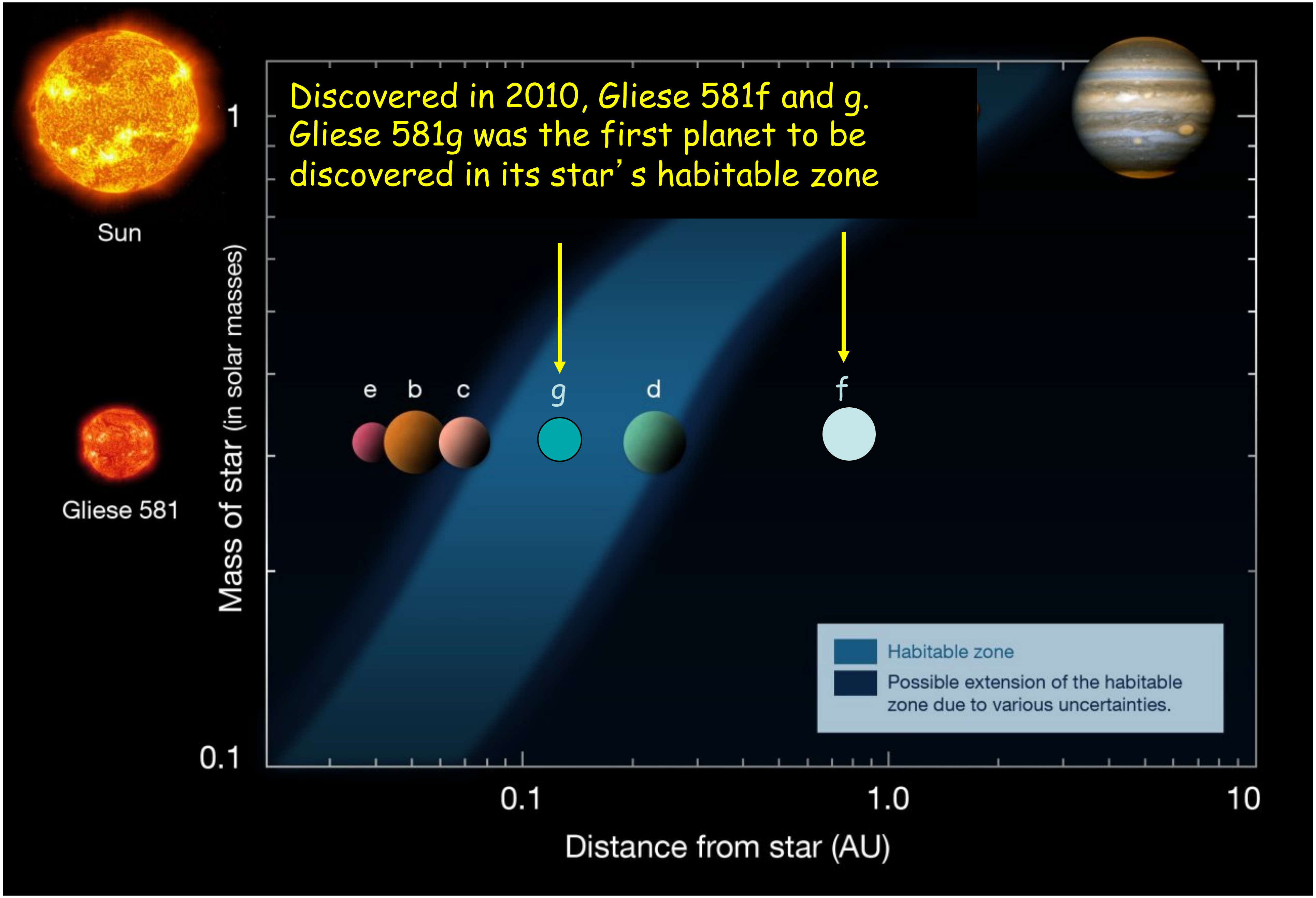
Gliese 581: 20 lyrs from earth, red dwarf, 1/3 solar mass, several planets!

Most of Gliese 581's doppler wobble is caused by a 15 earth mass planet very close to the star with an orbital period of only 5 days (Gliese 581 b).

Once that signal is subtracted out, weaker wobbles can be seen from two other planets whose masses are around 5 and 8 earth masses (Gliese 581 c and d).



Discovered in 2009, Gliese 581e was then the lowest mass extrasolar planet, weighing in at only 2 earth masses
Sun
Gliese 581
Mass of star (in solar masses)
1
0.1
e
b
c
d
Habitable zone
Possible extension of the habitable zone due to various uncertainties.
0.1
1.0
10
Distance from star (AU)



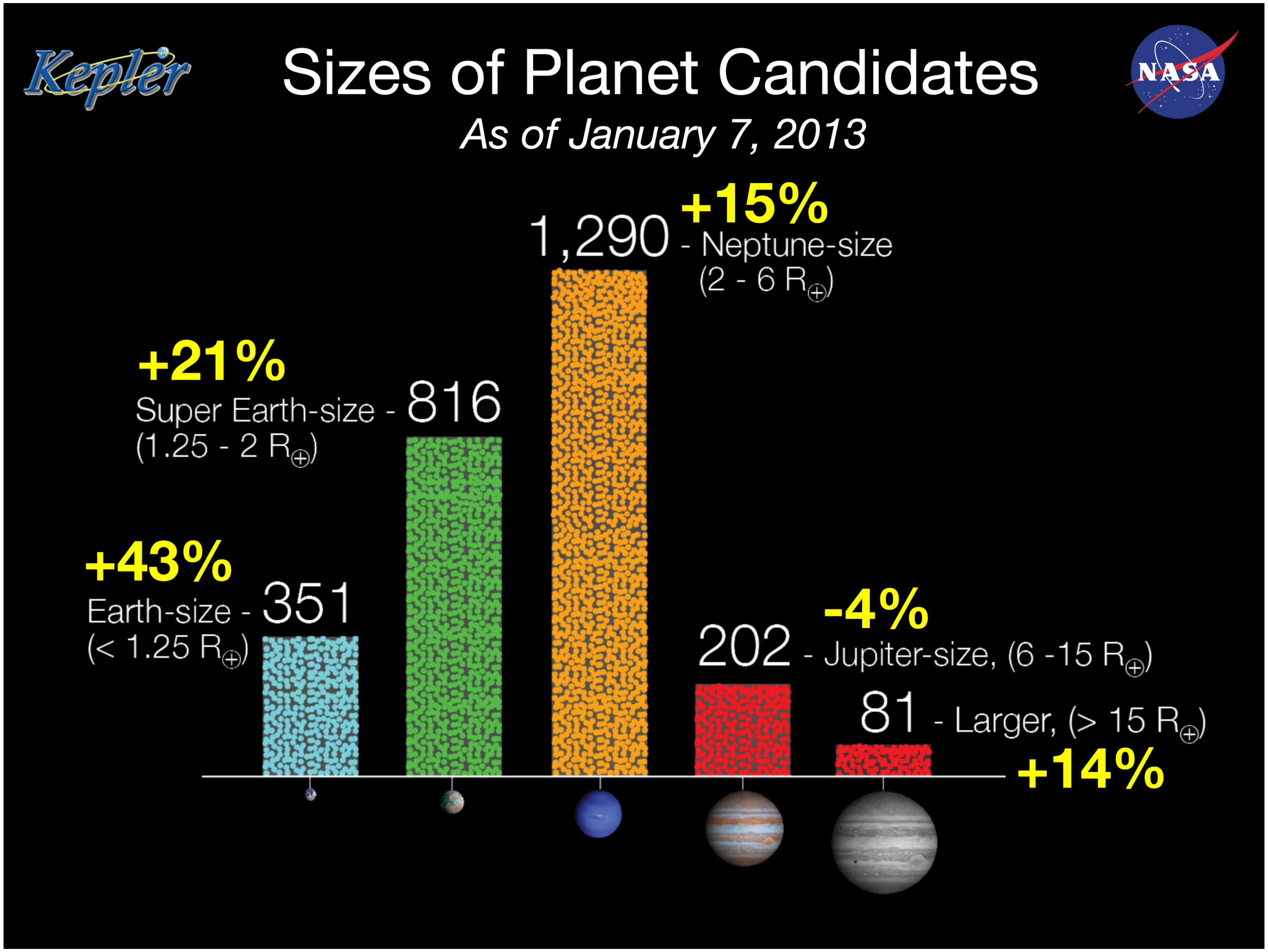
Discovered in 2010, Gliese 581f and g.
Gliese 581g was the first planet to be discovered in its star's habitable zone
Sun
Gliese 581
1
0.1
Mass of star (in solar masses)
e
b
c
g
d
f
Habitable zone
Possible extension of the habitable zone due to various uncertainties.
0.1
1.0
10
Distance from star (AU)

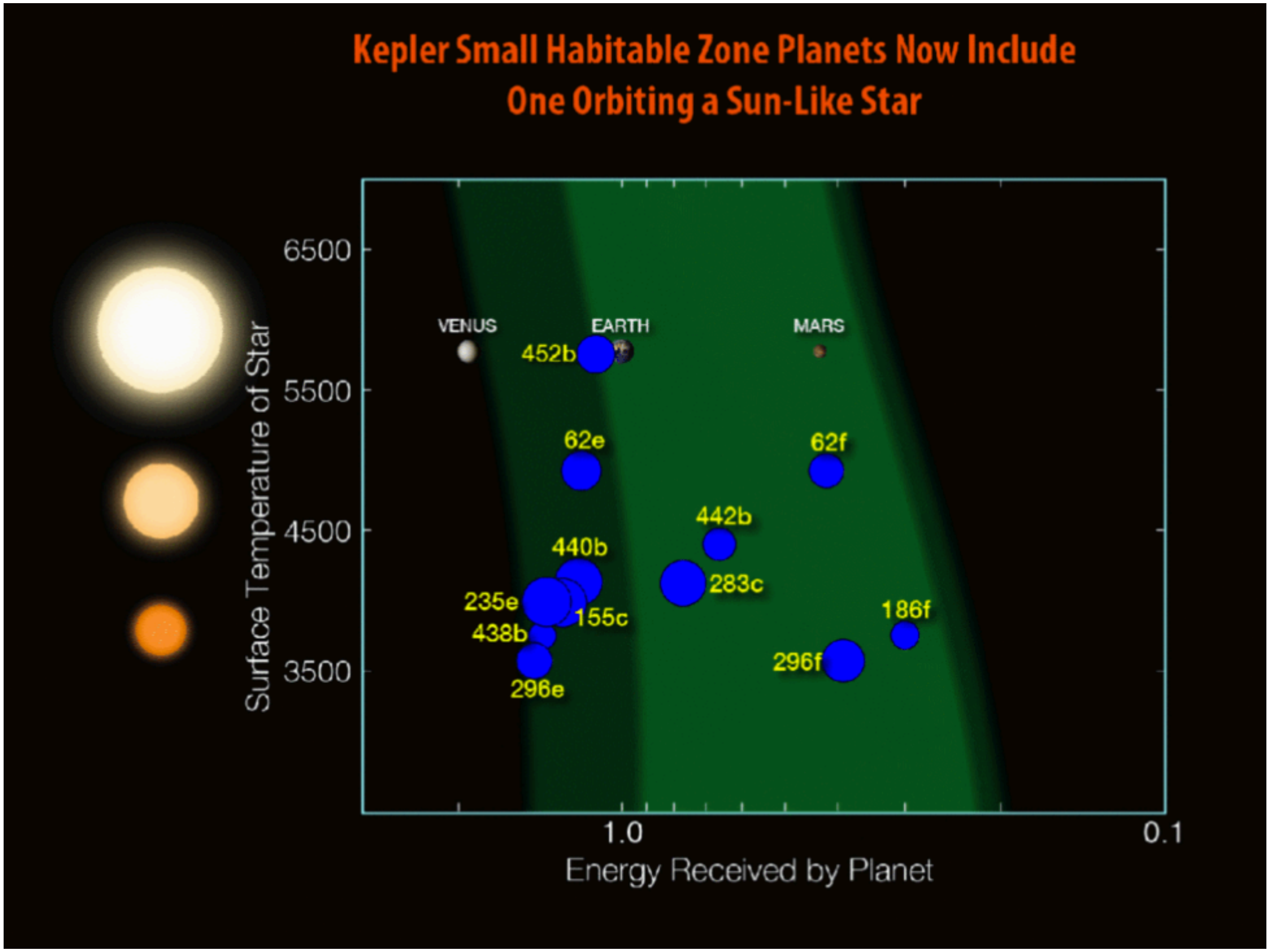
The Gliese 581 system[11]

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
e	≥1.7 $M_\oplus$	0.0284533 ± 0.0000023	3.14867 ± 0.00039	0
b	≥15.6 $M_\oplus$	0.0406163 ± 0.0000013	5.36841 ± 0.00026	0
c	≥5.6 $M_\oplus$	0.072993 ± 0.000022	12.9191 ± 0.0058	0
g	≥3.1 $M_\oplus$	0.14601 ± 0.00014	36.562 ± 0.052	0
d	≥5.6 $M_\oplus$	0.21847 ± 0.00028	66.87 ± 0.13	0
f	≥7.0 $M_\oplus$	0.758 ± 0.015	433 ± 13	0

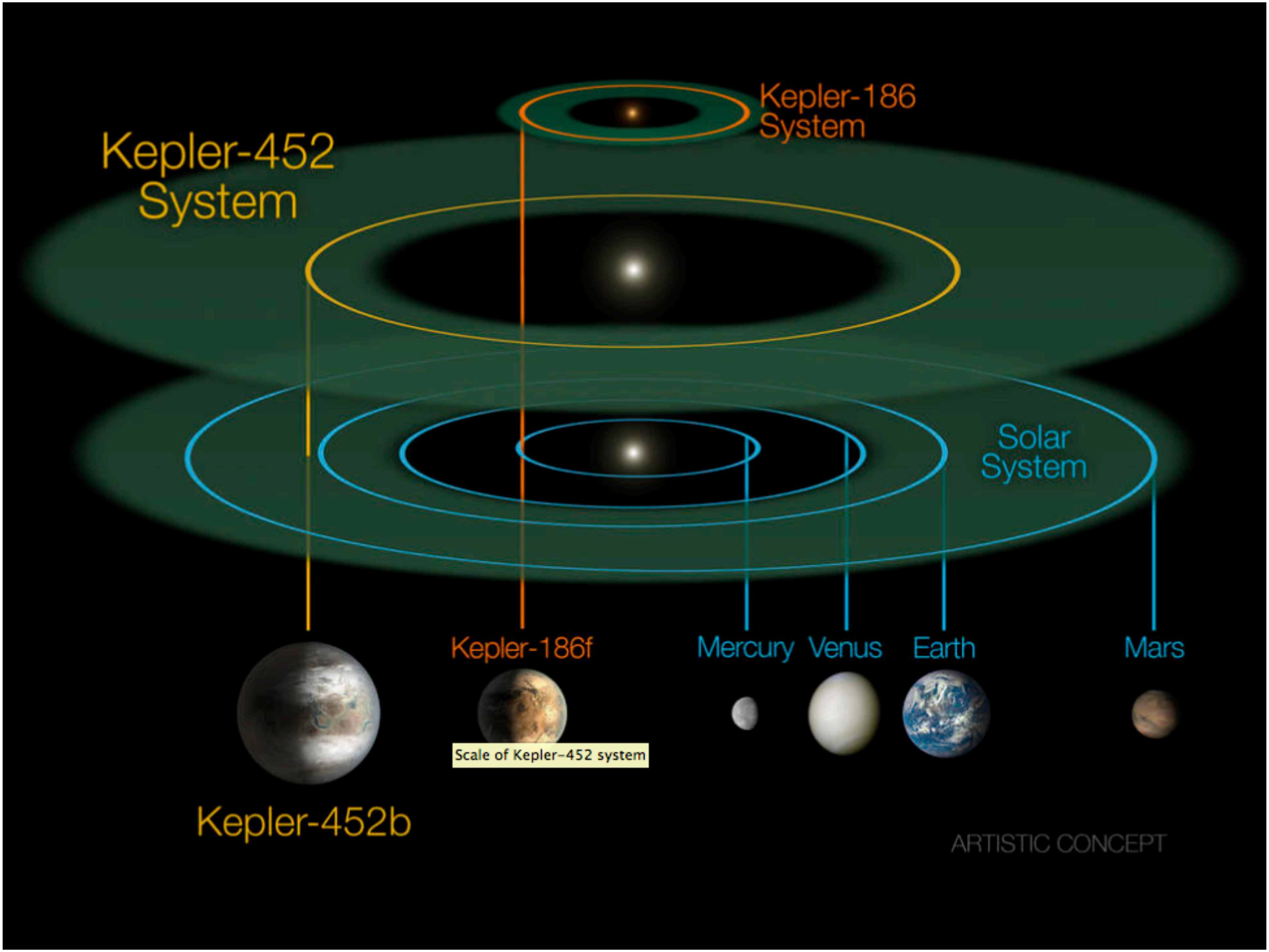
Masses are lower limits due to unknown inclination. Measurement is actually *m sin i* (where i is angle of inclination).

Kepler is making a big difference in our tally of Earth sized planets.

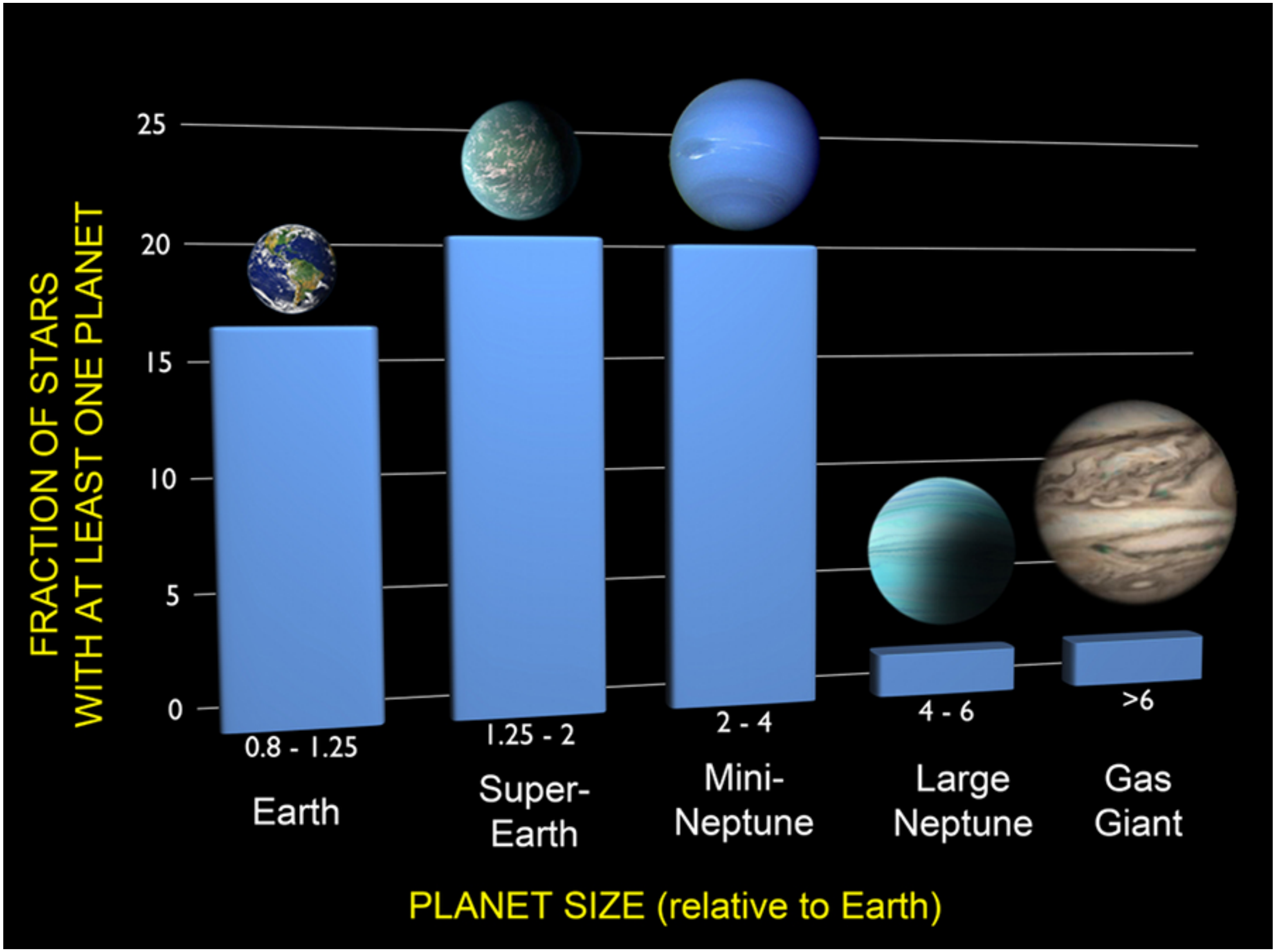




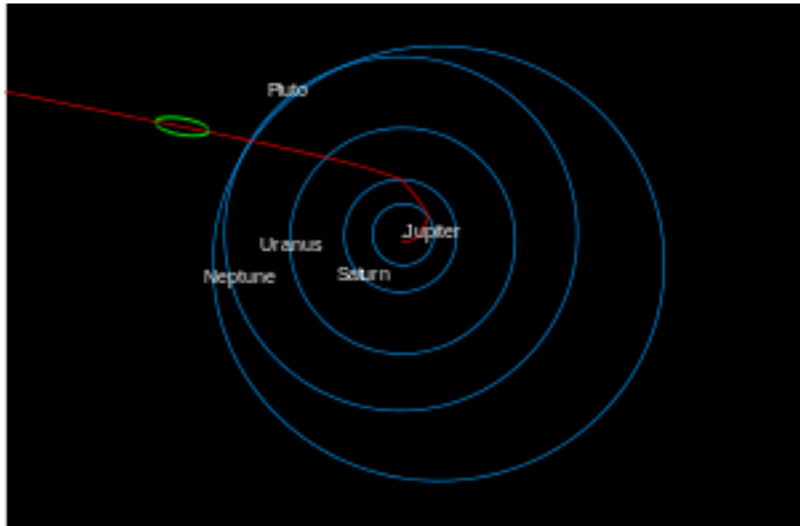
As of July 2015, Kepler had discovered 12 planets with masses up to 2 Earth masses in its star's habitable zone, including one around a sun like star.



Kepler-186
System
Kepler-452
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Scale of Kepler-452 system
Kepler-452b
ARTISTIC CONCEPT



17% stars in Milky Way host an Earth size planet - 17 billion Earths! (Although estimates apply to planets within Mercury-sized orbit)



Pluto
Jupiter
Uranus
Neptune
Saturn