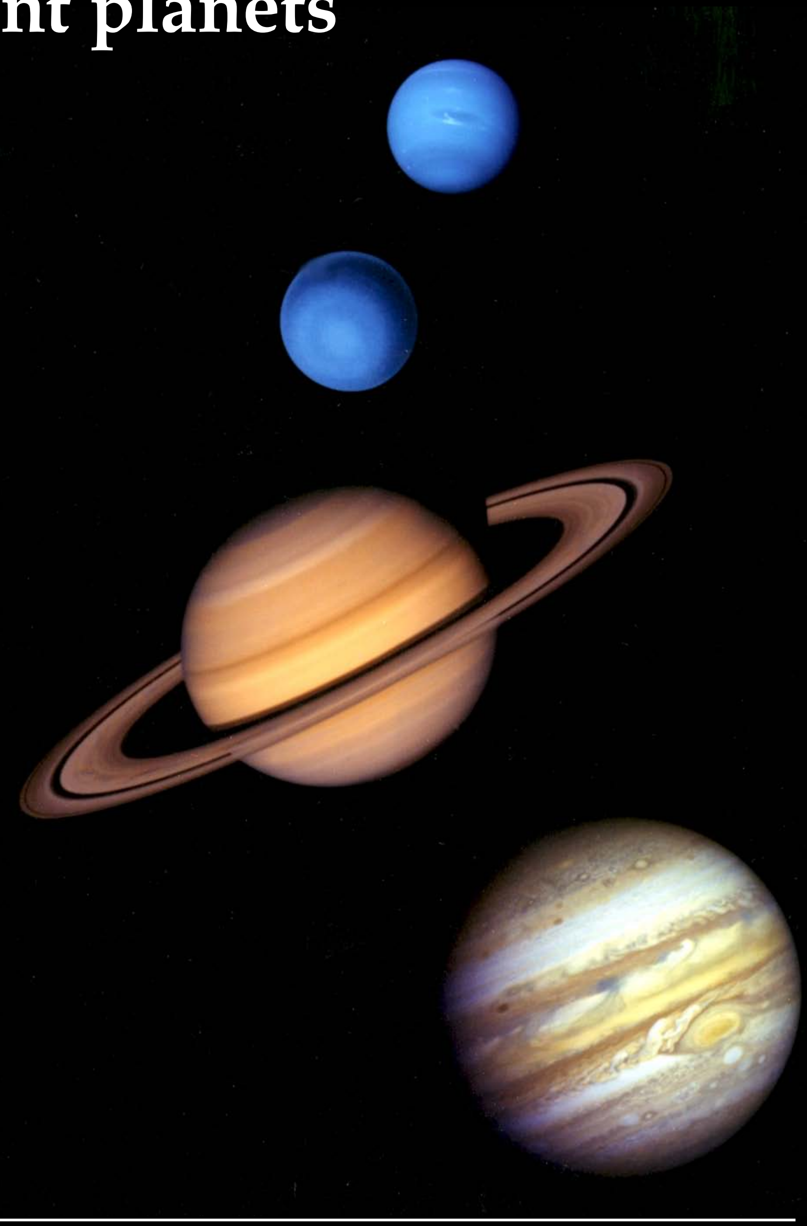
Today in Astronomy 111: giant planets and planetary atmospheres

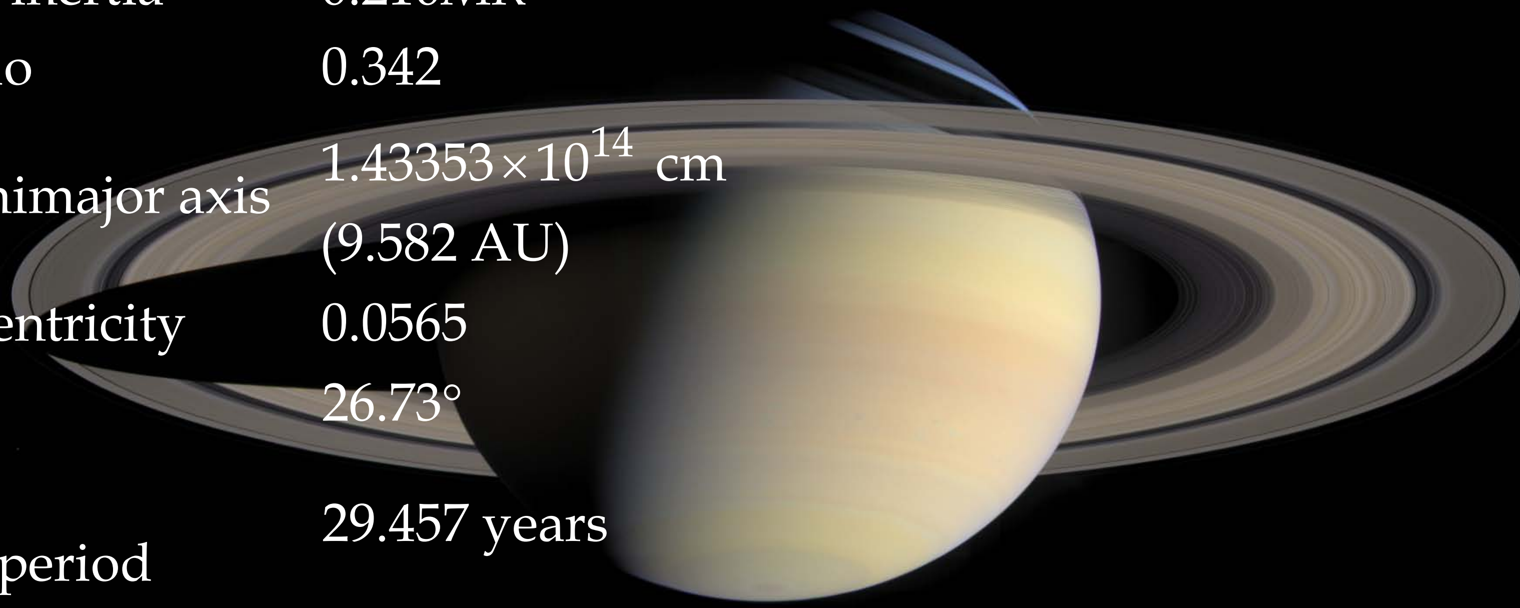
- The other giant planets
  - Vitals of Saturn, Uranus and Neptune
  - Gas giants and ice giants
- Vertical density and pressure structure of atmospheres



All four giant planets, on the same scale (Voyager images, JPL/NASA).

Saturn's vital statistics

Mass	5.6846×10^{29} gm ($95.2M_\oplus$)
Equatorial radius	6.0268×10^{9} cm ($9.45R_\oplus$)
Average density	0.687 gm cm^{-3}
Moment of inertia	$0.210MR^2$
Bond albedo	0.342
Orbital semimajor axis	1.43353×10^{14} cm (9.582 AU)
Orbital eccentricity	0.0565
Obliquity	26.73°
Sidereal revolution period	29.457 years
Sidereal rotation period	10.656 hours
Moons	62 and counting
Rings	7 major ones



Saturn, from *Cassini* (JPL/NASA)

Visits to Saturn

We have visited Saturn four times, including the visit currently in progress:

- Pioneer 11 (1979)
- Voyager 1 (1980)
- Voyager 2 (1981)
- Cassini (2004-)

The Voyager family portrait of Saturn and some of its larger moons (JPL/NASA)

Saturn: structure and composition

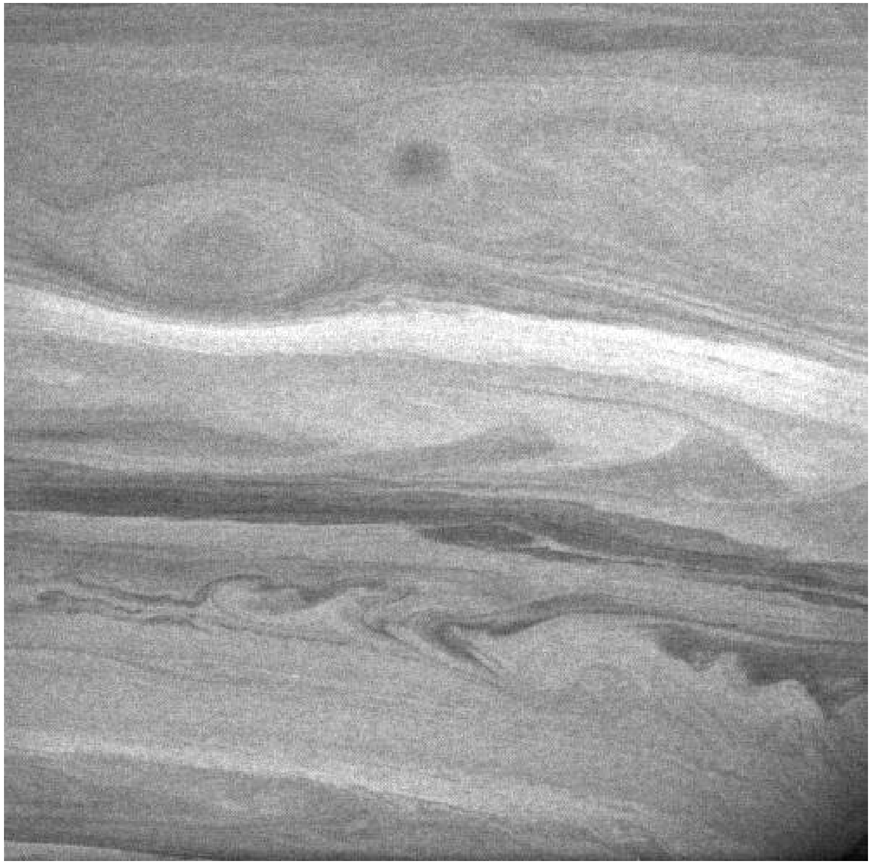
Like Jupiter, Saturn is a gas giant.

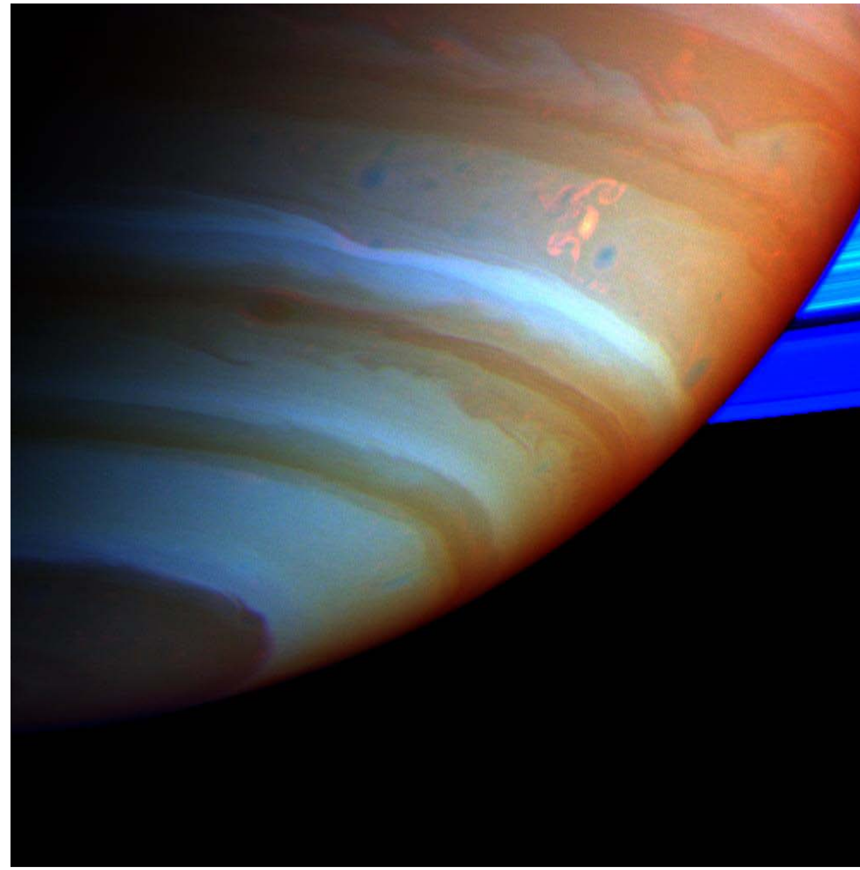
- Has the lowest average density of the planets, and a very low moment of inertia for its mass.
- Spins almost as fast as Jupiter, and its visible surface is even more distorted by its rotation than Jupiter (polar diameter 10% smaller than equatorial diameter), owing to lower density and larger rocky core.
- Definitely has a rocky core, $\sim 12 M_{\oplus}$.
- Elements heavier than H even more abundant than in Jupiter; e.g. $C/H \approx 10(C/H)_{\odot}$. Visible constituents: 96.3% H_2, 3.25% He, 0.45% CH_4, 0.013% NH_3, 0.011% HD, 0.0007% C_2H_6, 0.0004% H_2O.
- T = 95 K at the cloudtops. Compare to 83 K expected from heating by sunlight.

Saturn: structure and composition

- Thus Saturn emits 2.5 times as much power as it receives in sunlight, similar to Jupiter.
  - Related to major abundance difference from Jupiter? There's much less helium in Saturn's upper atmosphere, leading to suggestions of formation and precipitation of liquid helium droplets (**helium rain**) that gradually raises the density of the interior (thus reducing potential energy, increasing heat).
- Like Jupiter, Saturn has a strong magnetic field, indicating the presence of liquid metallic hydrogen and dynamo action in the surroundings of the rocky core.
- Despite the muted contrast in many pictures, Saturn's cloud and belt/zone system is much like Jupiter's.

I can't believe it's not Jupiter!





Images of clouds on Saturn, from [*Cassini*] *(JPL/NASA)*

And it has rings.

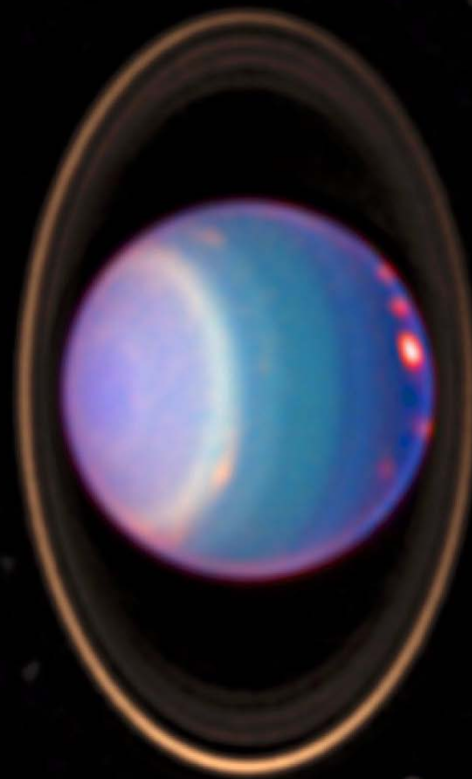
Ho hum, all the giant planets turn out to have rings.

- Distinctive feature of Saturn's rings: they're much icier than the others, and the ring particles have very high albedo (so they look much brighter). More on rings later.

The rings, seen by Cassini (JPL/NASA).

Uranus's vital statistics

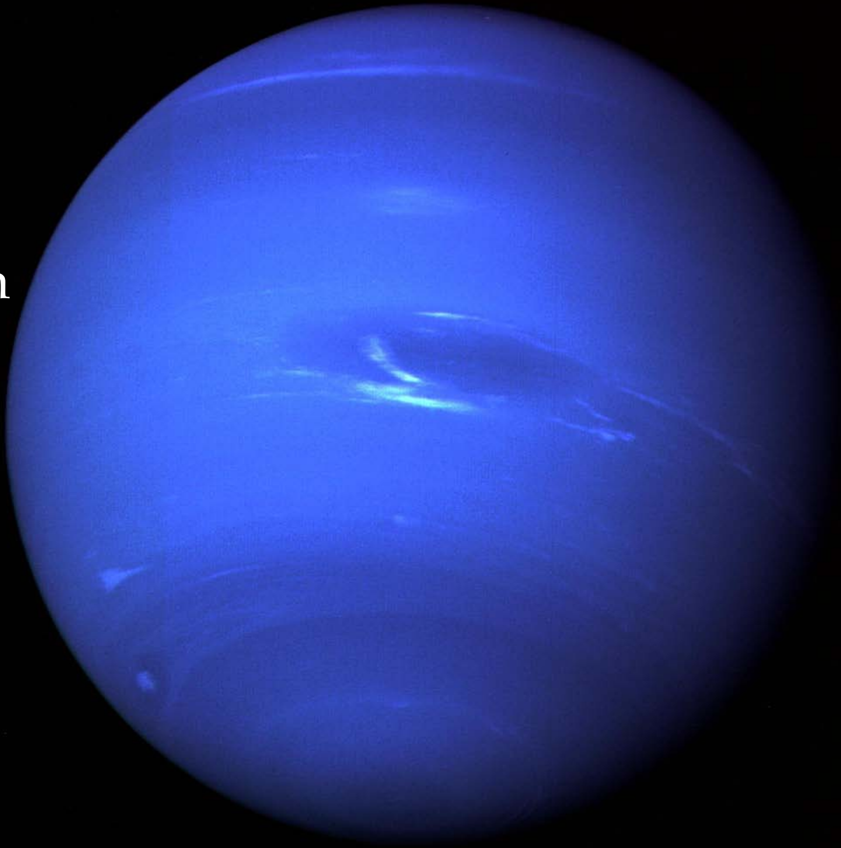
Mass	8.6832×10^{28} gm ($14.5 M_{\oplus}$)
Equatorial radius	2.5559×10^{9} cm ($4.01 R_{\oplus}$)
Average density	1.270 gm cm^{-3}
Moment of inertia	$0.225 MR^2$
Bond albedo	0.300
Orbital semimajor axis	2.87246×10^{14} cm (19.20 AU)
Orbital eccentricity	0.0457
Obliquity	97.77°
Sidereal revolution period	84.011 years
Sidereal rotation period	-17.24 hours (retrograde)
Moons	27 and counting
Rings	10 narrow ones



Uranus, from the Hubble Space Telescope (STScI/NASA)

Neptune's vital statistics

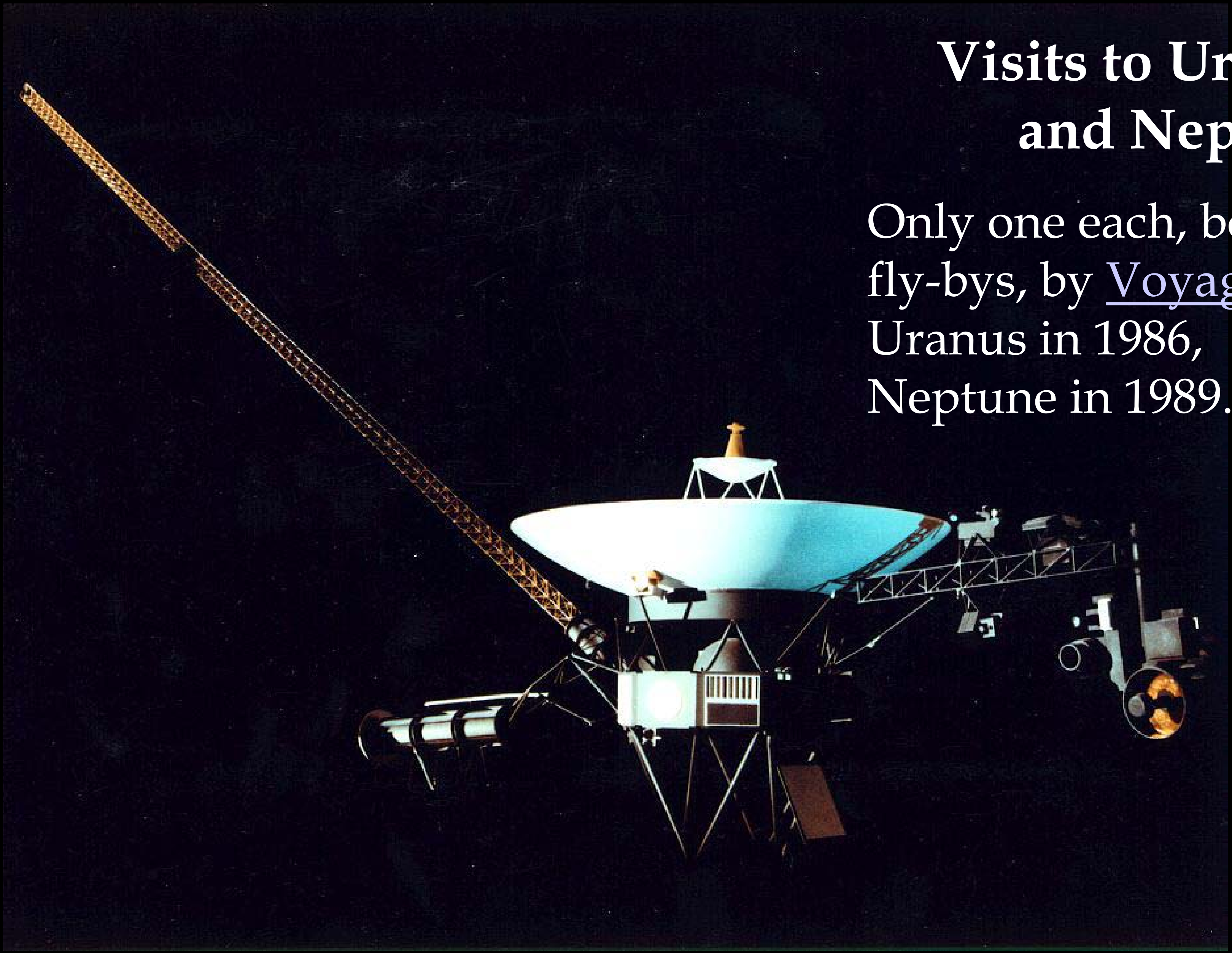
Mass	1.0243×10^{29} gm ($17.1M_\oplus$)
Equatorial radius	2.4764×10^{9} cm ($3.88R_\oplus$)
Average density	1.638 gm cm^{-3}
Moment of inertia	$0.23MR^2$
Bond albedo	0.290
Orbital semimajor axis	4.49506×10^{14} cm (30.05 AU)
Orbital eccentricity	0.0113
Obliquity	28.32°
Sidereal revolution period	164.79 years
Sidereal rotation period	16.11
Moons	13 and counting
Rings	6 narrow ones



Neptune, from Voyager 2 (JPL/NASA)

Visits to Uranus and Neptune

Only one each, both fly-bys, by Voyager 2: Uranus in 1986, Neptune in 1989.



Uranus and Neptune: structure and composition

- Nearly the same size (see page 1): Uranus is slightly larger, Neptune slightly more massive, so Neptune is significantly denser.
- Both have substantial cores, and a much larger fraction of their mass in the cores than Jupiter and Saturn.

Mass ($M_\oplus$)	Jupiter	Saturn	Uranus	Neptune
Total	318	95	15	17
Core	< 11	12	12	16
Atmosphere	>307	83	3	1

- They are rich in elements heavier than H and He, compared to Jupiter and Saturn.

Uranus and Neptune: structure and composition (continued)

- Their cores are not rocky in the usual (silicate and iron) sense: there is a lot of carbon, nitrogen and oxygen, and a lot of hydrogen, mixed in too, in solid and liquid phases.
  - Or, rather, lots of CH_4, NH_3, and H_2O -- hence the term **ice giant**, to emphasize this difference from the gas giants.
- Both have strong magnetic fields that are oriented at large angles from the rotation axis (59 and 47 degrees), and off center. The origin of these fields is still a major mystery.
- And they both have rings, and lots of satellites.

Distinctive features of Uranus

- Obliquity 98°: thus its rotation axis is almost parallel to the ecliptic plane, instead of perpendicular.
  - Component perpendicular to the ecliptic points the opposite direction of revolution: retrograde rotation.
  - The orbital plane of Uranus's moons is similarly tilted: thus one can't explain the odd tilt of the planet by invoking one big impact.
- Very low contrast among cloud bands leads to a nearly featureless appearance. It took until the Voyager 2 visits for us to be confident we know its rotation period.
- Cloud-top temperature 59.1 K, compared to 60 K expected from solar heating: no substantial internal source of heat as in Jupiter and Saturn.

Distinctive features of Uranus (continued)

Voyager 2 images of Uranus in true color and contrast (left), and with false color to enhance contrast (right) (JPL/NASA).

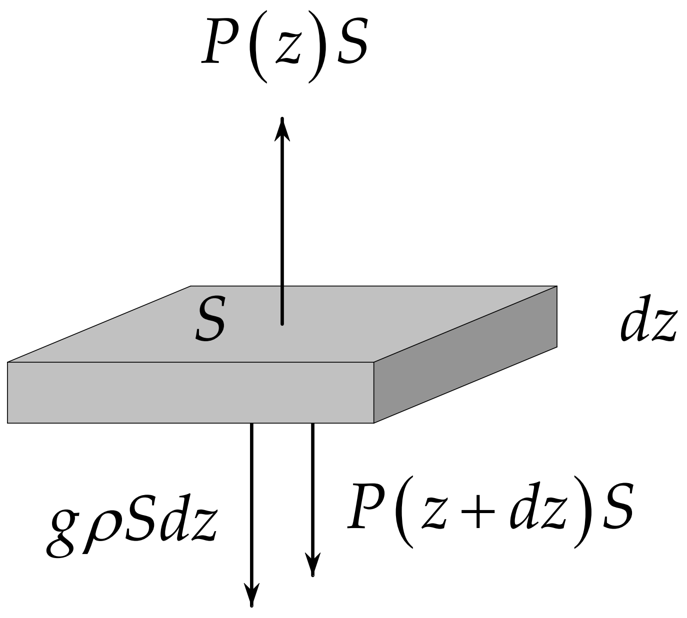
Distinctive features of Neptune

- Neptune has about the same cloud-top temperature as Uranus, 59.3 K. But it's a lot further from the Sun; it's only supposed to be 48 K.
  - Another planet with an internal heat source, like Jupiter and Saturn. Neptune emits about 3.5 times as much power as it receives from the Sun.
- The upper cloud deck rotates more slowly than the interior, unlike Jupiter, Saturn and Uranus.
- The winds are very high (~3400 km/hr), and the storms very violent, e.g. the Great Dark Spot.
  - Related to the internal heat source, as in the case of Jupiter.

Hydrostatic equilibrium

If a parcel of air does not move vertically, the forces from gravity and pressure are balanced, a condition called **hydrostatic equilibrium**.

- Consider an infinitesimally thin slab with thickness *dz*, area *S*, and constant density ρ.
- Forces are exerted on it by gravity (its own weight) and by pressure of the air above and below.
  - Pressure = force per unit area. Units: dyne cm^{-2} (1 Pascal/10).



g = gravitational acceleration

Hydrostatic equilibrium (continued)

- In one dimension (i.e. as drawn):

$$P(z)S = g\rho S dz + P(z+dz)S$$

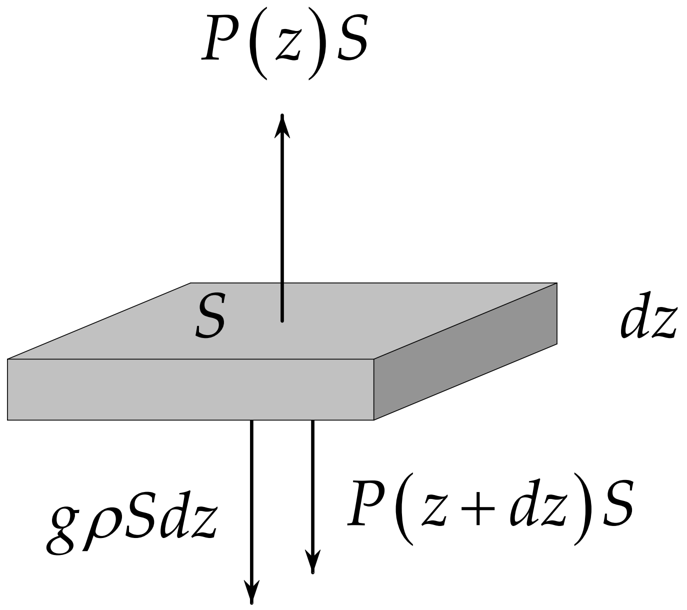
$$\frac{P(z+dz)-P(z)}{dz} = \boxed{\frac{dP}{dz} = -\rho g}$$

Equation of hydrostatic equilibrium

- In spherical symmetry,

$$\frac{dP}{dr} = -\rho g \quad ,$$

but mostly we will deal with atmospheres one thin, plane-parallel layer at a time, in Cartesian coordinates.



Exponential atmospheres and the scale height

Suppose that the atmosphere is

- plane-parallel: that is, thin compared to the radius of the planet's surface;
- made of an **ideal gas**; that is

$$P = nkT = \frac{\rho kT}{\mu} \quad \begin{cases} n = \text{ molecules per unit volume} \\ \mu = \text{mean mass of molecules in the atmosphere} \\ k = 1.381\times 10^{-16} \text{ erg K}^{-1} \text{ (Boltzmann constant)} \end{cases}$$

- has uniform temperature.

Then

$$\frac{dP}{dz} = -\frac{\mu P}{kT} g$$

Exponential atmospheres and the scale height (continued)

Rearrange and integrate from z = 0 to some arbitrary height:

$$\int_{P_0}^{P(z)} \frac{dP'}{P'} = -\frac{\mu g}{kT} \int_0^z dz'$$

$$\ln P(z) - \ln P_0 = -\frac{\mu g}{kT} z$$

$$P(z) = e^{\left(-\frac{\mu g}{kT} z + \ln P_0\right)} = P_0 e^{-z/(kT/\mu g)}$$

$$= P_0 e^{-z/H}$$ **Exponential atmosphere**

where $H = kT/\mu g$, the **isothermal scale height**, is the vertical distance over which pressure changes by $1/e$.

Scale heights for planetary atmospheres

Oddly, the scale heights of the atmospheres for terrestrial and giant planets are not hugely different in size, even though densities, pressures, temperatures and masses differ by many orders of magnitude.

- Typical values are in the tens of km, which indeed is small enough that the plane-parallel approximation is a good one over a few scale heights.

Planet	Isothermal scale height (km)
Venus	15.9
Earth	8.5
Mars	11.1
Jupiter	27
Saturn	59.5
Uranus	27.7
Neptune	20
Pluto	60