Lecture 6 - A tour of the planets

What's Important:
- planetary motion
- planets beyond the solar system

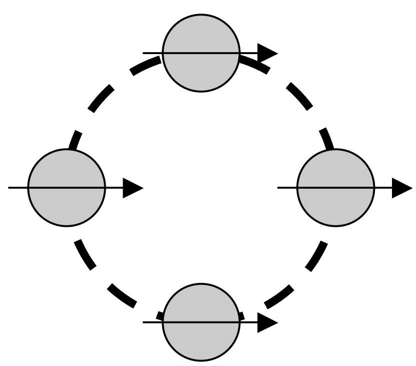
Text: Carroll and Ostlie, Chap. 19, 20, Sec. 21.5

Planetary motion

With the exception of Pluto, the orbital planes of all planets lie within a few degrees of the orbital plane of the Earth (referred to as the ecliptic plane).

Planet	orbital inclination to ecliptic (°)	inclination of equator to orbital plane (°)	mass (kg)
Mercury	7.00	2 (?)	3.3×10^{23}
Venus	3.39	177.3	4.87×10^{24}
Earth	≡0.00	23.45	5.97×10^{24}
Mars	1.85	25.19	6.42×10^{23}
Jupiter	1.30	3.12	1.90×10^{27}
Saturn	2.49	26.73	5.69×10^{26}
Uranus	0.77	97.86	8.68×10^{25}
Neptune	1.77	29.56	1.02×10^{26}
Pluto	17.14	118	1.31×10^{22}

The fact that the axis of rotation of Uranus and Pluto lie in the plane of their orbits makes for unusual seasons: the (distant) Sun is stationary overhead at the poles in local mid-summer.



Further, the orbital motion is **prograde**, meaning that the direction of travel is counterclockwise as seen from the direction of the Earth's north pole: *i.e.*, the orbital angular momentum vectors all point north. Further, the rotational motion of most planets and their satellites is also prograde, with the following exceptions:

Venus: direction is reversed, **L** points towards south pole
Uranus and Pluto: axis of rotation lies on its side, not far from the ecliptic plane
planetary satellites are discussed below - just a few are retrograde

The overwhelmingly prograde motion suggests condensation of the Sun and planets from a single spinning disk of material.

The densities of the planets provide clues as to their origin and composition. We'll segregate the inner (terrestrial) planets from the outer (Jovian) planets with enormous gaseous atmospheres.

Planet	density (kg/m^3)	surface gravity compared to Earth	escape speed (km/s)
Mercury	5430	0.39	4.3
Venus	5240	0.91	10.4
Earth	5515	≡1.00	11.2
Mars	3940	0.38	5.0
Jupiter	1330	2.5	59.5
Saturn	700	1.1	35.5
Uranus	1300	0.90	21.3
Neptune	1640	1.1	23.5
Pluto	2030	0.07	1.3

Amusingly, the surface gravity of the planets is surprisingly uniform, within a factor of two or so of Earth - only tiny Pluto has a "g" less than 10% that of Earth. The escape velocities span a wider range, especially for the Jovian planets, as seen in the table above. We return to the role of the escape velocity in retaining a planetary atmosphere in Lec. 8.

Of the terrestrial planets, only Mars has a density significantly lower than the other three. In spite of the abundance of iron oxide on its surface, the interior of Mars appears to be iron deficient. Surface rocks on Earth, silicates, have a densities near 3000 kg/m^3 (like the Moon), so they "float" on the more dense interior rocks. Density of iron *etc.*, is closer to 6000 kg/m^3.

Mercury, Venus, Earth:
  density ~5500 kg/m^3, lots of iron (^{56}Fe) and nickel (^{58}Ni) in the core
Mars, Moon:
  density ~3300 to 3500 kg/m^3, more silicates (SiO_2-based) in mantle
Jupiter, Saturn, Uranus, Neptune
  density ~700 - 1600 kg/m^3, gas giants with a rocky core
  composition of atmosphere is described in Lec. 8
Pluto

Moons

Although Mercury and Venus have no satellites, most planets have several moons and the four Jovian planets also have rings. Four of Jupiter's moons were first observed by Galileo in 1610; their measured periods later allowed an independent determination of

Jupiter's mass (see Lec. 4). We now know that the giant planets each have a sizeable number of moons:

Jupiter - 16 Saturn - 20 Uranus - 15 Neptune - 8 (as of 2002)

The masses of these satellites can be quite substantial, easily exceeding Pluto and even approaching Mercury:

satellite	planet	mass (kg)	radius (m)	avg. density (kg/m^3)
Ganymede	Jupiter	1.48×10^{23}	2.63×10^{6}	1940
Titan	Saturn	1.4×10^{23}	2.58×10^{6}	1950
Callisto	Jupiter	1.08×10^{23}	2.40×10^{6}	1870
Io	Jupiter	8.94×10^{22}	1.82×10^{6}	3540
Moon	Earth	7.35×10^{22}	1.74×10^{6}	3330
Europa	Jupiter	4.92×10^{22}	1.57×10^{6}	3035
Triton	Neptune	2.15×10^{22}	1.35×10^{6}	2090
compare				
	Mercury	3.30×10^{23}	2.44×10^{6}	5430

Almost all satellites orbit in the same direction as the planet rotates (prograde), the exception being the (large) satellite Triton of Neptune, and several very small satellites of Jupiter and Saturn.

Planetary systems beyond the solar system

As of January, 2008, the **exosolar** planet count stands at 271 with about 10% of Sun-like stars (that have been examined). We'll summarize the data in a moment, but first let's describe some of the observational methods (Marcy and Butler, *Ann. Rev. Astron. Astrophys.* **36**: 57-97 (1998).

Direct observation

- possible with Earth-bound detectors using interferometric techniques
- NASA plans to put a planet observatory in orbit in the time frame of a decade which will be able to resolve planets orbiting nearby stars (under certain conditions).

Astrometric detection

- the conventional approach of looking for perturbations in the position of a star arising from an orbiting companion.
- with current resolution, the companion must be close to the star (a few AU), and have a mass like Jupiter; see caveats below)

Photometric technique

- observe a change in the luminosity of a star from the transit of a planet, where the orbit of the planet intersects the line-of-sight from the Earth
- good technique, in that the radius of the planet can be determined from black-disk absorption, and the mass from other observations (speed from Doppler shift).

Hence, the density of the planet can be calculated
- 35 examples out of 271 planets
- there won't be too many examples of this, as the orbital plane has to fall into a narrow range: 2.7° of edge-on.

Doppler technique
- Doppler-shift observation of the change in radial speed of a star due to presence of nearby planets
- 257 examples out of 271 planets
- in our solar system, Jupiter and Saturn give contribute 12.5 and 2.7 m/s (yes, m/s!) to the speed of the Sun
- caveat: must distinguish orbital perturbations from pulsation of the stellar photosphere; for example, convection zones on the Sun rise at rates of 0.7 km/s and Cepheids may have surface (pulsation) velocities of a few tens of km/s.

Observations:
The measurements are most sensitive to large (Jupiter-like) planets executing orbits with small radii. Some masses range up to 50-60 M_{Jup}; of eight (low mass) examples quoted in 1998:

Example	Period (days)	minimum mass (in terms of M_{Jup})
1	1092	2.38
2	799	1.67
3	116.5	6.73
4	39.6	1.1
5	14.65	0.85
6	4.62	0.61
7	4.231	0.44
8	3.3125	3.66

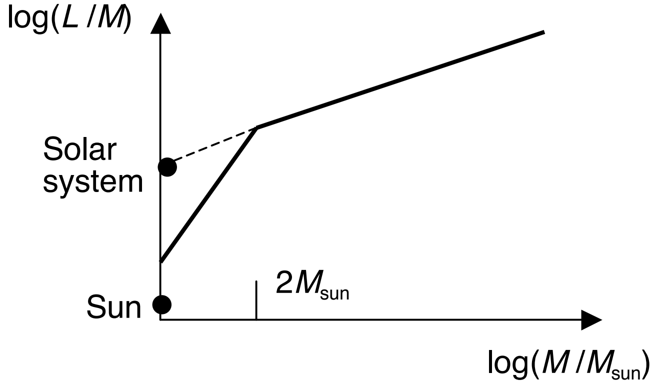
For example, HD 2094586 (observed photometrically) has a radius of 1.25-1.55 Jupiter's, a mass of 0.7 Jupiter's (density = 300-500 kg/m^3) but an orbital radius of 0.047 AU, astonishingly small. The mass distribution is (2008 data from http://exoplanet.eu)

0 - 2 Jupiter masses: 63%
2 - 4 Jupiter masses: 17%
4 - 6 Jupiter masses: 7%

Issues:
- The conventional model of our solar system argues that the terrestrial planets must lose their gaseous atmospheres - Jupiter-like planets can only occur at distance of about 5 AU. Thus, these close-in Jupiter's must have formed further out, and now be spiralling into their star. Why are there so many examples of this?
- Some of these objects have *really* short orbital periods, just a few days!

Expectations:
An interesting observation that may indicate the type of stars that are host to planetary systems comes from the angular momentum per unit mass. Extracting this quantity for a star must recognize that not only is there a mass gradient in the star (as a function of

radius), but also that there is a gradient in angular velocity. The (observed) angular momentum per unit mass L/M increases smoothly with stellar mass, undergoing an abrupt change at 2 solar masses:



Below the break point at 2 solar masses, L/M from higher mass stars extrapolates to the observed L/M of the solar system. However, the Sun contains just 1% of the angular momentum of the solar system, and its L/M lies well below both the extrapolated value and the observed values for similar mass stars.

If the total L/M of condensing regions follows the behaviour extrapolated from large mass stars, then the break at 2 M_{sun} may indicate that lower mass stars tend to be accompanied by planetary systems that carry the remainder of the system's angular momentum.