Class 16
Extra-solar planets

- The radial-velocity technique for finding extrasolar planets
- Other techniques for finding extrasolar planets

Class 15
Formation of the Solar System

- What does a successful model needs to explain?
  - The three key properties of the planetary system
  - The basic properties of the Sun
- The Solar Nebula Model
- Age of the Solar System
I : What do we need to explain?

- Three basic properties of the planetary system...
  - Size/composition of the terrestrial planets versus the Jovian planets
  - Directions and orientations of planetary orbits
  - Sizes of terrestrial planet orbits versus Jovian planetary orbits

- Even more fundamental fact that needs explaining... 99% of the angular momentum of the solar system is associated with the planetary orbits (mostly Jupiter, in fact) rather than the rotating Sun.

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- Basic properties of the Sun...
  - Contains 99.9% of the mass in the Solar System
  - Slowly rotates (in same direction as planetary orbits); but carries only tiny fraction of the solar system’s angular momentum
  - Composed mostly of hydrogen and helium
Composition of interstellar gas in our part of the Galaxy

Big Bang

Stars

Composition of the solar system (Sun, planets, and small bodies) by mass:

- Hydrogen: 71%
- Helium: 27%
- Other elements: 2%

Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Brainstorm possible scientific ideas for how solar system formed...
II : The Solar Nebula model

Basics of the idea...

- Start with an **interstellar gas cloud** that starts collapsing under the action of gravity
- Due to conservation of angular momentum, cloud flattens into a rotating disk as it collapses
- Large quantities of gas flow inwards through this **accretion disk**, and form the Sun
- Planets form in the remaining disk... terrestrial planets form in the hot inner part of the disk whereas Jovian planets form in the cooler outer parts of the disk
- A mini-version of this scenario plays out around each Jovian planet, producing the satellite system
Likely temperature distribution in the Solar Nebula

Mount Fuji (Japan)
- Dependence of temperature on distance from proto-Sun is important for planet formation...

- Inner solar system (inside the “snow line”)
  - Too warm for ices to freeze
  - Only the “rock-forming” materials condense into solid particles
  - Successive collisions: dust $\Rightarrow$ gravel $\Rightarrow$ boulders $\Rightarrow$ planetesimals $\Rightarrow$ planets
Jovian planet formation (beyond “snow line”)

- Core accretion model:
  - Due to freezing of ices, there’s a lot more solid material available than in inner solar system
  - Collisions built up a rock+ice object several times larger than Earth (took several million years)
  - Once core is large enough, gravitationally attracts the surrounding gas to form thick atmospheres
  - If correct, cannot form Neptune and Uranus in current locations... would need to have formed them closer in and be thrown out by Jupiter

- Disk instability model:
  - Hypothesizes that the solar nebula was gravitationally unstable... clumps could spontaneously form
  - Once large clump formed, it gravitationally pulls in more gas... does not need an initial rock/ice core
  - Uranus & Neptune could form in current location
Kuiper belt is a dusty/icy debris ring, gravitationally thrown to the outer solar system by the massive planets (mainly Jupiter)
III : How long ago did the Solar System form?

- Current estimate: 4.56 billion years ago
- Determine this by radioactive dating of meteorites...
- Basics of radio-active dating:
  - If the balance of protons-neutrons is wrong, an atomic nucleus is unstable
  - In a given time (the half-life), half of these unstable nuclei will split (decay) and form more stable nuclei
    - $^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$ (half-life 47.0 billion years)
    - $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ (half-life 4.5 billion years)
    - $^{14}\text{C} \rightarrow ^{14}\text{N}$ (half-life 5730 years)
  - Can estimate the age of a rock by how much of a particular unstable isotope is still present
  - Not a simple exercise... [discussion]

I : Radial velocity technique

- Star does not remain absolutely stationary as the planet orbits
  - Star and planet orbit about their common center of mass
  - For each orbit of the planet, the star makes one orbit about the center of mass
  - We can use spectroscopy to detect the motion of the star as it orbits its center of mass... this uses the Doppler effect

(a) A star and its planet
Planets are easier to detect if they cause star to move with large velocities, and have short periods compared with the length of the observing campaign (~15 years)...

So, you tend to detect massive planets that are close to their star.
As of now... **313** extrasolar planets have been detected around **267** stars (from PlanetQuest)

Most extrasolar planets found to date have been found with radial velocity technique...

Some surprising properties...
- Finding many **“hot Jupiters”**...
  - Massive planets; must be gas giants
  - Orbiting close to star with short period
  - E.g., first planet found (around 51-Pegasi in 1995) has $M>0.46M_{\text{Jup}}$ and orbits at 0.052AU (4.23 day period)
  - Could not have possibly formed there... must have formed further out and “migrated” in!
- Some planets have large eccentricities
  - Much larger eccentricities than found in our solar system (see diagram on following slide)

http://www.astro.lu.se/~danielm/
II : The Transit technique

- Consider special case when planet will pass directly in front of its star...
- Can then watch planet block (eclipse) some fraction of the star light.
  - Measure size of planet by depth of eclipse of star
  - Measure composition of planet’s atmosphere using absorption lines during eclipse of star
  - Measure temperature of planet by looking at drop in infrared flux as star eclipses planet
- E.g. HD 209458...
  - $M=0.69M_{\text{Jup}}$, but $R=1.32R_{\text{Jup}}$, very low density
  - Orbits at 0.047AU... surface temperature 1130K!
  - Spectrum shows H, C, O and Na (sodium) being evaporated off surface of planet by starlight!
III : Other techniques...

- Direct imaging
  - Currently have a very small number of cases
  - Rationale behind TPF mission
- Astrometric technique
  - Search for the motion of the star induced by planetary orbits
  - Rationale behind SIM mission
- Gravitational microlensing
  - Use gravitational effects of planet on light form background star...
Terrestrial Planet Finder Interferometer

Apparent motion of Sun due to planets (as seen from 10pc)