Lecture 9: Formation of the Solar System; Extrasolar planets

Astronomy 111
Origin of the Solar System
Birth of planetary systems

- Where did the solar system come from?
- What caused the orderly patterns of motion in our Solar System?
Origin of the Solar System: key concepts

How the Solar System formed:
A cloud of gas & dust **contracted** to form a disk-shaped solar nebula.
The solar nebula **condensed** to form small planetesimals.
The planetesimals **collided** to form larger planets.

When the Solar System formed:
Radioactive age-dating indicates the Solar System is 4.56 billion years old.
Clues to how Solar System formed: how things move (dynamics)

All planets **revolve** in the same direction. Most planets **rotate** in the same direction. Planetary orbits are in nearly the same plane.
What things are made of
(more chemistry!)

**Sun:** Mostly hydrogen (H) and helium (He).

**Jovian planets:** Rich in H and He, low density.

**Terrestrial planets:** Mostly rock and metal, high density.
Stars produce elements heavier than Hydrogen & Helium, these “metals” eventually find their way to clouds of gas from which new stars and planets are formed.
A cloud of gas and dust contracted to form a disk-shaped nebula

The Solar System started as a large, low-density cloud of dusty gas. Such gas clouds can be seen in our Milky Way and other galaxies today.
Nebular theory

The solar system formed from the gravitational collapse of a large cloud of gas

Postulated by Kant & Laplace
Conversion of Gravitational Potential to Kinetic Energy ➔ **Heating**

Decreasing Size ➔ conservation of angular momentum ➔ **Spins Faster**

Collisions between Particles ➔ **Flattening**
The gas cloud initially rotated slowly. As the cloud contracted under its own gravity, it rotated faster. (Conservation of angular momentum!)

Quickly rotating objects become flattened.
Conserving Energy & Momentum

1. As a slowly rotating interstellar cloud collapses because of gravity, it rotates faster.

2. Rotation slows collapse perpendicular to but not parallel to the axis, so the cloud flattens.

3. Eventually the cloud collapses from the inside out, and an accretion disk and protostar form.

Protostar

Accretion disk
The flat, rapidly rotating cloud of gas and dust was the **solar nebula**.

The central dense clump was the **protosun**.

Similar flat, rotating clouds are seen around protostars in the Orion Nebula.

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**Protoplanetary Disks Orion Nebula**

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O’Dell (Rice University), NASA
The contraction of the solar nebula made it spin faster and **heat up**. (Compressed gas gets hotter.)

Temperature of solar nebula:

- > 2000 Kelvin near Sun; < 50 Kelvin far from Sun
The solar nebula condensed to form small planetesimals

Approximate condensation temperatures:

1400 Kelvin: metal (iron, nickel)
1300 Kelvin: rock (silicates)
200 Kelvin: ice (water, ammonia, methane)

Inner solar system: over 200 Kelvin, only metal and rock condense.

Outer solar system: under 200 Kelvin, ice condenses as well.
Particles collide and stick to form planetesimals.

1. Gas motions in a protoplanetary disk blow small particles around more easily than large particles.
2. Small particles are blown into larger particles...
3. ...forming larger and larger aggregations.

The gravity of a growing planetesimal draws in additional material.
The solar nebula condensed to form small planetesimals

As the solar nebula cooled, material condensed to form **planetesimals** a few km across.

**Inner Solar System:**
- Metal and rock = solid planetesimals
- Water, ammonia, methane = gas.

**Outer Solar System:**
- Metal and rock = solid planetesimals
- Water, ammonia, methane = solid, too.
The planetesimals collided to form larger planets.

Planetesimals attracted each other gravitationally.

Planetesimals collided with each other to form Moon-sized protoplanets.
Schematic of a typical TTauri Star - SU Aurigae?
Protoplanets collided with each other (and with planetesimals) to form **planets**.

**Inner Solar System:**
Smaller planets, made of rock and metal—**rocky seeds**

**Outer Solar System:**
Larger planets, made of rock, metal and ice—**icy seeds**

In addition, outer planets are massive enough to attract and retain H and He.
Moons of jovian planets form in miniature disks:

- As planetesimals accreted to form terrestrial planets in the inner solar system...
- …farther out, huge icy planetesimals gathered hydrogen and helium gas to form jovian planets...
- …while the disk forms large moons by condensation and accretion, and captures small moons.
Collisions between protoplanets were not gentle!

Venus was knocked “upside-down”, Uranus and Pluto “sideways”.

Not every planetesimal was incorporated into a planet.

Comets = leftover icy planetesimals.
Asteroids = leftover rocky and metallic planetesimals.
Inner vs. outer Solar System

**Inner solar system:**
where rocks & metals could condense into solids

**Frost Line:**
point where Hydrogen compounds can form ices (solids)

- **Within the frost line,** rocks and metals condense, hydrogen compounds stay gaseous.
- **Beyond the frost line,** hydrogen compounds, rocks, and metals condense.

98% of the solar nebula is hydrogen and helium that remains gaseous everywhere.
Inner vs. outer Solar System

Inner solar system: where rocks & metals could condense into solids

Frost Line: point where Hydrogen compounds can form ices (solids)
Inner Part of Accretion Disk

Gravitational energy of infalling material is converted into heat.

Material that lands in the inner disk has fallen farther and thus has more energy to convert to heat.

Protostar is also contracting and heating up the inner disk.
How does this “nebular theory” explain the current state of the Solar System?

**Solar System is disk-shaped:**
- It formed from a flat solar nebula.

**Planets revolve in the same direction:**
- They formed from rotating nebula.

**Terrestrial planets are rock and metal:**
- They formed in hot inner region.

**Jovian planets include ice, H, He:**
- They formed in cool outer region.
Testing the Nebular Model

We see this disk edge-on around the star AU Microscopii, confirming its flattened shape.
Our Solar System
Summary of Solar System formation:
How old is the Earth and the rest of the Solar System?

One of the basic questions in almost all cultures and religious systems.
Archbishop Ussher (AD 1650): 6000 years.
Hinduism: eternal cycle of creation and destruction.
18th century:
Realization among European geologists that the Earth is much older than had been assumed.

Earth has a huge number and variety of fossils (the White Cliffs of Dover consist entirely of tiny shells).
Trilobite
Also, the Earth contains thick layers of sedimentary rock and deeply eroded canyons.

Exact measurement of the Earth’s age proved to be difficult.
Radioactive age-dating

Radioactive decay: Unstable atomic nuclei emit elementary particles, forming a lighter, stable nucleus.

Example: Potassium-40 (19 protons + 21 neutrons = 40)
89% of the time, Potassium-40 decays to Calcium-40.
11% of the time, Potassium-40 decays to Argon-40.
Radioactive age-dating

**Half-life** of a radioactive material: time it takes for half the nuclei to decay.

**Example:**
Potassium-40 has a half-life of 1.3 billion years.

**Now:**
200 atoms of Potassium-40.

**In 1.3 billion years:**
100 atoms of Potassium-40
89 atoms of Calcium-40
11 atoms of Argon-40.
Radioactive age-dating

In principle, you can find the age of a rock by measuring the ratio of potassium-40 to argon-40.

100 atoms of potassium-40, 11 atoms of argon-40: age equals 1.3 billion years.

Higher potassium/argon ration: younger.
Lower potassium/argon ration: older.

In practice, it is more subtle: Argon is an inert gas; if the rock melts, the argon escapes.

Thus, the “radioactive clock” is reset each time the rock melts. But other elements can be used as well.
Radioactive age-dating

Age of oldest Earth rocks = 4 billion years
Age of oldest Moon rocks = 4.5 billion years
Age of oldest meteorites (meteoroids that survive the plunge to Earth) = 4.56 billion years

Radioactive age-dating indicates that the Solar System is 4.56 billion years old.
Our Solar System is not unique

- Physical processes that formed our solar system should be commonplace
- We see young stars with disks
-- But what about other planets outside our solar system?
Basic problem:

A good scientific theory has to be tested, but we only have one Solar System and we cannot go back in time.

We needed to find other extrasolar planets!

So we did…
Extrasolar planets

As of 9/24/10, astronomers know of 490 extrasolar planets!

http://exoplanets.eu
Detecting extrasolar planets

Direct Methods:
- Pictures or spectra of the planets

Indirect Methods:
- Precision measurements of stellar properties (position, brightness, spectra) that reveal the effects of orbiting planets
  - Doppler shift
  - Microlensing method
  - Planetary transits
Difficult since the star is much brighter than the planet, but sometimes possible at infrared wavelengths.

Brown dwarf star with a Jovian planet
Most detected planets are 1 to 10 times more massive than Jupiter; many are “Hot Jupiters”.

Astronomers have directly imaged only two exoplanets to date. Large future telescopes will be able to image more exoplanets.
**Doppler technique**

Measures motion of star along our line-of-sight seen as shifts in the star's spectrum—due to gravitational force of planet on the star (remember the extra credit problem?).

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**Figure 9**

- A periodic Doppler shift in the spectrum of the star 51 Pegasi indicates the presence of an unseen planet.
- The velocity change gives us the star's speed, which tells us the planet's mass.
- The pattern repeats every 4 days, indicating the planet's orbital period.
- Stellar motion caused by tug of planet results in redshifted and blueshifted starlight towards and away from Earth.
We can see this effect in our own Solar System: Jupiter causes a Doppler shift of the Sun!
Extrasolar planets are usually found from the wobble they cause in the motion of the star they orbit.

Tau Boötes

55 Cnc:
- $3.835 \, M_J$ at 5.8 AU

HD 37124:
- $0.61 \, M_J$ at 0.53 AU,
- $0.68 \, M_J$ at 3.2 AU,
- and $0.6 \, M_J$ at 1.6 AU

14 Her:
- $2.1 \, M_J$ at 6.9 AU

* Multiple planet system with other planets not shown due to size constraints.
Planetary transits

A transit occurs when a planet passes in front of its star, slightly dimming the light from the star.
Planetary transits

Artist’s rendering of HD209458

© 1999 Lynette Cook
Planetary transits

Kepler (a recent NASA mission) was launched to detect planetary transits.

Just getting started but Kepler has found 700 planet candidate(s) so far!
Planets can be discovered via gravitational distortion of the light from background stars.

- Uses mass of planets to “bend” the light from a very distant star towards us.
- We see that light and can analyze the amount to get the mass and separation of the planet.
Gravitational microlensing
Many extrasolar systems are unlike the Solar System

Orbits are highly eccentric & close to their stars

(this is a bias due to using the Doppler technique)
Masses of extrasolar planets

Most planets discovered so far are more massive than Jupiter.

Improved technology is enabling more discoveries of planets less massive than Jupiter.

No planets with masses as small as Earth’s have been discovered.
Questions astronomers are still resolving

• Are there extrasolar planets similar to the Earth?
  – Why are most extrasolar planets “hot Jupiters”?

• Are there extrasolar planetary systems similar to our Solar System?

• Is there life on planets other than Earth?
Few closing questions:

1) Can planets still form in our Solar System?
2) Is the Sun older or younger than the planets?
3) Can you think of another consequence of the discussed model of the Solar System origin?
4) Organic life is based on carbon. Where did this carbon come from?
5) Should other planetary systems resemble ours?