Formation of the Solar System
Early Hypotheses

- **catastrophic hypotheses**, e.g., passing star hypothesis:
  
  Star passing the sun closely tore material out of the sun, from which planets could form (no longer considered)

- **evolutionary hypotheses**, e.g., Laplace’s nebular hypothesis:
  
  Rings of material separate from the spinning cloud, carrying away angular momentum of the cloud → cloud contracts further (forming the Sun)

Catastrophic hypotheses predict few stars should have planets

Evolutionary hypotheses predict many/most stars should have planets
The Solar Nebula Hypothesis

Basis of modern theory of planet formation

Planets form at the same time from the same cloud as the star.

Planet formation sites observed today as dust disks around young/forming stars

Sun and our Solar System formed ~ 5 billion years ago
Dust Disks

Many young stars in the Orion Nebula show the dust disks out of which we believe planetary systems form.
Survey of the Solar System

Relative Sizes of the Planets

If we reduced all bodies in the Solar System so that the Earth had a diameter of 0.3 mm:

- **Sun:** ~ size of a small plum
- **Mercury, Venus, Earth, Mars:** ~ size of a grain of salt
- **Jupiter:** ~ size of an apple seed
- **Saturn:** ~ slightly smaller than Jupiter’s “apple seed”
- **Pluto:** ~ speck of pepper
All planets in almost circular (elliptical) orbits around the sun, in approx. the same plane (ecliptic).

- Sense of revolution: counter-clockwise
- Sense of rotation: counter-clockwise (with exception of Venus, Uranus, and Pluto)

Exceptions:
- Mercury (7°)
- Pluto (17.2°)

(Distances and times reproduced to scale)
Two Kinds of Planets

Planets of our solar system can be divided into two very different kinds:

Terrestrial (Earthlike) planets: Mercury, Venus, Earth, Mars

Jovian (Jupiter-like) “gas giant” planets: Jupiter, Saturn, Uranus, Neptune
Terrestrial Planets

Four inner planets of the solar system

Relatively small in size and mass (Earth is the largest and most massive)

Rocky surface

Surface of Venus can’t be seen directly from Earth because of its dense cloud cover
Craters on Planets’ Surfaces

Craters (like on our Moon’s surface) are common throughout the Solar System.

Craters not seen on Jovian planets because they don’t have a solid surface.
The Jovian Planets

- Much lower average density
- Mostly gas; no solid surface
- All have rings (not only Saturn!)
Space “Debris”

In addition to planets, small bodies orbit the sun: asteroids, comets, meteoroids

Asteroid Eros, imaged by the NEAR spacecraft
Comets

Icy nucleus “evaporates” (sublimates), blown into space by Solar wind pressure

Mostly objects in highly elliptical orbits, occasionally coming close to the sun
Meteoroids

Small (µm – mm sized) dust grains throughout the solar system

If they collide with Earth, they vaporise in the atmosphere

Visible as streaks of light: meteors (“shooting stars”)
Our Solar System

Table 19-1  Characteristic Properties of the Solar System

1. Disk shape of the solar system
   Orbits in nearly the same plane
   Common direction of rotation and revolution

2. Two planetary types
   Terrestrial—inner planets; high density
   Jovian—outer planets; low density

3. Planetary ring systems and large satellite systems for Jupiter,
   Saturn, Uranus, and Neptune

4. Space debris—asteroids, comets, and meteors
   Composition
   Orbits

5. Common ages of about 4.6 billion years for Earth, the moon,
   Mars, meteorites, and the sun
How to Make a Planet

Planets formed from the same protostellar material as the Sun, still found in the Sun’s atmosphere

Rocky planet material formed from clumping together of dust grains in the protostellar cloud

Mass of less than ~ 15 Earth masses:
  Planets can not grow by gravitational collapse
  Earthlike planets

Mass of more than ~ 15 Earth masses:
  Planets can grow by gravitationally attracting material from the protostellar cloud
  Jovian planets (gas giants)
Condensation of Solids

To compare densities of planets, compensate for compression due to the planet’s gravity:

Only condensed materials could stick together to form planets.

Temperature in the protostellar cloud decreased outward.

Further out from Sun → protostellar cloud cooler → metals with lower melting point condensed → change of chemical composition throughout Solar System.

### Table 19-2 - Observed and Uncompressed Densities

<table>
<thead>
<tr>
<th>Planet</th>
<th>Observed Density (g/cm³)</th>
<th>Uncompressed Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5.44</td>
<td>5.30</td>
</tr>
<tr>
<td>Venus</td>
<td>5.24</td>
<td>3.96</td>
</tr>
<tr>
<td>Earth</td>
<td>5.50</td>
<td>4.07</td>
</tr>
<tr>
<td>Mars</td>
<td>3.94</td>
<td>3.73</td>
</tr>
<tr>
<td>(Moon)</td>
<td>3.36</td>
<td>3.40</td>
</tr>
</tbody>
</table>

### Table 19-3 - The Condensation Sequence

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Condensate</th>
<th>Planet (Estimated Temperature of Formation; K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>Metal oxides</td>
<td>Mercury (1400)</td>
</tr>
<tr>
<td>1300</td>
<td>Metallic iron and nickel</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>Silicates</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>Feldspars</td>
<td></td>
</tr>
<tr>
<td>680</td>
<td>Trolite (FeS)</td>
<td>Venus (900)</td>
</tr>
<tr>
<td>175</td>
<td>H₂O ice</td>
<td>Earth (600)</td>
</tr>
<tr>
<td>150</td>
<td>Ammonia–water ice</td>
<td>Mars (450)</td>
</tr>
<tr>
<td>120</td>
<td>Methane–water ice</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Argon–neon ice</td>
<td>Jovian (175)</td>
</tr>
</tbody>
</table>

Mercury (1400)
Formation and Growth of Planetesimals

Planet formation starts with clumping together of grains of solid matter: **planetesimals**

Planetesimals (few cm to km in size) collide to form planets

Planetesimals grow through condensation and accretion

Gravitational instabilities may have helped in the growth of planetesimals into protoplanets
The Growth of Protoplanets

Simplest form of planet growth:

Unchanged composition of accreted matter over time

As rocks melted, heavier elements sank to the center ➔ *differentiation*

This also produces a secondary atmosphere ➔ *outgassing*

Refinement of this scenario:
Gradual change of grain composition due to cooling of nebula and storing of heat from potential energy
The Jovian Problem

Two problems for our current theory of planet formation:

1. Observations of extrasolar planets indicate that Jovian planets are common

2. Protoplanetary disks tend to evaporate quickly (typically within ~ 100,000 years) from the radiation of nearby massive stars

   ➔ Too short a timescale for Jovian planets to grow

Solution: Computer simulations show that Jovian planets can grow by direct gas accretion without forming rocky planetesimals
Explaining the Characteristics of the Solar System

The Solar Nebula Hypothesis explains:

1) **Disk shape and common sense of revolution:**
   Inherited from the disk shape and rotation of the Solar Nebula

2) **Division of Terrestrial / Jovian Planets:**
   Result of decreasing temperature throughout the Solar Nebula ➔ Further out, lighter elements condensed out to form heavier, gaseous planets

3) **Icy Comets:**
   Originating in the Oort Cloud, very far away from the sun, in the coldest parts of the Solar Nebula
Clearing the Nebula

Remains of the protostellar nebula were cleared away by:

- Radiation pressure from the Sun
- Solar wind
- Sweep-up of space debris by planets
- Ejection by close encounters with planets

Surfaces of the Moon and Mercury show evidence for heavy bombardment by asteroids.
Evidence for Ongoing Star Formation: Dust Disks Around Forming Stars

Dust disks around some T Tauri (young) stars can be imaged directly (e.g., with HST)
Extrasolar Planets

Modern theory of planet formation is evolutionary

⇒ many stars should have planets

⇒ planets orbiting around other stars = “Extrasolar planets”

Extrasolar planets can’t be imaged directly

Detection using similar methods as in binary star systems:

Look for “wobbling” motion of the star around the common center of mass – also **transits** (planet moving in front of star) and **microlensing**
Indirect Detection of Extrasolar Planets

Observing periodic Doppler shifts of stars with no visible companion:

Evidence for the wobbling motion of the star around the common center of mass of a planetary system

Indirect evidence through wobbling motion of stars detects primarily Jupiter-like, large planets

Over 100 extrasolar planets detected so far
Evidence for “Extrasolar Asteroids”

Large amount of dust around young planetary systems might provide evidence for the presence of asteroids, producing dust in collisions.

This might currently still be going on in our own Solar System.
Direct Detection of Extrasolar Planets

Only in exceptional cases can extrasolar planets be observed directly

Preferentially in the infrared:

Planets may still be warm and emit infrared light; stars tend to be less bright in the infrared than in the optical
Class Announcements

• Lecture PDFs and other materials available from: web.science.mq.edu.au/~zucker/Astronomy_170.html
• Assignment #2 is due Monday, 29 March in box on 2nd floor of E7B, next to bridge to E7A
• Sign up sheet for Observatory practical available now and on my door (E7A 317) – the final session (the backup night for Session A) is tonight!
• Observatory practicals start at 8 PM and finish by 10 PM
• Observatory weather updates by 5 PM on the day at www.astronomy.mq.eduobservatory/public or call (02) 9850 8914 for a recorded message